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Future southcentral US wildfire probability due to climate change

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Abstract Globally, changing fire regimes due to climate is one of the greatest threats to ecosystems and society. In this paper, we present projections of future fire probability for the southcentral USA using downscaled climate projections and the Physical Chemistry Fire Frequency Model (PC2FM). Future fire probability is projected to both increase and decrease across the study region of Oklahoma, New Mexico, and Texas. Among all end-of-century projections, change in fire probabilities (CFPs) range from − 51 to + 240%. Greatest absolute increases in fire probability are shown for areas within the range of approximately 75 to 160 cm mean annual precipitation (MAP), regardless of climate model. Although fire is likely to become more frequent across the southcentral USA, spatial patterns may remain similar unless significant increases in precipitation occur, whereby more extensive areas with increased fire probability are predicted. Perhaps one of the most important results is illumination of climate changes where fire probability response (+, −) may deviate (i.e., tipping points). Fire regimes of southcentral US ecosystems occur in a geographic transition zone from reactant- to reaction-limited conditions, potentially making them uniquely responsive to different scenarios of temperature and precipitation changes. Identification and description of these conditions may help anticipate fire regime changes that will affect human health, agriculture, species conservation, and nutrient and water cycling.

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1 Introduction

Changing fire regimes due to climate is one of the greatest threats to ecosystems and society (IPCC 2012). Long-term historical records of fire regime characteristics have shown global fire activity which is associated with temperature changes at century to millennial time scales (Power et al. 2008). At continental to regional extents, shorter-term fire regime changes also include influences by ignitions and vegetation (fuels) (Parisien and Moritz 2009; Keeley and Syphard 2016). Currently, limited tools are available to predict future fire regime responses to climate change. Additional approaches to predicting changes in future fire regimes would help guide fire policies and mitigate wildfire costs that currently exceed billions of dollars in property losses, suppression costs, and reduced recreation expenditures, among others (Hoover and Bracmort 2015; USDA 2015).

Although details of the physics and inorganic chemistry of fire regimes may seem distant from wildland fire issues, wildfire activity fundamentally relies on chemical reactions of carbon compounds and oxygen within a complex ecological and abiotic framework (Chandler et al. 1983). Carbon bond formation and breakdown occur within primary ecosystem processes that are affected by climate, such as plant growth, decomposition, and fire (Krawchuk et al. 2009). Global fire activity is expected to respond to future increases in temperature and variable precipitation (Krawchuk et al. 2009; Moritz et al. 2014). Increased temperature is predicted to cause fire frequency to either increase or decrease depending on initial conditions and the physical chemistry of future fire regimes (Batllori et al. 2013; Guyette et al. 2014, 2017). Initial conditions related to fire frequency response often consider limitations by reactions (e.g., rates, number of ignitions) and reactants (e.g., fuels).

1.1 Physical Chemistry Fire Frequency Model

The Physical Chemistry Fire Frequency Model (PC2FM) was developed as an empirically based, spatially explicit, mechanistic model of landscape fire frequency parameterized with temperature and precipitation data (Guyette et al. 2012). Parameterization was accomplished using pre-industrial era (pre-1850 CE) climate and mean fire interval (i.e., fire frequency) data from across the continental USA (Guyette et al. 2012). Model formulation integrated experimental physics and chemistry (Atkins 1986; Harris 1987), fire ecology concepts (Chandler et al. 1983), and ancillary fire history evidence (Pyne 2010). The combined use of physics, chemistry, fire occurrence, and climate data to formulate a model of wildfire rates allows for estimating changes in future fire frequency (fire occurrence rates) from climate projections. As a physical chemistry model, the PC2FM has no geographic bounds; whether the reaction environment is a laboratory bench top or an ecosystem, ambient conditions and reactant concentrations follow laws of combustion reactions in a predictable manner (Wright and Bailey 1982; Bernard and Nimour 2007).

Formulation, calibration, and validation of the PC2FM considered fire occurrence rates as a function of an environmental reaction rate parameter (ARterm) and a reactant concentration parameter (PTrc); these are the two basic components of any non-nuclear chemical reaction (Eq. 1, Fig. 1; Guyette et al. 2012). Terms and estimates for the PC2FM were calibrated using multi-century fire frequency datasets from 170 sites representing diverse climates of the USA (see Supplemental Data in Guyette et al. 2012). Multiple regression coefficients translated the relatively fine-scale units of molecular reactions (e.g., mol L^{-1} s^{-1}) to units relevant to landscape-scale wildfire occurrence rates (e.g., mean fire interval (MFI) per ~ 1 km^2). MFIs

are the ecological analog of rate constants (k) in the Arrhenius equation. The PC2FM model form is given as:

$$MFI = A_o e^{\left(E_a/RT\right)} + 1/\left(P^2/T\right) \qquad (1)$$
$$\text{(ARterm)} \qquad\qquad \text{(PTrc)}$$

where $A_o e^{(E_a/RT)}$ is the ARterm parameter and takes the Arrhenius equation form for the effects of physical chemistry on fire frequency (i.e., reaction rate). The PTrc parameter is a proxy for fuel availability (concentration and moisture). Model variables are the following: A_o term = P^2/ppO$_2$; e = 2.718; E_a = 132 kJ mol^{-1}; R = 0.00831 kJ mol^{-1} K^{-1} (the universal gas constant); P = mean annual precipitation (MAP) in centimeters; T = mean annual maximum temperature (MMT) in degrees Kelvin; ppO$_2$ = partial pressure of oxygen.

The PC2FM is currently the only empirical climate-fire frequency model based on multi-century fire records. Currently, the PC2FM is being utilized across the USA and beyond to describe pyrogeography (Stambaugh et al. 2014; Lafon et al. 2017) and emphasize fire's historical ecological importance (Dey and Schweitzer 2014; Noss 2012). Recently, the PC2FM was applied to make projections of future fire probabilities from coarse-scale global climate change projections (Guyette et al. 2014) and to project future fire-climate envelopes for three primary southcentral US ecosystems (Stroh et al. 2018). In this paper, we present mid- and
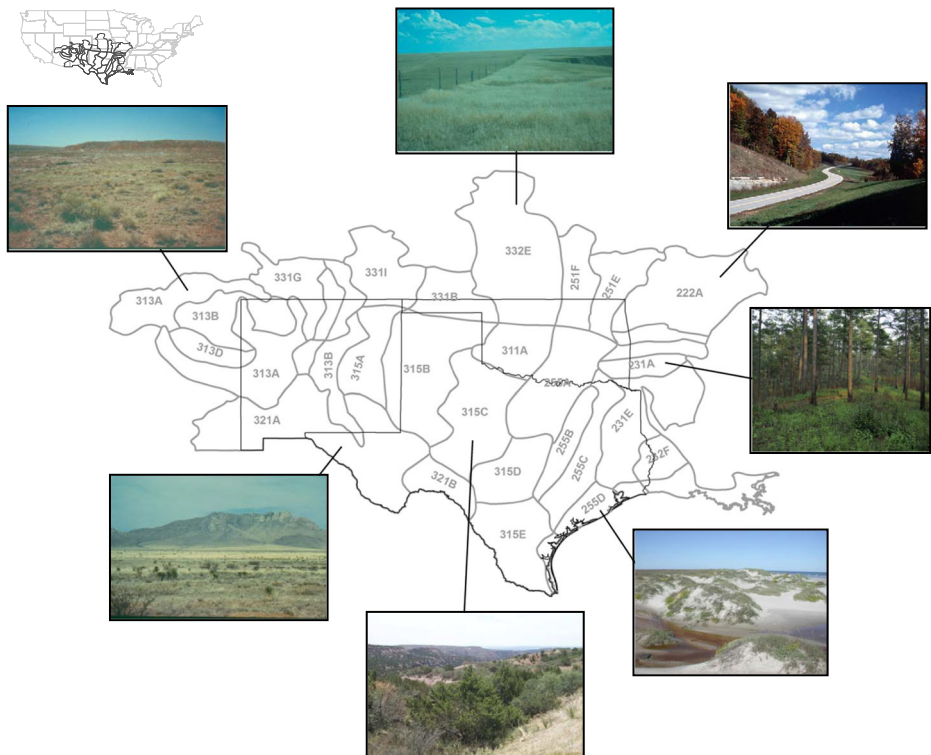

Fig. 1 Ecological sections of the southcentral US Representative photos from McNab et al. 2007. Section names are listed in Table 1

late-twenty-first century estimates of future fire probability for the southcentral USA using downscaled climate projections. Our objectives were to use downscaled climate projections and the PC2FM to (1) calculate and map future changes in fire probability and (2) quantify and locate fire regime tipping points in southcentral US ecosystems. We hypothesized that, due to increases in temperature and changes in precipitation, future fire probability will increase across the majority of the southcentral USA regardless of which global climate models are considered. Within this effect, we further expected areas to show fire regimes cross tipping points whereby future fire probabilities decrease due to increasingly reactant (fuel)-limited conditions associated with desertification.

2 Methods

2.1 Study region

For the purpose of this study, we identified the southcentral US study region as the ecological sections occurring within or intersecting Oklahoma, Texas, and New Mexico (Bailey 1995). The study region was composed of 53 ecological sections ranging from dry to humid temperate climates and supporting broadleaf and coniferous forests, prairies, semi-desert woodlands and shrublands, and deserts (Fig. 1). Significant west to east gradients exist for increased growing season relative humidity, increased precipitation, decreased wind speeds, decreased solar radiation, and increased cloud cover. In totality, these conditions cause a west to east fire regime transition from reactant- to reaction-limited conditions (Moritz et al. 2012; Guyette et al. 2015). In reactant-limited conditions, increased temperatures and decreased precipitation are expected to decrease fire frequency. In reaction-limited conditions where fuel amounts are not limiting fire frequency, but ignitions and fuel-moisture are, the same climate changes are expected to increase fire frequency.

Despite highly varied vegetation and fire regimes within the study region, broader climate conditions (e.g., wetter, colder, drier, and hotter) exist across the USA. PC2FM parameterization relied on relationships developed from these broader climate-fire frequency conditions. To ensure that a sub-regional PC2FM did not have an improved parameterization or performance, we explored re-parameterization using historical fire occurrence datasets limited to the study region. Through multiple model and data considerations following the approach of Guyette et al. (2012), we concluded that a sub-regional PC2FM model was not more powerful than the original PC2FM and, hence, proceeded with calculations of baseline and future fire probabilities in the study region.

2.2 Climate datasets

Climate datasets from three atmosphere-ocean general circulation models (AOGCMs) were input to the PC2FM. Datasets were accessed from Inside Idaho Interactive Numeric & Spatial Information Data Engine (http://cloud.insideidaho.org/webapps/search/iso_browse. aspx?filter=Climatology/Meteorology/Atmosphere) and represented model output downscaled to 4-km resolution using the Bias Corrected Statistical Downscaling (BCSD) method and applying the Parameter-elevation Relationships on Independent Slopes Model (PRISM) to account for topographic effects. The PRISM utilizes a digital elevation model (DEM) and climate station data to weight grid cells based on physiographic conditions (Daly

et al. 2004). The three AOGCMs were the following: dominance of drier conditions (GFDL)-CM2.1 from the Geophysical Fluid Dynamics Laboratory (NOAA 2009), dominance of regionally wetter conditions (CGCM) 3.1 T47 from the Canadian Centre for Climate Modeling and Analysis (Flato et al. 2000), and UKMO-mixed changes (HadCM3) from the Hadley Centre for Climate Prediction and Research (Gordon et al. 2000). Model outputs are from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset A1B scenario. The A1B mid-emission storyline is one of the very rapid economic growths, a global population peak in mid-century followed by a subsequent decline, and rapid introduction of new and more efficient technologies. We selected this scenario, because it represents a balanced future that does not rely too heavily on one particular energy source and assumes improvements to all energy supply and end use technologies. Through the models above, A1B produces highly variable results for precipitation patterns across the study region, which we expected could be useful in demonstrating a wide range of plausible future fire probability outcomes.

Within a GIS environment, we compiled 30-year averaged rasters for MMT and MAP for each AOGCM using monthly datasets available for the period from 1900 to 2100 CE. These specific climate projection datasets were of particular interest, because they were available as hindcasts and forecasts based on the same models and because initial PC2FM modeling utilized PRISM climate data. We calculated the cumulative sum of monthly data and then averaged over 30-year periods using R software (R Development Core Team 2008) and the ncdf 1.6.8 package (Pierce 2014). Rasters representing period averages were calculated for a baseline period (1900 to 1929 CE), mid-twenty-first century (2040 to 2069 CE), and end-of-century (2070 to 2099 CE). We chose 30-year periods because (1) climate data are commonly normalized to 30-year averages and (2) a 30-year period allowed us to consider two future time periods within the twenty-first century.

2.3 Fire probability

Fire probability (i.e., ignition and spread) is influenced by ecological and chemical characteristics of the reaction environment (Parisien et al. 2012). Mean fire interval estimates generated by the PC2FM are the chemical analog of time and likelihood-based rate constants in combustion reactions (Guyette et al. 2014). Therefore, for landscapes, the rate of fire occurrence over time (i.e., MFI) is an estimate of its average probability. We calculated fire probabilities as the reciprocal of MFI. Fire probabilities were generated for the baseline, mid-, and late-century periods for each AOGCM. We assessed the magnitude of change in fire probability for each AOGCM by calculating percent change in fire probability (CFP) from the baseline to future periods where:

$$CFP = ((\text{Fire probabilty}_{future} - \text{Fire probability}_{baseline})/\text{Fire probability}_{baseline}) \times 100$$

We present CFPs as a percentage change from baseline conditions, because some locations initially have inherently low or high fire probabilities, and absolute changes in fire probability are less meaningful for comparisons. We summarized CFPs (ranges and means) by ecological sections using the zonal statistics tool within ArcGIS software (2016). Maps of fire probability at the baseline period and CFPs to mid- and late-twenty-first century were created to visualize spatial patterns. For this, CFPs were condensed into six classes representing increases, decreases, and no or minimal change. In addition, we constructed vector plots to demonstrate CFP magnitudes and directions using a subset of 413 randomly chosen locations. Vector plots were presented on combustion-climate diagrams of the PC2FM (Guyette et al. 2017) that

included MAP, MMT, and fire probability. Vector termini represented baseline and end-of-century fire probabilities predictions, respectively.

3 Results

3.1 Mean maximum temperature

Within the study region, baseline MMTs ranged from 4.6 to 30.6 °C (Fig. 2). Overall, spatial representation of baseline temperature patterns was consistent across AOGCMs. Lowest MMTs occurred in the highest elevations, particularly in the Southcentral Highlands Section of northern New Mexico. Highest baseline MMTs were located in the Rio Grande Plain Section in southernmost Texas. Within ecological sections, the greatest variability in MMTs occurred in New Mexico in association with high topographic variability of mountain ranges.

Projections of increasing MMTs to the mid-century were relatively consistent across AOGCMs. The greatest increases were projected for northern and western portions of the region (i.e., mountains, highlands, southcentral Great Plains). Generally, sections along the Gulf Coastal Plain were projected to have the smallest increases in MMTs. Baseline to mid-century MMTs for ecological sections were projected to increase from 2.3 to 4.8 °C. For the entire study area, mean regional increases in baseline to mid-century MMTs ranged from 3.4 to 3.5 °C between all AOGCMs.

End-of-century projections of changes in MMTs were more variable across AOGCMs compared to those of the mid-century. Similar to mid-century projections, the greatest end-of-century increases in MMTs were projected for western and northern portions of the study region. Generally, ecological sections along the Gulf Coastal Plain were projected to have the smallest increases in end-of-century MMTs. Among AOGCMs, baseline to end-of-century
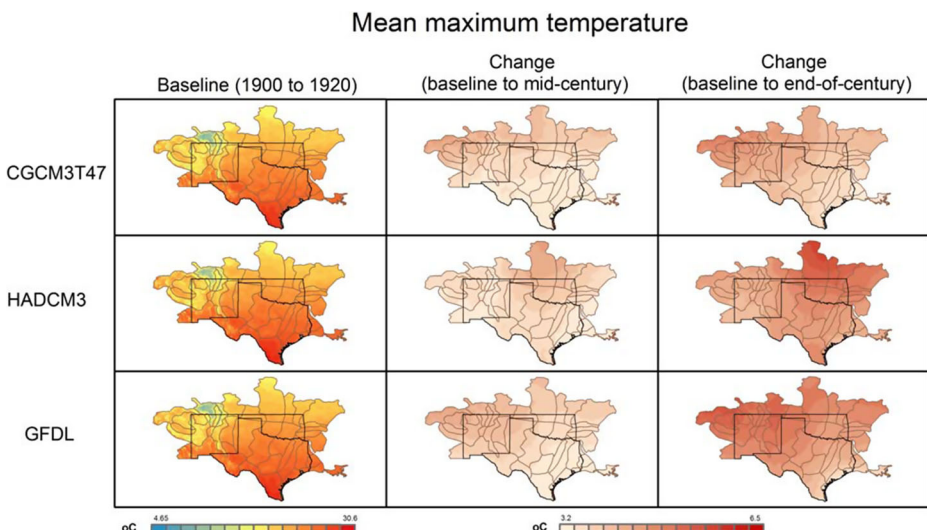

Fig. 2 Baseline and future projected changes in mean maximum temperature for the southcentral USA based on output from three AOGCMs under A1B scenario

changes in MMTs across sections were projected to increase by 3.0 to 5.7 °C with mean regional increases in baseline to end-of-century MMTs ranging from 3.9 to 4.5 °C.

3.2 Mean annual precipitation

Baseline period MAP ranged from 13 to 193 cm across the study region (Fig. 3). Spatial representation of baseline period MAP patterns was similar across AOGCMs. The GFDL model showed slightly wider range of MAP values overall (− 2 to + 12 cm relative to other AOGCMs). The driest portions of the region were located in the westernmost ecological sections (e.g., Basin and Range, Mountains, Highlands), particularly at lower elevations, while the wettest portions were located in the southern and easternmost ecological sections (e.g., Gulf Coastal Plains and Ozark, Boston, Ouachita Mountains).

Projected changes in MAP from baseline to mid-century varied widely across AOGCMs. MAP projections ranged from dominance towards regionally drier conditions (HadCM3 and GFDL) to CGCM. Among AOGCMs, the only common trend was for decreased MAP in the Grand Canyon Lands Section of western New Mexico extending into Arizona. Greatest projected baseline to mid-century changes in MAP were + 20 cm (CGCM) and − 39 cm (GFDL), respectively. Greatest decreases from baseline to mid-century MAP were projected for ecological sections in western Oklahoma (Redbed Plains, South Central Great Plains Sections) and along the Gulf Coast.

Baseline to end-of-century projections of MAP showed three scenarios of change: CGCM, HadCM3, and GFDL. For all AOGCMs, projected end-of-century MAP values ranged from − 32 to + 36 cm; both extremes were represented in the GFDL projection. Model agreement in end-of-century MAP changes only existed in the western ecological sections (e.g., Grand Canyon Lands Section). In summary, unlike MMT, high variability in MAP patterns was projected by the AOGCMs.
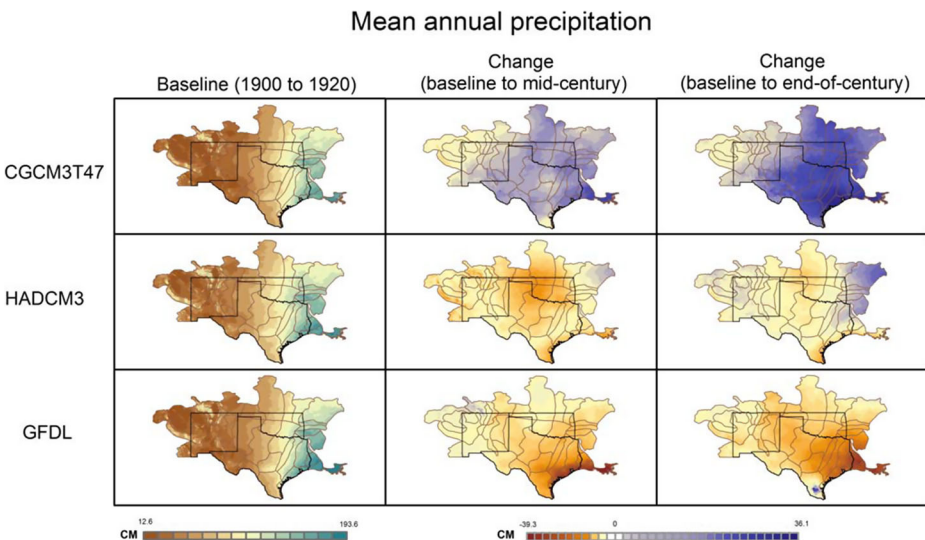

Fig. 3 Baseline and future projected changes in mean annual precipitation for the southcentral USA based on output from three AOGCMs under A1B scenario

3.3 Fire probability

Future fire probability was projected to either increase or decrease depending on geographic location within the southcentral USA (Table 1, Fig. 4) (Stambaugh et al. 2018). From baseline to mid-century, CFPs varied from − 47 to + 165%. At mid-century, CFPs were projected to be positive in the eastern portions of the study region and negative in western portions. Despite mid-century decreases in fire probabilities projected across large western extents (HadCM3, GFDL), across all models, greatest increases in fire probabilities were projected for high elevations (e.g., > 2700 m a.s.l.) of New Mexico (Grand Canyon Lands, South central Highlands) and locations where ecological sections extend farther north and west into Colorado and Arizona. Locations with small to no change in fire probability (white areas, Fig. 4) were projected only in western portions of the study region for the CGCM model, and along a north-south line through the center of the study region for HadCM3 and GFDL. This line is the potential climate-fire threshold bisecting the region into reactant-limited ecosystems to the west and reaction-limited ecosystems to the east (Guyette et al. 2015). Change in fire probability data for each GCM baseline and future period are available online (Stambaugh et al. 2018).

Overall patterns of CFPs predicted for mid-century were also predicted to persist until the end-of-century. Across all end-of-century projections, CFPs ranged from − 51 to + 240%. Larger areas of positive CFPs were projected for the CGCM and HadCM3 AOGCMs, while smaller areas of negative CFPs were projected for the GFDL model. High elevation locations in the mountainous northwest portions of the study region were projected to continue to have the greatest increases in fire probabilities. Additional areas of relatively high CFPs (> 100% increase in fire probability from baseline to end-of-century) were projected for the eastern edge of the study region based on the GFDL model. Areas with small to no CFPs were expanded in the end-of-century period excluding the GFDL model.

Based on vector plots showing direction and magnitude of fire probabilities from baseline to end-of-century periods, greatest increases were projected within the range of approximately 75 to 160 cm MAP, regardless of AOGCM (Fig. 5). Decreased fire probabilities were limited to conditions where MAP was less than about 80 cm. Conditions with MAP between approximately 45 and 75 cm showed the most variable responses in future fire probability. Decreases in future fire probability due increasingly fuel-limited conditions (i.e., desertification) were confined to the lowest precipitation ranges.

4 Discussion

PC2FM model output suggests ecosystems of the southcentral USA will undergo varied responses to fire probability based on future climate projections. Recent studies have divided fire regimes into two fire frequency conditions: reactant-limited (e.g., limited by amount and production of fuels; southern and western ecoregions) and reaction-limited (e.g., limited by combustion potential; north and eastern ecoregions) (Guyette et al. 2015). These conditions are relevant to the future, because they represent the initial conditions from which future changes in climate, vegetation (fuels), and fire activity will depart. Based on this study, although fires are predicted to be more frequent across most of the southcentral USA due to climate conditions, regional trends may remain similar (i.e., negative to positive CFPs from west to east). This assumes that changes in MAP are not significantly more spatially variable since, with warming, extensive increases in MAP (e.g., MAP projections by CGCM3 model) were

Table 1 Statistical summaries of projected changes in fire probability (CFP) for southcentral US ecological sections from a baseline period (1900 to 1929) to mid- (2040 to 2069) and end-of-twenty-first century (2070 to 2099)

Changes in fire probability (CFP, %)

| | | CGCM | | | | | | HadCM3 | | | | | | GFDL | | | | | |
| | | Mid-century | | | End-of-century | | | Mid-century | | | End-of-century | | | Mid-century | | | End-of-century | | |
Code	Ecological section	Min	Max	X̄	Min	Max	X̄	Min	Max	X̄	Min	Max	X̄	Min	Max	X̄	Min	Max	X̄
222A	Ozark Highlands/Boston Mountains	21	45	33	41	66	55	−32	66	19	−10	84	34	−9	46	17	−26	56	10
231A	Ouachita Mountains	36	61	45	37	54	47	43	81	61	61	101	79	27	62	44	31	81	54
231E	Mid Coastal Plains, Western	−1	44	10	26	50	38	−47	60	−29	−28	74	−11	−39	64	−27	−51	69	−39
231F	Eastern Gulf Prairies and Marshes	−17	150	49	27	32	30	−28	156	47	−3	140	60	−19	115	46	−29	198	63
231G	Arkansas Valley	43	70	58	38	57	47	46	86	59	64	108	79	50	97	71	64	133	93
232E	Louisiana Coast Prairies and Marshes	42	72	57	28	40	33	55	82	68	71	101	88	40	75	60	50	99	78
232F	Coastal Plains and Flatwoods, Western Gulf	−2	101	28	31	38	34	−30	161	21	−7	154	37	−33	151	22	−43	240	24
251E	Osage Plains	13	37	24	38	59	50	−43	−1	−32	−23	26	−10	−31	13	−14	−45	−1	−30
251F	Flint Hills	−1	93	18	38	51	43	−32	154	3	−7	140	25	−20	137	8	−30	224	7
255A	Cross Timbers and Prairie	−23	159	5	31	45	37	−42	165	−7	−11	160	21	−21	120	6	−37	204	−6
255B	Blackland prairies	−22	52	4	30	41	33	−39	90	−20	−14	96	6	−33	84	−7	−46	116	−21
255C	Oak woods and prairies	12	45	23	26	39	32	−37	45	−24	−18	57	−5	−36	45	−30	−50	45	−44
255D	Central Gulf Prairies and Marshes	14	48	27	23	30	27	−44	−4	−27	−21	23	−5	−41	11	−25	−51	−3	−41
311A	Redbed Plains	24	37	30	34	50	38	−34	49	8	−1	64	31	−10	33	10	−29	39	2
313A	Grand Canyon Lands/White Mtn—San Fran Peaks	18	47	31	−9	136	16	−6	79	34	7	92	49	−19	73	23	−31	95	22
313B	Navajo Canyonlands/Sacramento—Monzano Mtns	−17	24	−7	−7	82	14	−41	33	−25	−10	45	7	−16	18	−8	−32	8	−23
313D	Painted Desert	43	61	47	−10	30	−2	49	86	61	66	108	78	53	97	67	66	134	87
313E	Northern Rio Grande Intermontane	5	55	14	9	65	20	−32	85	−19	−6	89	6	−21	78	−11	−34	106	−23
315A	Pecos Valley	17	33	24	19	83	36	−32	7	−16	−13	23	1	−42	1	−24	−47	−6	−35
315B	Texas High Plains	38	57	48	23	105	47	54	91	70	71	111	87	53	99	77	65	144	106
315C	Rolling Plains	29	49	37	33	81	49	34	68	51	47	84	65	33	82	61	34	123	81
315D	Edwards Plateau	18	40	28	31	58	40	11	67	35	18	79	46	−12	63	28	−3	81	34
315E	Rio Grande Plain	−8	81	33	23	68	43	−40	127	−20	−25	124	−3	−44	116	−19	−48	202	−32
315F	Southern Gulf Prairies and Marshes	18	36	26	25	40	32	9	62	29	16	72	40	−17	55	17	−9	67	15
321A	Basin and Range	14	28	21	1	146	54	−16	28	7	−4	39	18	−37	6	−17	−40	12	−18

Table 1 (continued)

| | | Changes in fire probability (CFP, %) | | | | | | | | | | | | | | | | | |
| Climate model | | CGCM | | | | | | HadCM3 | | | | | | GFDL | | | | | |
| Period | | Mid-century | | | End-of-century | | | Mid-century | | | End-of-century | | | Mid-century | | | End-of-century | | |
Code	Ecological section	Min	Max	$\overline{X}$	Min	Max	$\overline{X}$	Min	Max	$\overline{X}$	Min	Max	$\overline{X}$	Min	Max	$\overline{X}$	Min	Max	$\overline{X}$
321B	Stockton Plateau	26	34	31	49	106	70	48	62	54	63	86	72	66	94	77	86	124	102
331B	Southern High Plains	23	53	34	24	45	33	−29	0	−17	−14	14	0	−45	−31	−40	−43	−19	−33
331F	Southern Parks and Ranges	23	33	27	9	114	36	50	72	62	60	92	82	64	102	88	75	117	103
331G	South-Central Highlands	30	35	32	3	152	58	48	57	53	63	82	75	60	83	73	70	96	85
331I	Arkansas Tablelands	18	37	27	11	52	21	17	59	38	24	75	50	−1	80	41	15	91	52
331J	Upper Rio Grande Basin	−8	41	15	9	113	27	−27	19	−8	−26	28	−3	−43	2	−32	−26	89	0
332E	South-Central Great Plains	−3	20	11	29	46	40	−21	24	−3	−18	34	4	−32	6	−17	0	24	12
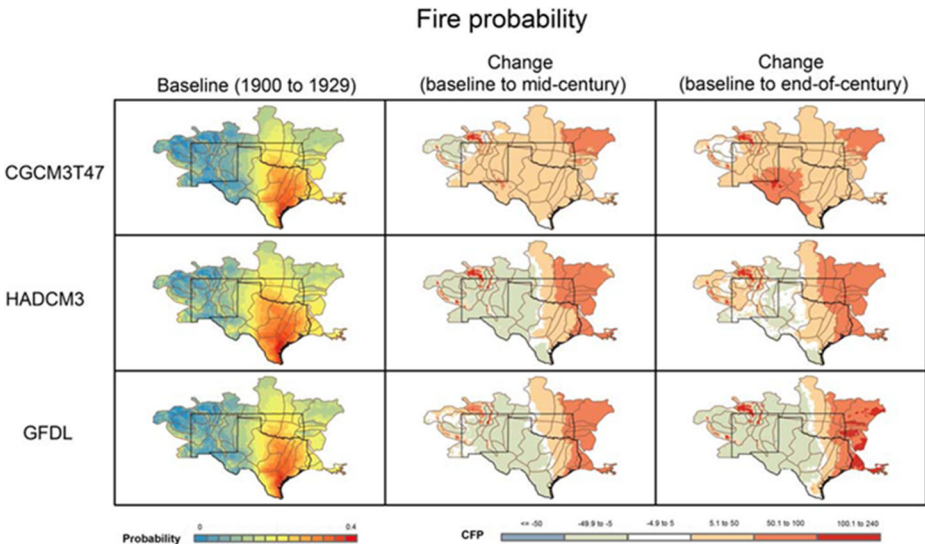
Fig. 4 PC2FM-derived future changes in fire probability from baseline period (1900 to 1929) to mid- (2040 to 2069) and end-of-century (2070 to 2099) time periods

predicted to cause larger areas to experience increased fire probabilities, presumably due to fire frequency being in a reactant-limited condition across many ecological sections.

Patterns of future projected CFPs support similar projections made at coarser scales and with varied materials and methods (Krawchuk et al. 2009; Gonzalez et al. 2010). Our projected CFPs and trends are also consistent with projections for comparable biomes (Moritz et al. 2012). A potential limitation of our projections is that the PC2FM was developed using annual climate means (i.e., MMT, MAP), and in cases when fires are moisture regime or seasonally constrained and high intra-annual climate variability is projected, the ability to consider these conditions may improve projections (Keeley and Syphard 2016; Margolis et al. 2017). Other factors not considered by the PC2FM may serve to further offset or enhance projections such as those affecting net primary productivity (e.g., nutrient cycling, atmospheric CO_2 concentration; Melillo et al. 1993). Future versions of gridded climate datasets (Strachan and Daly 2017) and the PC2FM may also improve fire probability projections.

Perhaps one of the most important results of this study was the recognition that future climate conditions may produce varied fire probability response. Climate parameters utilized by the PC2FM (i.e., MMT, MAP) appear to be capable of identifying the conditions of these tipping points. Here, we define tipping points as conditions where CFP response to changing climate reverses from decreasing to increasing or vice versa. CFP response and PC2FM-derived tipping points could be further validated by long-term fire occurrence datasets across southcentral US climate-fire gradient (Fig. 5). Evidence for tipping points in fire activity exists in global fire occurrence patterns (e.g., fire activity across desert-forest biome transitions). Temporal evidence of tipping points can be found in historical changes in regional fire potential during short-term climatic events such as droughts, reflecting the sensitivity of regional fire regimes to short- and long-term vegetation (fuels) changes (Chamrad and Box 1965, Mensing et al. 2006; Hanson et al. 2010). Additional physical fire environment changes are possible as climate changes may alter vegetation and reactivate regional sand dunes and sheets (Risser 1988; Muhs and Maat 1993). A more comprehensive and detailed analysis
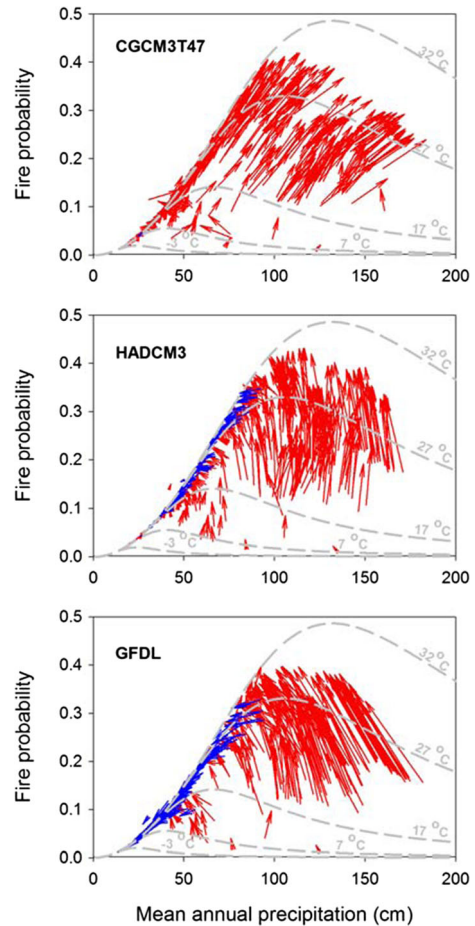
considering vegetation growth strategies, topography, antecedent climate conditions, and vegetation (fuel) species would further determine more individualized ecosystem responses and CFPs. Within the wildland fire context, consideration of lagged climate effects and feedback mechanisms are needed since vegetation can be resistant (e.g., drought adapted) and/or resilient (e.g., long-lived) and increased burning frequency may result in increased evaporative demand and decreased soil moisture (Briggs and Knapp 1995).

5 Conclusion

This modeling work demonstrated where changes in southcentral US fire regimes are predicted to occur (if at all) under projected future climate conditions. Within the context of fire frequency and future fire probability, southcentral US ecosystems will have unique responses to the diverse combinations of temperature and precipitation changes. The locations and estimated direction of CFPs (+/−) can inform fire management, which is faced with broad challenges that include human health, agriculture, species conservation, and carbon and water

cycling (North et al. 2012; Mitchell et al. 2014; Scasta et al. 2016). Variable climate projections from different AOGCMs allowed for multiple future outcomes and fire rates demonstrating varied response through the end of the twenty-first century. Implications of these results for management programs are particularly relevant to perceptions of fire risk, policies related to wildland fire and fuels management, and the potential of adapting communities to future conditions.

We suggest that PC2FM projections have utility for understanding fire regime-climate dynamics. In particular, identifying relevant climate variables and understanding fire-climate tipping points will aid proactive fire planning. In the southcentral USA, geographic variation in climate conditions causes fire frequency to transition from reactant-limited to reaction-limited along a west to east gradient (Guyette et al. 2015; Keeley and Syphard 2016). From this, future changes in temperature, precipitation, and their interactions can gradually or rapidly change fire probability (Fig. 4). For fire and natural resource managers, model results based only on climate data may leave out many important factors that influence fire probability (e.g., ignition sources, topography, vegetation type, and land use), but the advantage of this approach is the ability to isolate climate influences from these other factors. Future fire probability in the southcentral USA is expected to be sensitive in the future projected climate changes with potential for significant departures from early twentieth century levels.

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