Project Title: Impacts of Mega-Fire on Large U.S. Urban Area Air Quality under Changing Climate and Fuels

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I. Abstract

Mega-fires can adversely impact air quality in the United States and the impacts are likely to become more serious in the future due to the possibility of more frequent and intense mega-fires in response to the projected climate change. This study investigated U.S. mega-fires and fuel conditions and their environmental impacts under the changing climate. A comprehensive approach of data analysis, algorithm development, and numerical modeling was used to understand present mega-fires, project their future trends, and simulate fuel loading and smoke transport. Dynamical downscaling of regional climate change was used to obtain present and future fire potential indices and atmospheric conditions. Ensemble was made based on the results obtained under multiple combinations of global-regional climate model simulations. The major accomplishments included building mega-fire-climate relationships using historical data, revealing the spatial and temporal features of climate conditions for fires, developing mega-fire occurrence probability projection models using extreme value theory, projecting future mega-fire trends using the dynamically downscaled regional climate change scenarios, projecting future fuel loading using a dynamic global vegetation model with a developed algorithm for filling the time gap with the climate change scenarios, projecting the impacts of climate change on escape risk and burn windows of prescribed burning, and estimating emission changes in response to changing fire and fuel and the smoke impacts on air quality.

The research with this project led to some major findings on climate, fuel, and fire interactions. Close relationship was found between mega-fires and the Keetch-Byram Drought Index, which was substantially different between the inactive and active mega-fire episodes transited in the mid-1990s. Future fire potential would become more severe by one grade in many regions. The fire concurrent probability, however, would become smaller in summer for all regions except North Central and Northeast. The mega-fire projection model is capable of simulating the distribution of fire occurrence with abnormal KBDI category. The mega-fires are projected to increase by nearly 60% by middle this century, despite large variability among regional climate change scenarios. An increase in fuel load was projected for the future, mainly in the western U.S. An algorithm was developed to fill the time gap with the regional climate change scenarios to improve ecosystem modeling of fuel load. The prescribed burn windows are expected mostly to become shorter in the future in the eastern U.S., the Pacific coast and southwestern border areas due to increasing escape fire risks. The $PM_{2.5}$ emissions from mega-fires increased several times from the inactive fire episode of 1980-1996 to the active fire episode of 1997-2013 and are expected to increase remarkably in the future, leading to more deteriorative air quality conditions in some large U.S. cities.

The research findings were delivered to land managers and researchers through a workshop, 9 presentations, and 6 published journal / book chapter papers with several other manuscripts are complete or in preparation. The datasets for present and future mega-fire events, climatology of current and future fire indices, future change in fuel loading and particle concentrations are provided.

II. Background and Purpose

Wildfire is one of the major natural disasters in the United States. About 100 thousands of wildfires occurred that burned out about 4.4 millions of acres of federal lands annually from 1960 to 2012 (http://www.nifc.gov/). The major damages by wildfires are caused by the uncontrollable "mega-fires", which are often characterized by 3B (big intensity, big impacts, and big efforts for relief), and occur mostly under severe drought conditions. These large fires together represent less than 1% of all wildfires but cause most damages by accounting for 90% of the area burned and 80% of suppression costs (Williams 2004). The 2003 Southern California fires, for example, led to 22 human lives lost, 4,000 homes destroyed, and billions of dollars cost.

Wildfires in the U.S., including mega-fires, have increased remarkably in the past two decades (Westerling et al. 2006, Dennison et al. 2014). The total annually burned area during this period was doubled in comparison with that during the past five decades (http://www.nifc.gov/). One urgent issue the fire community needs to address is if and how much mega-fires would continue to increase this century under the changing climate. Climate is one of the major driving forces for wildfire occurrence and spread (Pyne et al. 1996). Under warm and dry conditions, a fire season becomes longer, and fires are easier to ignite and spread. Climate models have projected that the greenhouse effect would result in significant climate change (IPCC 2013), including an overall increase in temperature worldwide and a drying trend in many subtropical and mid-latitude areas. Thus, it is likely that wildfires would increase in these areas. Efforts have been made to project future fire trends under changing climate in the U.S. (e.g., Brown et al. 2004, Liu et al., 2005, Balshi et al. 2008, Flannigan et al 2009, Spracklen et al. 2009, Yue et al. 2013).

Wildfires can also produce severe environmental consequences by degrading air quality (Riebau and Fox 2001) and therefore affecting human health. Projection of the environmental consequences of the future mega-fires under changing climate is another important issue for the fire community to address. Efforts have been made to assess the air quality effects of projected increases in wildfires. Spracklen et al (2009), for example, projected an increase by 54% by the 2050s for annual mean area burned in the western U.S., near doubling of wildfire carbonaceous aerosol emissions, increasing summertime organic carbon aerosol concentrations by 40% and elemental carbon concentrations by 20% based on a GCM climate projection and chemical model simulation.

Projection of future mega-fire trends and the environmental impacts due to climate change, however, is a great challenge. One problem arises when the traditional statistical distributions are used to model extreme weather and the related wildfires. Extreme weather and wildfires occur in the very far tail of both magnitude and frequency distributions. They may not meet the conditions required for the statistical distributions. Thus, there might be less reliable relationships connecting the extremes to their predictors using regular statistical theory. Furthermore, statistical distributions are built based on a large amount of observations. Extreme weather and large fires, however, are rare events. Observations are much fewer than the normal values.

New statistical tools such as the extreme value theory (EVT) have been applied recently as a solution to the problem. Different from regular statistical tools that describe mean, variance and skewness (the first, second, and third moments of probability distribution function), EVT describes the tail (fourth moment). The dynamic or non-stationary features (i.e., temporary trends or time dependence) of extreme event magnitude, frequency, duration, etc. are analyzed through extreme value models directly or through generalized linear models (GLM) separately. The EVT has been applied to extreme weather and climate events that are closely related to wildfires such as hot spells and heat wave (Photiadou et al. 2014). The value of EVT for wildfire was also recognized long time ago (Alvarado et al. 1998). Recently Barbero et al. (2014) projected large fires (>10k ha) over the 1984-2010 period across ecoregions under changing climate using empirical generalized linear models. Keyser et al. (2014) predicted high severity fire occurrence and area burned in a changing climate for three western U.S. regions using logistic regression and generalized Pareto distribution (GPD) to determine presence / absence and annual area burned of high severity fire (500 acres or larger).

Another problem is the change with fuel condition, which is one of the three environmental factors for wildfire in addition to climate and topography. Fuel loading is also a factor for fire emissions together with burned area, emission factor, and consumption efficiency. The mass of a fuel will change under changing climate besides the possible shift from a species type to another. Zhang et al. (2009) projected large change in fuel loading in the southeastern U.S. in response to climate change. The importance of the fuel mass change as one of the contributors to the environmental impacts of future wildfires has yet to be sufficiently examined. The dynamic global vegetation models (DGVMs) have been greatly improved in both capacity and reliability, providing a useful tool for projecting fuel change.

Climate projection is often one of the major sources of uncertainty in fire and smoke study. The climate change scenarios produced by general circulation models (GCMs) have spatial resolutions of several hundreds of kilometers. They poorly resolve the substantial western U.S. terrain that is one of the major factors for the fire weather regime. Statistical downscaling of the GCM projections can produce very high-resolution climate with high computation efficiency. However, it is based on observations which are usually sparsely distributed in mountains; local physical processes such as the snow-albedo feedback (Mass et al. 2010) are largely missed. A solution to be used for this study is dynamic downscaling of GCM projections using regional climate models (RCMs). RCMs have spatial resolutions at tens of kilometers or higher and are often equipped with more detailed schemes for local and regional properties. One uncertainty with dynamical downscaling is model dependence, which could lead to different projection of future wildfire trends from one model to another. Both statistical and dynamic downscaled regional climate change datasets have been developed for assessing the impacts of climate change in the U.S.

The purpose of this JFSP project was to project future trends in mega-fires and fuels and their environmental impacts using advanced extreme value theory, dynamic

vegetation modeling, and dynamically downscaled regional climate change scenarios. The objectives to be achieved included building mega-fire-climate relationships, developing mega-fire occurrence probability projection models, projecting future mega-fire trends, fuel loading, the impacts of climate change on prescribed burning, and estimating emission changes and the smoke impacts on air quality. The new knowledge on the future mega-fire trends and impacts from this project are expected to provide essential and useful information to land managers, policy makers, and researchers for developing climate change adaptation and mitigation strategies and for further evaluating the potential impacts on climate, ecosystems, and human health.

III. Study Description

A. Analysis and synthesis of climate and fire relationship

The relationship was analyzed as scientific foundation for developing mega-fire projection models. Historical climate and fire datasets were used. The meteorological elements of temperature, precipitation, humidity, and wind were obtained from the North American Regional Reanalysis (NARR) (Mesinger et al. 2006). The data were produced by combined approach of meso-scale meteorological modeling and data assimilation. The data are available at a horizontal grid spacing of 32 km and 3-hour frequency from 1979 throughout now.

The historical wildfire data were obtained from the Federal Wildland Fire Occurrence (FWFO) Data (wildfire.cr.usgs.gov), which contains over 677,000 fire records from 1980 through 2013 collected by Federal land management agencies. Forty mega-fires were identified with the criteria of burned areas greater than 200k acres. All but two occurred in the western U.S. (Figure 1), including 14 in the arid southwestern region, 5 in the Mediterranean Pacific region, and rest in the intermountain / mountain regions. The data period was divided into inactive and active fire episodes separated by the year of 1996 with a majority of fires (34) occurred in the second episode. Most fires (32) occurred in summer, 6 in spring, and 2 in fall. Another fire dataset, the Monitoring Trends in Burn Severity (MTBS) (http://www.mtbs.gov/) was also used, which includes large wildland fires (>1000 acres in west, 500 acres in east) during1984 – 2012.

The fire-climate relationships from previous studies were reviewed and synthesized. New analyses were made through comparing the large anomalies of the fire weather indices and meteorological elements corresponding to mega-fires. Four fire weather indices were calculated: Keetch–Byram Drought Index (KBDI) (Keetch and Byram 1968). KBDI is an indicator of soil moisture deficit. It is an accumulated property of dry or wet conditions, which makes it useful for assessing large fires potential. (2) Fosberg fire weather index (FFWI) (Fosberg, 1978). One of the recognized limitations with KBDI is that it does not include humidity and wind, which are also closely related to fire occurrence and behavior (Flannigan and Harrington 1988). FFWI is dependent on temperature, relative humidity, and wind speed, but independent of precipitation. (3) Large fire potential - meteorological conditions (LFPM). LFPM measures windy and dry (unsaturation degree) conditions. It is mainly used in southern California where the Santa

Ana wind is one of the major wildfire factors. (4) Evaporative stress index (ESI), a ratio of actual to potential evapotranspiration. It becomes smaller during a dry and hot period. Individual meteorological elements of temperature, precipitation, relative humidity, and wind were used as well.
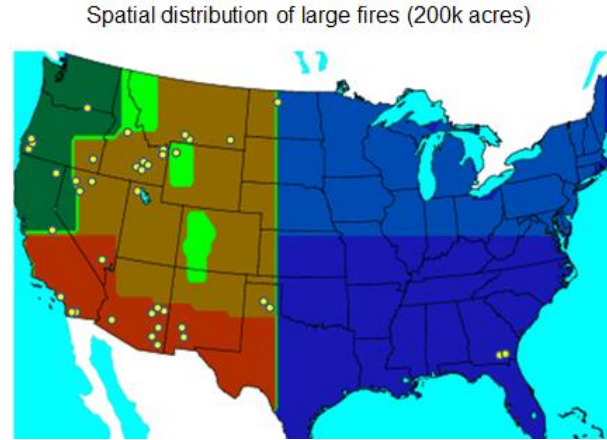

Figure 1 The mega-fires during 1980-2014.

B. Projection and analysis of future fire potential

Future fire potential measured by KBDI and modified FFWI was projected using the dynamically downscaled regional climate change scenarios generated by the North American Regional Climate Change Program (NARCCAP) (Mearns et al. 2012). Data are available for the present period of 1971-2000 and the future period of 2041-2070 at a spatial resolution of 50 km for the IPCC A2 emission scenario. There are total 10 climate change scenarios are available from various GCM-RCM combinations. Seven of them with complete datasets were used for this project.

Concurrence probability of wildfire was used to indicate how often when large wildfires occur in a same season between two regions. It was calculated using the FWFO fire data to understand present feature, and using fire weather index calculated based on the regional climate change scenarios to project the future trends. An algorithm was developed to calculate the concurrence probability.

C. Model development and projection of mega-fire occurrence

The mega-fire projection model was developed based on climate-fire relationship and EVT (Figure 2). Poisson distribution, a useful EVT tool to model frequency of extreme events was used in model development:

$$P_r(Y = y) = \frac{e^{-\mu}\mu^y}{y!} \qquad (1)$$

and the linear regression equation:

$$f(\mu) = \beta_0 + \sum_{n=1}^{N}(\beta_n x_n) \qquad (2)$$

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where *Y* is wildfires with burned areas greater than a threshold of *y*. μ is both average and variance of *Y*, that is $\mu=ave(Y)=var(Y)>0$. *F* is a linear or nonlinear function of the statistical property of wildfire, which is the average / variance for this case. *X* is prediction factor determined by climate condition. *β* is coefficient to be determined. *N* is the number of predictors. The peak probability of an event following the Poisson distribution becomes smaller with increasing *μ*, implying smaller occurrence chance for larger fires. In addition, the probability decreases with increasing distance between the threshold and *μ* values. Thus, fires at a certain threshold have the largest possibility when the threshold is equal to the average of burned areas. The regional climate data needed for calculating the model parameters were from the NARCCAP.
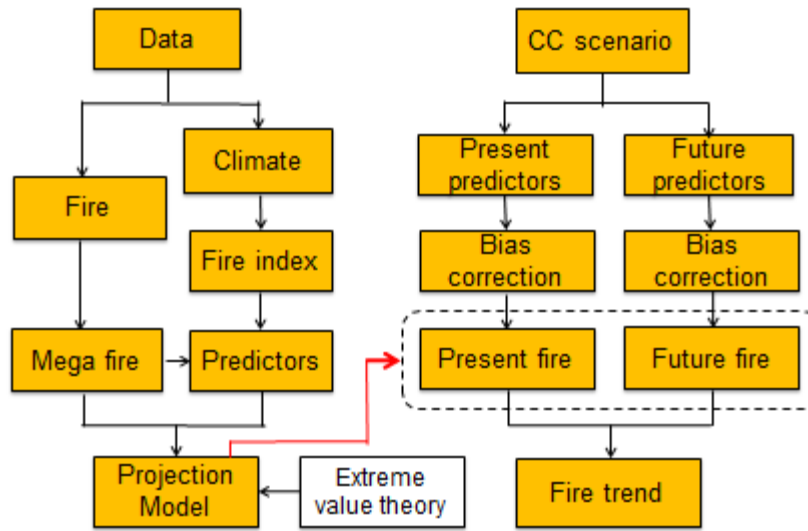

Figure 2 Steps for model development and mega-fire projection

D. DLEM fire module (DLEM-Fire) development and burned area projection

A process-base fire module was developed in the Dynamic Land Ecosystem Model (DLEM) (Tian et al. 2010), a dynamic global vegetation model developed in Auburn University. DLEM is capable of estimating burned area, fire emissions and fire impacts on ecosystem function and structure by simulating fuel loading, number of fires, and fire behavior. The module was developed based on Arora and Boer (2005). Lightning strike and human activity were considered as two sources of ignition. The probability to start a fire event depended on three independent constraints, namely, fuel load, fuel moisture, and human suppression. Fire spread velocity was calculated by vegetation property, and then was scaled by fuel moisture factor and wind speed factor. The fire duration was estimated through fire danger index. The grid-based satellite-adjusted scalar was used to regulate magnitude and spatial distribution of fires.

Temporal and spatial patterns of burn area across the continental U.S. under the A1B climate scenario were projected. The decadal mean climate from 2011 to 2020 were used to drive the model to reach the equilibration stage. Then the de-trend climate between 2011 and 2020 were repeated three times (i.e. 30 years in total) to drive the

model for spin-up. Finally, the model was run in transient mode with daily climate data under A1B emission scenario.

E. Technique development for missing climate change information

The NARCCAP climate change scenarios provide no data for a period of 40 years (2001-2040). The data during this period is need for future fuel loading projection using DLEM, which has to run continually from present to future. A "decomposition" approach using Fourier series was developed to fill the time gap. The approach focuses on the trends in temporal variations from current to future periods. A monthly series of a meteorological variable such as temperature or precipitation is first constructed for an individual month over the years of current or future period. Fourier expansion is performed to the time series. The resulted Fourier coefficients are averaged over the current and future periods at each time frequency. The averaged coefficients are then used to construct a data series for the time gap period. A dataset from gridded climate projections without time gap was used to implement and evaluate the approach. The algorithm was used to fill the NARCCAP data during 2001-2040.

F. Projection of fuel loading

Fuel loading was projected using the DLEM. The model simulates four types of vegetation species of fuels, woody biomass, woody debris, litter and duff, and herb. An algorithm was used to incorporate model vegetation types into the default (contemporary) fuel load map developed by the Fuel Characteristic Classification System (FCCS) (Ottmar et al. 2007) to generate high resolution fuel load datasets that reflect the spatial-temporal dynamics of fuel load from present to future in response to climate change.

Three stages of equilibrium run, spin-up, and transient run were implemented. Equilibrium run aimed to determine the initial condition in 1970. During this stage, DLEM was driven by average climate condition from 1971 to 2000 and other environmental conditions at the level of the year 1970. A 100-year spin-up during which the DLEM was driven by all the detrended time series of all driving forces was then conducted. In the transient mode, the DLEM was driven by all input data from 1971 to 2070, in which climate data during 2001-2040 was from gap-filling. To analyze potential changes in fuel load in response to other factors than climate, atmospheric and nitrogen deposition and to investigate effects of climate data gap-filling on fuel load estimation, totally 5 scenarios were examined.

G. New algorithm development of mega-fire smoke detection

Improving the capacity in detecting large wildfires and smoke transport is one of the important approaches to evaluate their impacts. A novel detection algorithm was developed that combines advantages of two commonly used approaches, that is, more accuracy and reliability with the multi-temporal NDVI or reflectance change detection and more practicality with the empirical spectral threshold, which is based on knowledge of post-fire spectral information. The algorithm consists of four statistical differences of

spectral and composite predictors and a support vector machine classification for MODIS 500-meter surface reflectance data. It is a single day burn detection scheme, but historical statistical information is also involved in the determination of burned pixels. Therefore, it has the potential for monitoring and tracking spatial developments of burned areas in rapid response applications. The algorithm was applied to detection of several mega-fires.

H. Projection of the impacts of climate change on prescribed burning

Prescribed burning (Rx) reduces wildfire risks and the catastrophic damage through eliminating hazardous fuels. Rx can be impacted by both changing climate and fuel conditions. More dry and hot weather in future means more wildfires and therefore more Rx activity on one hand, and more escape fire risk and therefore reduced burning window on the other hand. The trends, magnitudes, geographic distributions, and seasonal variations of the safety and effectiveness threats and burn windows under changing climate were investigated.

The safety threats and windows were assessed based on the prescription parameters and suggested preferable values, which depend on geographic regions and fuel types. Burn windows were measured by the difference of the total number of days during a period and the sum of all days with safety and effectiveness threats. The datasets of the present and future precipitation and ground temperature, specific humidity and wind speed used in this study were provided by NARCCAP.

I. Air quality effects

A large amount of $PM_{2.5}$ and other air pollutants is emitted from wildfires. The pollutants are transported in the atmosphere and affect air quality conditions in downwind metropolitan regions. Fire emissions were estimated using

$$E_k = A \times FL \times CE \times EF_k \quad (3)$$

where E_k is total emission of a species in g; A is burned area in acre, obtained from historical fire data or projected by model; FL is fuel loading in kg/acre, projected by the DLEM; CE is consumption efficiency, calculated using the method described in FEPS (Anderson et al. 2004) with 1000-hour fuel moisture calculated using the method described in the NFDRS (Cohen and Deeming 1985); and EF_k is emission factor of a species in g/kg, obtained from EPA document (Battye and Battye 2002). In addition, the emission scheme in the DLEM was also used.

The air quality impacts of future mega-fires were simulated using the atmospheric transport and chemistry models including HYSPLIT (Draxler 1992). The meteorological data for the present and future periods were from NARCCAP. The impacts were examined through several mechanisms of emission change due to increasing fires, emission change due to changes in fuel loading, and transport change due to changing atmospheric conditions.

IV. Key Findings

A. Fire-climate relationships

The four fire weather induces corresponding to each fire were calculated. Average was made over a number of gird points around the fire location with weighting factors inversely proportional to squared distance between the fire location and a grid point of the meteorological data. The meteorological data for the month when a fire started was used. For the 40 mega-fires, the normalized values with a corresponding sign occurred 32, 26, 29, and 31 times for KBDI, FFWI, LFPM, and ESI, respectively (Figure 3). The absolute values were one or greater occurred 19, 12, 13, and 18 times, respectively, indicating the best relationship between KBDI / EPI and mega-fires. However, the negative normalized KBDI values with the magnitude of one or greater also occurred four times. A possible reason is that some large fires might ignite after strong cold front passage, which brought cold temperature and therefore lower than normal KBDI. Close relationship with fires also occurred for relative humidity

The fire potential measured by KBDI was substantially different between the inactive and active mega-fire episodes (Figure 4). Large increases from the inactive to active episodes occurred in southern and middle Mediterranean Pacific, southern portion of Southwest, and much of Nevada and Utah in both spring and summer. Increases also occurred in southern Plains and Gulf coast, mainly in summer. These changes corresponded well to the increased mega-fires in the arid southwestern and Mediterranean Pacific during the active fire episode.
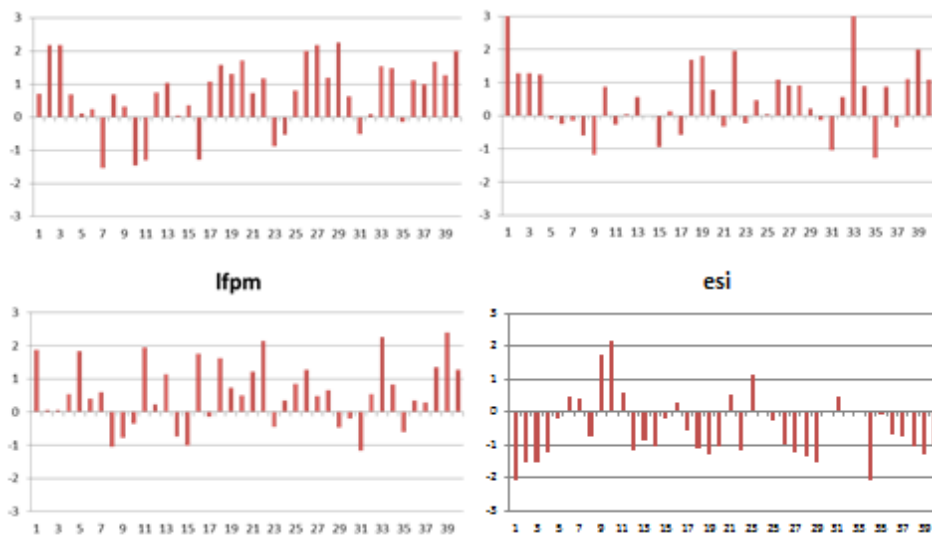

Figure 3 Normarized fire weather indices corresponsing to the 40 megafires. kbdi, ffwi, lfpm, and esi represent Keetch-Byram Drought Index, Fosberg Fire Weather Index, Large Fire Potetial – meterological condition, and Evaporative Stress Index.
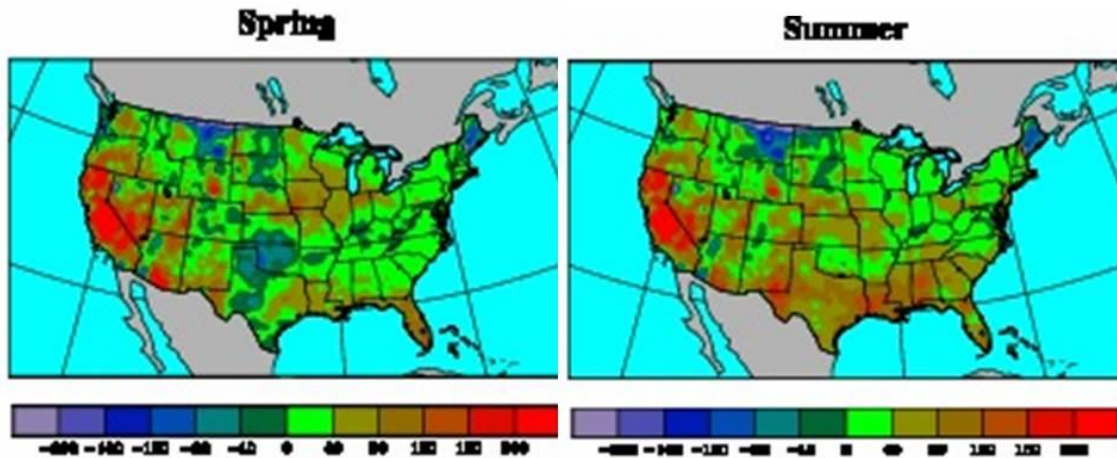
Figure 4 Difference in spring (left) and summer (right) KBDI between the active (1997-2013) and inactive (1980-1996) fire episode.

B. Increasing future fire potential

Future fire potential was projected to increase remarkably. Figure 5 shows the projection of KBDI from HadCM-HRM climate change scenario. KBDI values are expected to increase in the Southwest, Rockies, and the northern Great Plains by 100 with many areas over 200 in all four seasons. KBDI would also increase in a large portion of the eastern U.S. by over 100 in summer and autumn with the largest increase of over 200 in autumn. The increase suggests that the fire potential could become more severe by one grade (from low to moderate or from moderate to high risk) in many regions. The length of a fire season, measured by the number of the months with high or extreme fire potential level, will increase by1–3 months. The future warming is a more important contributor to projected increasing fire potential than the change in precipitation.

The fire potential projections vary, depending on the regional climate change scenarios. Projections from five out of seven scenarios show large fire potential increases. The magnitude obtained from the HadCM-HRM climate change scenario approximately represents the average intensity of the projected increase from all scenarios. The regions with large fire potential increase also vary among the scenarios. Large increases are seen in southern California and western Southwest in some scenarios. The largest increases are seen in summer and fall in most scenarios.

C. Decreasing future spatial fire concurrence probability

For historical fires with burned areas greater than 50 k acres during summer, two fires occurred during a same season in two of the western regions (the Pacific South, Pacific North, Southwest, or Northwest) at a percent between 20 and 50. The probability is slightly lower in spring and fall. In contrast, two fires occurred during a same season in two of the eastern regions (South Central, North Central, Southeast, and Northeast) at a percent less than 10 in summer.
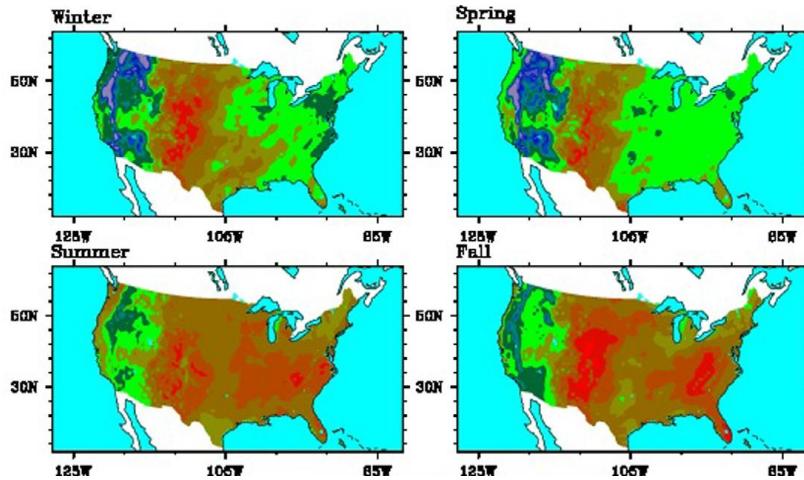
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Figure 5 Differences in seasonal between future (2041-2070) and present (1971-2000) period. The four panels are for winter, spring, summer, and autumn.

The probability for current fire occurrence calculated using the NARCCAP climate is larger in the central regions (Figure 6). In future (2041-2070), the probability would become smaller in summer for all regions except North Central and Northeast. For the Southwest region, for example, the large area of 41.9% probability (statistically significant at 99% confidence level) would be replaced by 35.5% probability (95% confidence level). Similar calculations performed to temperature and precipitation indicate that the increasing spatial variability in rainfall is the major contributor to the decreased fire concurrence probability.
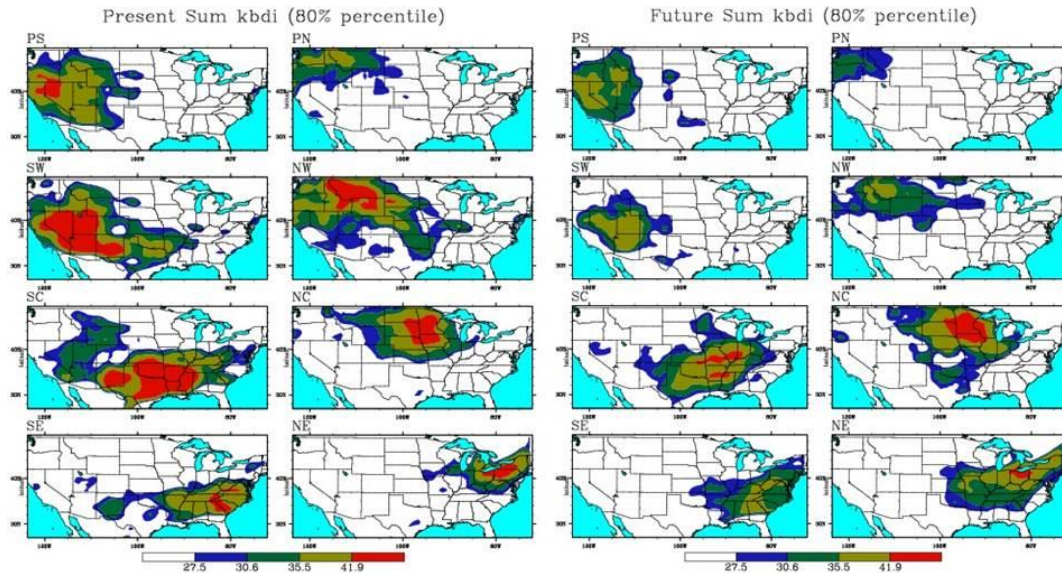

Figure 6 Fire concurrence probability for present (1971-2000) on left and future (2041-2070) on right. Each panel for a period represents the relation of a central point in a region with other grid points of the region and other regions. The bar label numbers indicate the criteria for various confidence levels.

D. Mega-fire projection model

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According to the fire-climate relationship obtained from this study, the following prediction model was developed using normalized KBDI and RH as predictors:

$$c_s c_t \frac{\mu_m}{N_{KBDI,m}} = \beta_0 + \beta_1 KBDI_m + \beta_2 KBDI_m^2 + \beta_3 RH_m \tag{4}$$

where $KBDI_m$ (m=1,2, …, M; M=8) are fixed values of −1.75, −1.25, −0.75, −0.25, 0.25, 0.75, 1.25, and 1.75, representing the ranges of ≤−1.5, −1.5~−1.0, −1.0~−0.5, −0.5~0.0. 0.0~0.5, 0.5~1.0, 1.0~1.5, and ≥1.5, respectively. RH_m is relative humidity corresponding to $KBDI_m$. μ_m and $N_{KBDI,m}$ are corresponding average fire number and grid number where KBDI falls into its mth range. $c_s=N_{go}/N_g$ and $c_t=N_{yo}/N_y$ are space and time adjustment coefficients, respectively, where N_g and N_{go} are number of grid points within a region and its reference value (for this model, it is the number of grid points of the NARR dataset). N_y and N_{yo} are number of years of a period and its reference value (for this model, it is the number of years of the NARR dataset). The coefficients are listed in table 1.

The model is statistical significance at the 95% confidence level as measured by the Chi square and deviance values. It simulated the fire-KBDI category relation with high fitting rate (Figure 7). Instead of a straight increasing line with KBDI anomaly, the number of measured mega-fires has a small peak at the KBDI value of -1.75. It decreases first and reaches the bottom value at the KBDI value of -1.25 and then gradually increases. The model only uses KBDI as a predictor reproduces the linear increasing trend, but misses the smaller peak at the beginning. The slope is also much smaller. The model further including square KBDI shows much closer variation pattern. The model further including RH improves fitting accuracy. However, the model further adding wind makes no meaningful difference.
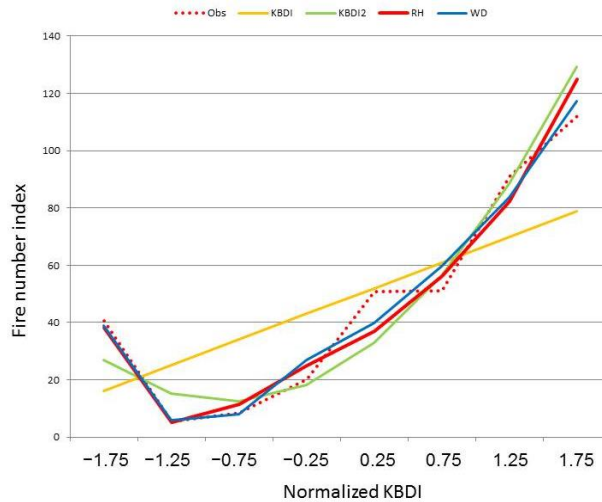

Figure 7 Distributions of mega-fire index with abnormal KBDI categories. The red dotted line is measurement. The red real line is generalized Poisson model using KBDI, KBDI^2 and relative humidity as predictors. The yellow, green and blue lines are models using KBDI, KBDI and KBDI^2, and KBDI, KBDI^2, relative humidity and wind, respectively.

Table 1 Mage-fire projection model coefficients.

Fire size criteria	Period	β_0	β_1	β_2	β_3
200k acres	1980-2013	14.58	-0.29	24.0	-12.43
	1981-2010	5.22	-13.31	30.45	-17.35
100k acres	1980-2013	61.75	17.15	52.72	-29.4
	1981-2010	40.68	-20.51	78.52	-50.98

E. Increasing trends in future mega-fire occurrence

Mega-fires are projected to increase by middle this century. The model developed using the mega-fires during a 30-year period (1981-2010) projected large variability of future mega-fire number among the seven regional climate change scenarios, ranging from little change for HadCM-MM5 and CGCM-WRF to about 120% for GFDL_HRM (Figure 8). The average mega-fires number over all scenarios is 23.2 for the present climate and 36.6 for the future climate, an increase by 57.8%. The corresponding numbers projected by HadCM_HRM are 25.3, 38.5, and 52.2%, close to the averages.
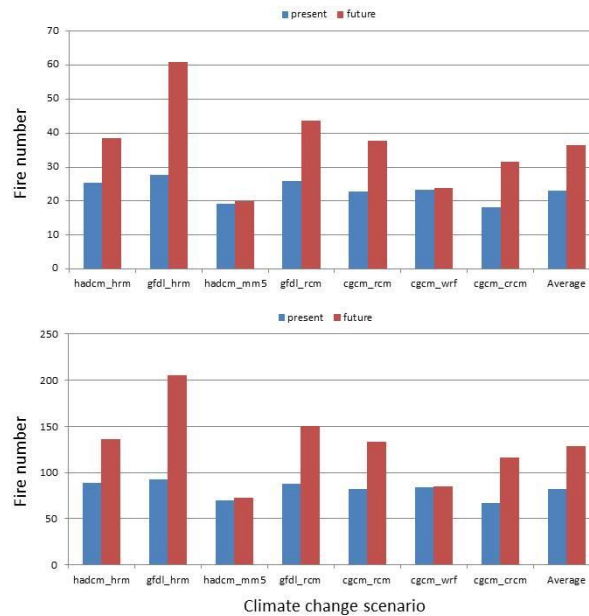

Figure 8 Projected mega-fire using a model developed based on historical fires during 1981-2010 for present and future periods under seven regional climate change scenarios. The criteria for mega-fires are 200k (top) and 100k (bottom) acres.

Similar increasing fire trends are found if using 100k acres as criteria for mega-fires. The projected average number of fires changes from 81.8 for the present climate to 129.8 for the future climate, an increase rate of 58.7%, very close to that for the criteria of 200k acres. However, for the projection model developed using the fires over 200k acres during the 34-year period (1980-2013), the corresponding numbers are 26.4, 40.7, and 54.2%. The projected fire numbers are 3~4 larger than those using the model with 30-year period from 1981-2010. This suggests that a model developed using fire data for a more active period would project more fires for both present and future times. This, however, did not affect the increase rate.

F. Different trends in future fuel loading across the continental U.S.

The simulated total fuel load with the HadCM_HRM varied from 30.4 to 33 Pg C/yr across the continental U.S. during 1971-2070 (Figure 9). The model projected an increase of fuel load by 0.76 Pg C/yr during 2041-2070, Fuel load would experience large increase in the western U.S., but decrease in the eastern U.S. Wood biomass and live herb would increase, while woody debris and litter and duff would experience obvious decrease, which could be resulted from increasing soil respiration in response to warmer climate. In comparison, the simulated fuel load with GFDL_HRM ranges from 34.3 to 36.3 Pg C/yr and would increase by 0.88 Pg C/yr during 2041-2070 in both western and eastern U.S, with higher increase in the west.
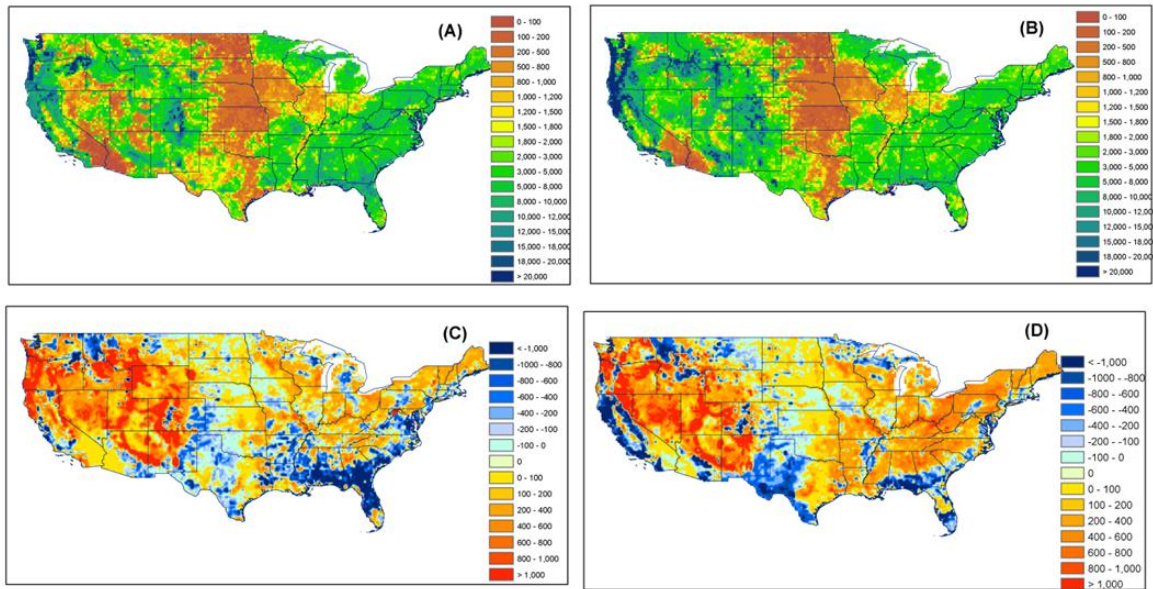

Figure 9 Simulated average fuel load for the present (1971-2000) driven by the HadCM_HRM (a) and the GFDL_HRM (b) climate change scenario, and the corresponding future changes by 2041-2070 [(c) and (d)].

G. Time gap filling of dynamical climate change downscaling

The developed "decomposition" approach was applied to a dataset from gridded climate projections and compared to a "repeat-trend" approach, which is based on adjusted current data and linear trends between current and future period and therefore emphasizes the trends in averages instead of temporal variations. The results with the decomposition approach show smooth and close seasonal and interannual variations between the original and filled time series within the gap period. The errors are smaller than those from the "repeat-trend" approach.

The filling procedure for the NARCCAP regional climate change gap show noticeable impacts on fuel loading projection. A large difference appears between the simulated fuel load driven by gap-filled climate and only by future climate, in which an equilibrium state is assumed to reach in the year of 2040 (Figure 10). Future projection

only using climate data during 2041-2070 would result in much higher increase fuel load (around 5.3 Pg C/yr) in comparison with the transient simulations for the period 1971-2070. The results indicate that big uncertainties would exist if historical simulation and future projection are conducted separately driven by two periods of climate data sets.
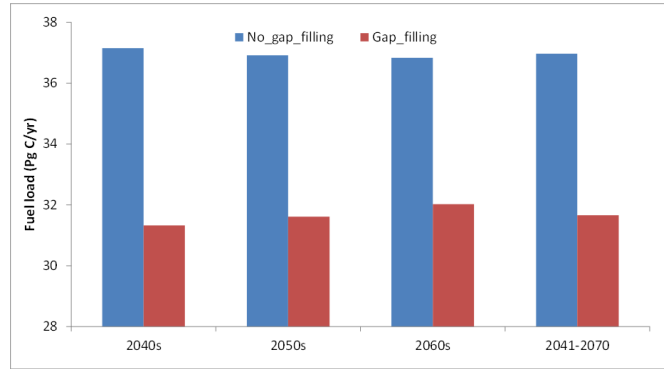

Figure 10 Comparison of changes in fuel load during 2041-2070 driven by the HadCM_HRM regional climate change scenario with gap-filled climate and that without gap-filled climate, relative to a 30-year average of 1971-2000.

H. Improving capacity of meg-fire smoke detection

Experimental results of the developed mega-fire detection technique were validated using fire perimeter database generated by the Geospatial Multi-Agency Coordination Group or GeoMAC, and compared with the MODIS level 3 monthly MCD45 product. The algorithm was found consistent in spatial distribution for tested fire cases, and effective and accurate in quantitative analyses, as seen from Figure 11 for the Wallow Fire, which started May 29, 2011 in Arizona, burned over 535k acres in approximately 5 weeks.
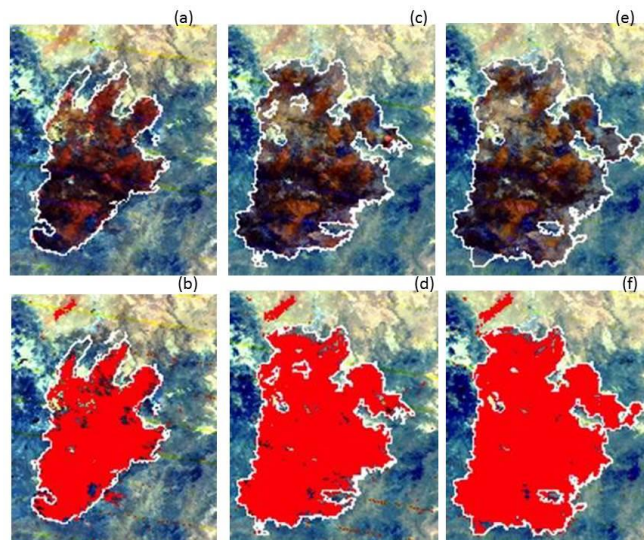

Figure 11 Burn mapping of the Wallow Fire. (a), (c), (e) images on Jun. 7, 14, and 21, 2011, respectively. (b), (d), and (f) are the corresponding detection using the new algorithm.

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I. Rx burning risk and window trends under changing climate

The safety threats to Rx are expected to become more severe by middle this century under changing climate, as indicated by the increasing red-flag day number nationwide expect a small area in the Northwest (Figure 12). A majority of the eastern U.S. is likely to see an increase by one month each year. The largest increase of about 40 days is expected in the Mississippi Valley and the surrounding areas. Same magnitude of increases is also found in some spots in the western Great Plains and southern Rockies. The effectiveness threats to Rx, however, are expected to reduce by 10-30 days per year nationwide expect a small area in the Northwest, Southeast, and the tip of southern Plains. The largest decrease occurs in some spots in the Rockies, inter-mountains, the northern Plains, the Great Lakes, and the Appalachians.

The burn windows are expected mostly to become shorter in the future in the eastern U.S., the Pacific coast and southwestern border areas, changing from about 30 days in the southern portion to about 10 days in the northern portion of the East. Burn windows however become slightly longer in the western Mountains, the Great Lakes, and the Northeast.
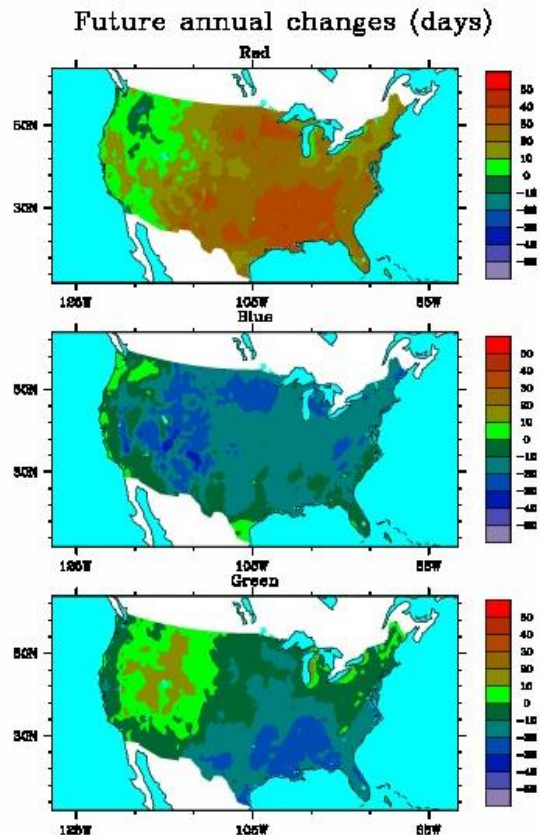

Figure 12 Future changes in the numbers of the annual red-flag days (top), effective burning days (middle) and burning windows (bottom) for prescribed burn.

J. The effects of mega-fires on air quality

Mega-fires usually occurred in remote rural areas. However, some of them have occurred in the areas close to metro cities, leading to direct invasion of smoke plume and deterioration of air quality and visibility conditions. This situation is especially serious in southern California and the Gulf coastal regions. For example, the simulated smoke plume from the 2007 Okefenokee fires on the Georgia / Florida border passed over Tampa and other Florida cities (Figure 13).

Such smoke events have increased in recent two decades. The $PM_{2.5}$ emissions from mega-fires were found to have increased by about 500% from the inactive fire episode of 1980-1996 to the active fire episode of 1997-2013. Such smoke events also are expected to increase in the future. The increasing severity is mainly caused by two factors. One is increasing number of mega-fires. This leads to increased total $PM_{2.5}$ emissions for the continental U.S. from about 0.47 Tg for 1981-2010 to 0.72 Tg for 2041-2070 (Figure 14). The other is larger fuel loading, which leads to increased total $PM_{2.5}$ emissions to 0.53Tg in the future period. The combined emission increase is nearly 80%. The cities are expected to be affected most are those in the Southwest and southern Pacific coast due to increased mega-fires and fuel loading. The impacts could be more complex in the cities in the Southeastern where fires are expected to increase but fuel loading is expected to decrease under some regional climate change scenario.
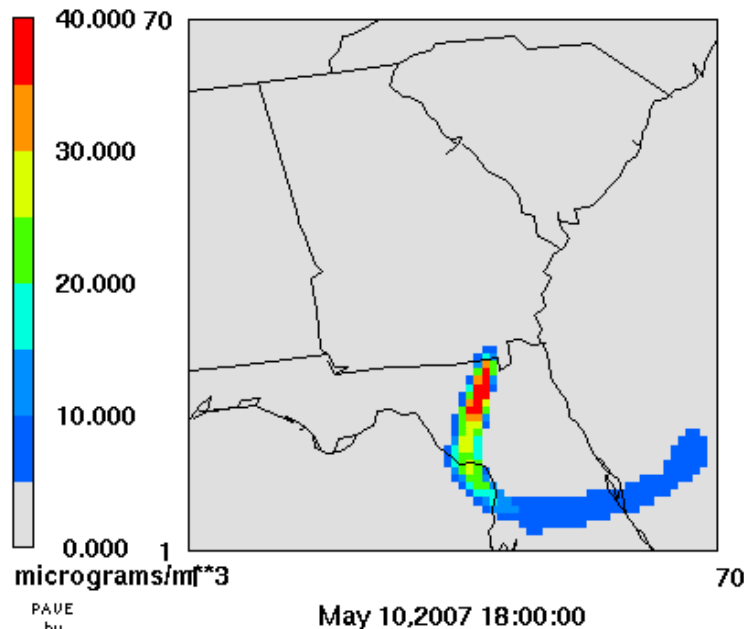

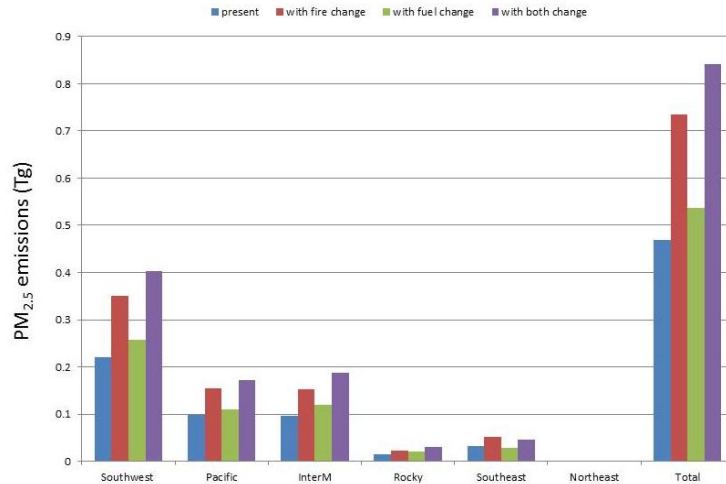Figure 13 Simulated smoke plume from the 2007 Okefenokee fires.

Figure 14 PM$_{2.5}$ emissions from mega-fires at regional and national levels. The results are provided for present (1981-2010), future (2041-2070) with fire change, future with fuel loading change, and future with both changes.

K. Outreach

1. This project organized a half-day workshop on climate downscaling for fire management during the Large Fire Conference held at Missoula, Montana during May 19-23, 2014. During the workshop, we instructed more than 20 fire mangers as well as researchers and graduate students on the topics on Climate and Fire Background, Global Climate Modeling and Downscaling, Dynamic and Statistical Downscaling Methods, and Downscaling Software. We also interacted with the audience through discussion to learn the fire management needs and issues for climate information, which is useful for our future fire-climate interaction research.

2. Researchers from this project were interviewed by a reporter from New York Times on wildfires and climate change in 2013.

3. The results from this project were described to the Southern Fire Exchange and a webinar was planned.

L. Manuscript publications

Published

1. Liu Y.-Q., Goodrick, S., Stanturf J., 2013, Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario, Forest Ecology and Management. 120–135. DOI: 10.1016/j.foreco.2012.06.049.

2. Liu Y.-Q., Goodrick S.A., Heilman W.E., 2013, Wildland fire emissions, carbon, and climate: Wildfire-climate interactions, Forest Ecology and Management. http://dx.doi.org/10.1016/j.foreco.2013.02.020

3. Yang J., Tian H., Tao B., Ren W., Kush J., Liu Y.-Q., Wang Y., 2014, Spatial and temporal patterns of global burned area in response to anthropogenic and environmental factors: Reconstructing global fire history for the 20th and early 21st centuries. JGR- Biogeosciences. 119, 249–263, DOI: 10.1002/2013JG002532

4. Mitchell R.J., Liu Y.-Q., O'Brien J.J., Elliott K.J., Starr G., Miniat C.F., Hiers J. K., 2014, Future climate and fire interactions in the southeastern region of the United States. Forest Ecology and Management, 327, 316–326. DOI: 10.1016/j.foreco.2013.12.0033.

5. Liu Y.-Q., 2014, A Regression Model for Smoke Plume Rise of Prescribed Fires Using Meteorological Conditions. J. Appl. Meteor. Climatol., 53, 1961–1975. doi: http://dx.doi.org/10.1175/JAMC-D-13-0114.1

6. Liu, Y.-Q., J. Prestemon, S. Goodrick, T. Holmes, J. Stanturf, J. Vose, G. Sun, 2014, Future Wildfire Trends, Impacts, and Mitigation Options in the Southern United States, In: Vose, James M.; Klepzig, Kier D., eds. Climate change adaptation and mitigation management options: A guide for natural resource managers in southern forest ecosystems. Boca Raton, FL: CRC Press. 85-126.

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Zhang R., J. Qu, Y.-Q. Liu, X. Hao, X. Zhan, 2014, Detecting burned area of mega-fires using single-day and historical average MODIS surface reflectance, Int'l J. Remote Sensing. (under minor revision).

Complete / nearly complete / to be written

Yang J., H. Tian, B. Tao, W. Ren, S. Pan, Y.-Q. Liu and Y. Wang, A growing importance of larger fires in the Conterminous United States during 1984 – 2012. (complete)

Liu Y.-Q. et al., 2014, Increasing mega-fires in the continental U.S. under changing climate. (nearly complete)

Tao, B., Tian, H., Liu, Y.-Q., Yang, J., Projecting changes in fuel load across the conterminous US driven by a regional climate model output under the SERS A2 scenario (nearly complete)

Liu, Y.-Q., S. Goodrick, J. Stanturf, Applications of climate downscaling to wildland fire research (nearly complete)

Liu, Y.-Q. and L. Mearns, 2014, Wildfire concurrence probability in the continental U.S. (in preparation)

Liu, Y. –Q., H. Tian, B. Tao, J. Yang, An approach for filling time gaps of dynamic climate downscaling (to be written)

Liu, Y.-Q. et al., Emissions and air quality impacts of future mega-fires in the continental U.S. under changing climate. (to be written)

M. Presentations

1. Liu, Y.-Q., 2012, Projecting future changes in U.S. forest fuel and fire conditions using NARCCAP regional climate change scenarios. The 2012 North American Regional Climate Change Assessment Program Users' Meeting, Boulder, Colorado, April 10-11, 2012.

2. Liu, Y.-Q., L. Mearns, 2012, Analyzing and Projecting U.S. Wildfire Potential Based on NARCCAP Regional Climate Simulations, 2012 American Geophysical Union Meeting, December 3-7, 2012. San Francisco, CA

3. Yang, J, Tian, H, Tao, B, Lu, C, Ren, W, Liu, Y, 2012, Global wildfire emissions as controlled by multifactor environmental changes from 1901 through 2010. 2012 American Geophysical Union Meeting, December 3-7, 2012. San Francisco, CA

4. Liu, Y.-Q., S. Goodrick, J. Stanturf, H. Tian, B. Tao, J. Yang, 2013, Future trends in mega-fire and fuel in the United States under a changing environment, 4th International Fire Behavior and Fuels Conference Raleigh, North Carolina, USA February 18-22, 2013

5. Liu, Y.-Q., S. Goodrick, J. Stanturf, H. Tian, B. Tao, J. Yang, Future Trends in Large Fire and Smoke in the United States under Changing Climate, International Smoke Symposium, The University of Maryland University College, October 21-24, 2013.

6. Liu, Y.-Q., S. Goodrick, J. Stanturf, H. Tian, B. Tao, J. Yang,, Wildfire Emissions and Air Quality Impacts in the United States under Changing Climate, AMS 2014 Annual Meeting, Atlanta, GA, February 02 - 06, 2014

7. Liu, Y.-Q., S. Goodrick, J. Stanturf, Climate Downscaling for Fire Management, Large Wildland Fires, Missoula, MT, May 19-23, 2014 (Training presentation, abstract, PPT).

8. Liu, Y.-Q., S. Goodrick, J. Stanturf, 2014 Large Fires in the United States under Changing Climate, IUFRO Congress, Salt Lake City, UT, October 5-11, 2014.

9. Liu, Y. –Q., H. Tian, B. Tao, J. Yang, 2015, An approach for filling time gaps of dynamic climate downscaling. To be presented at the 95th American Meteorological Society Annual Meeting, Phoenix, AZ, January 5-8, 2015.

N. Students /Post Doc supported

Bo Tao, Auburn University

Jia Yang, Auburn University

Rui Zhang, George Mason University

Marcus William, University of Georgia and USDA Forest Service

V. Management Implications

A. Different natural resource needs and geographic distributions

Similar to some recent studies, this study projected increasing wildfires by middle this century due to global warming. This suggests the increasing needs in fire management resources and coordination efforts in the future. The projections identified the geographic regions where future fire risks likely increase, which provides scientific basis for possible change in fire resources.

As a part of operational forest management efforts, fire risk assessments and logistic/dispatch supports are provided at various geographic centers, including six western regions and two eastern regions. The concurrence probability investigated in this study is useful information for current and future fire management because firefighting and fire resource coordination become a bigger challenge when firefighters have to work on large fires in more than one region during a same fire season or even at the same time of the season. The new finding that the concurrent fire probability among adjacent regions is expected to decrease suggests possibly reduced challenge in this regard in the future.

B. More Rx needs but reduced burning windows

It is projected in this study fuel loading is expected to increase across the continental U.S., especially in the west in the future, suggesting a need in more frequent Rx to remove the ground fuels. Furthermore, more frequent Rx is needed as an approach to reduce mega-fire risks, which are expected to increase. However, burning windows are expected to reduce under changing climate due to increasing risks for escape fires. New Rx strategy and resources are needed to deal with this challenge issue. One positive change with changing climate is the increased days for Rx during winter time in the future, which would be considered to be too cold or too wet to burn effectively at present time. This suggests that future burning could be planned more for cool seasons.

C. Uncertainty with NARCCAP climate change scenarios

The NARCCAP scenarios are provided for two separate period of present (1971-2000) and future (2041-2070). This study indicates that the projections of future fuel loading

would be much different with and without filling the data gap from 2001 to 2040. There have been a large number of applications of the NARCCAP climate change scenarios to assessing the impacts of climate change on ecosystems and other slow processes that need continuous simulations from present to future period. The scientific basis provided by these studies for management strategy development could be biased without first filling the time gap.

D. Climate change information for land managers

Weather has long been useful information for daily land management. There are however increasing needs for land managers to use climate information for seasonal planning and long-term strategy development for mitigating the possible impacts of climate change. Dynamic climate downscaling is an important approach to obtain climate change information. The technique however is relatively complicated with many uncertainties. This project improved understanding of the downscaling information through collaborating with the climate research community, including the National Center for Atmospheric Research which was a leading institution for the NARCCAP data development. The learned information on climate downscaling and fire applications was passed to land managers through a training workshop as well as a review paper in preparation. This would help managers use climate information more extensively and effectively for land management.

VI. Relationship to other recent findings and ongoing work

A. Recent fire projections

The extreme value theory (EVT) has been used in some fire projection studies recently. Keyser et al. (2014) predicted high severity fire occurrence and area burned in a changing climate for three regions in the western U.S. using logistic regression and GPD to determine presence / absence and annual area burned of high severity fire (500 acres or larger). It was found that western U.S. area burned in high severity fire can be accurately predicted using a GPD model with covariates of climate, weather, and topography. Barbero et al. (2014) projected large fires under changing climate using empirical generalized linear models to model large fires (>10kha) over the 1984-2010 period across ecoregions. It was found that models using fire danger predictors were more skillful than models using meteorological variables alone. Mega-fire probabilities for the mid-21st century were projected with the geographic areas of significant change identified. The study used vegetation factors in addition to meteorological ones as predictors. It also used statistically downscaled CMIP5 climate projections.

The results from this study provide additional evidence for the increasing trends in future fires. This study projected large fires using a model developed based on EVT. It focused on much larger mega-fires, fuel changes, and their air quality impacts. The projection model used the Poisson distribution with KBDI category as major projectors. Also, ensemble results were provided using multiple dynamically downscaled regional climate change scenarios instead of global projections or statistical downscaling.

B. Other climate change and air quality research efforts supported by JFSP

Among a few JFSP supported projects, the project 13-1-01-6 deals with some similar issues as this project, including dynamic downscaling, consideration to the dynamic behavior of vegetation and fuel loads, stochastic model estimate of current and future fire activity, and fire emissions and air quality respond to climate change. A comparison of the results from this study with this and other JFSP projects should be useful to find and interpret uncertainties in research on these issues.

C. Research efforts in improving fire modeling capacity in climate system models

As described in VII.C below, wildfires can feedback atmospheric conditions through emitting smoke particles, which can absorb and reflect solar radiation and therefore impact regional climate. This feedback is largely missed in the current climate models. To improve the capacity of climate models in simulating the roles of wildfire emissions, USDA, DOE, and NSF are jointly supporting a collaborative research project to improve fire-climate interaction modeling. Two of the PIs of this JFSP project participate in the research effort. The findings from this JFSP project will help the new project by providing scientific foundations, new algorithms and models for climate system model improvement.

VII. Future work needed

A. Role of fuel change under changing climate

Fuel is one of the three factors for fire behavior. Fuel conditions such as species distribution, growing seasons, mass (loading), and moisture are expected to change under the changing climate. This would affect future wildfire ignition and spread and therefore affect fire emissions and air quality. This project projected future fuel loading change and indicated the important impacts on fire emissions. Other fuel properties and their roles in fire occurrence and spread need to be investigated in the future.

B. Uncertainties with fuel load projection

Current fuel load estimations vary greatly among existing models, which will directly influence estimations of burned area and greenhouse gases emission from fires. The fuel load simulation and projection in this study was at a spatial resolution of 0.25 degree, which may underestimate the heterogeneity in the land surface, thus bring uncertainties in fuel load estimates. The potential effects of future land use change and potential changes in fuel load managements were not included, which could affect prediction of fuel load in the future. These issues need to be addressed in future research.

C. The impacts of atmospheric feedback to wildfires

Mega-fires occur mostly under prolong drought conditions. The synthesis study partially supported by this project (Liu et al. 2013) have indicated that wildfires can feedback atmospheric conditions through emitting smoke particles, which can absorb and reflect solar radiation. This would in turn modify the atmospheric conditions for fire spread. This is a new research area and there are many uncertainties. One issue among others needs to be addressed is to develop approaches to include the fire-climate interactions and feedback in fire behavior and air quality models.

D. Ensemble results with more climate change scenarios

This study indicated large variability in future mega-fire projection among regional climate change scenarios. These scenarios were generated through dynamic downscaling, which has the advantages of physical consistence with GCMs, less dependence on historical data, and better representation of complex topography in comparison with statistical downscaling. However, only few sets of scenarios are available because of dramatically large computation resources needed for running regional climate models. Statistical downscaling has an advantage in this regard. Also recent progress has made it possible to provide more variables than the traditionally provided temperature and precipitation with statistical downscaling. An ensemble study of projecting future mega-fires and the air quality impacts are needed using a large set of climate change scenarios provided by statistical downscaling.

E. New climate change scenarios

The regional climate change scenarios used in this study were downscaled from the Coupled Model Intercomparison Project Phase 3 (CMIP3) global climate projections. The CMIP5 have become available and used for the IPCC fifth assessment report (AR5). CMIP5 used new emission scenarios and their projections have been downscaled using statistical approach in many studies, but have not yet for a systematic dynamic downscaling project such as NARCCAP. When they become available, the new dynamic scenarios need to be used for mega-fire projections and air quality impact simulations to understand the possible differences due to new IPCC emission scenarios.

VIII. Deliverables Cross-Walk

Deliverable Type	Description	Status
Datasets	Present mage-fire events	Complete (SHRMC computer)
	Projected future mage-fire events	Complete (same as above)
	Seasonal regional climate at present and in future	Complete (same as above)
	Present fuel loading	Complete (same as above)
	Projected future fuel loading	Complete (same as above)
	Smoke trajectory at present and in future	Complete (same as above)
	Smoke concentrations at present and in future	Complete (same as above)
Fire probability functions	Algorithm to project future mega-fires	Developed
Websites	Posting at shrmc.ggy.uga.edu, fp.auburn.edu/sfws/esra/	Active
Presentations	Present results at project meetings and professional conferences	9 presentations at conferences, some sponsored by JFSP; Virtually participated in JFSP SSP Science Status Workshop, Oct 14-15, 2014.
Referred publications	3~4 peer reviewed journal manuscripts	6 published (5 journal, 1 book chapter); 1 submitted (minor revision); 4 complete / nearly complete: 3 to be written.
Non-publications	Annual report	Complete
	Final report	Complete
Training session	A workshop / training session on climate, fire and air quality	Complete Climate Downscaling for Fire Management (a half-day training session held at the Large Wildland Fire conference, Missoula, MT, May 19-23, 2014).

Access to datasets stored in SHRMC computer:
 Website link: http://shrmc.ggy.uga.edu/research_projects.php
 Download: http://shrmc.ggy.uga.edu/upload

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