Will Future Climate Favor More Erratic Wildfires in the Western United States?

LIFENG LUO

Department of Geography, and Center for Global Change and Earth Observations, Michigan State University, East Lansing, Michigan

YING TANG

Department of Geography, Michigan State University, East Lansing, Michigan

SHIYUAN ZHONG

Department of Geography, and Center for Global Change and Earth Observations, Michigan State University, East Lansing, Michigan

XINDI BIAN AND WARREN E. HEILMAN

Northern Research Station, Forest Service, U.S. Department of Agriculture, East Lansing, Michigan

(Manuscript received 26 November 2012, in final form 19 June 2013)

ABSTRACT

Wildfires that occurred over the western United States during August 2012 were fewer in number but larger in size when compared with all other Augusts in the twenty-first century. This unique characteristic, along with the tremendous property damage and potential loss of life that occur with large wildfires with erratic behavior, raised the question of whether future climate will favor rapid wildfire growth so that similar wildfire activity may become more frequent as climate changes. This study addresses this question by examining differences in the climatological distribution of the Haines index (HI) between the current and projected future climate over the western United States. The HI, ranging from 2 to 6, was designed to characterize dry, unstable air in the lower atmosphere that may contribute to erratic or extreme fire behavior. A shift in HI distribution from low values (2 and 3) to higher values (5 and 6) would indicate an increased risk for rapid wildfire growth and spread. Distributions of Haines index are calculated from simulations of current (1971–2000) and future (2041–70) climate using multiple regional climate models in the North American Regional Climate Change Assessment Program. Despite some differences among the projections, the simulations indicate that there may be not only more days but also more consecutive days with HI ≥ 5 during August in the future. This result suggests that future atmospheric environments will be more conducive to erratic wildfires in the mountainous regions of the western United States.

1. Introduction

A number of large wildfires occurred across the western and central United States during August of 2012. The monthly total area burned reached 1.47 million ha, which ranked the highest in any August since 2000 (National Climatic Data Center 2012). The number of fires during the month was 6948, however, which ranked the second least for the same period. As a consequence, the average fire size became the largest, reaching 211.8 ha per fire, whereas the 10-yr (2001–10) average fire size is only 83.2 ha per fire (National Climatic Data Center 2012). The increase in average fire size was likely the result of the combination of multiple factors, including fuel and meteorological conditions. A similar situation was observed during the summer of 1988 over the Yellowstone National Park. Accumulated fuel, severe drought, and exceptionally dry atmospheric conditions all contributed to the famous Yellowstone fires of 1988. The Yellowstone fires started on 14 June and finally ended in late autumn when cool and moist weather arrived in the region, but not before a total of 321 272 ha had been

Corresponding author address: Lifeng Luo, Dept. of Geography, Michigan State University, East Lansing, MI 48824.
E-mail: lluo@msu.edu

DOI: 10.1175/JAMC-D-12-0317.1

burned (Christensen et al. 1989; Rothermel et al. 1994; Hardy-Short and Short 1995).

Large wildfires like these are driven by natural factors such as fuel availability, temperature, precipitation, wind, humidity, and the location of lightning strikes and by anthropogenic factors (Westerling et al. 2003). In particular, favorable meteorological conditions such as lower atmospheric dryness and instability can contribute to erratic and extreme fire behavior, thus increasing the risk of losing containment of a fire, which may result in catastrophic damage and property loss. Global climate change may have a significant impact on these factors, thus affecting potential wildfire activity across many parts of the world (Flannigan et al. 2009). For example, Gillett et al. (2004) demonstrated that human-induced climate change has had a detectable influence on forest fires in Canada in recent decades. Stocks et al. (1998) used four general circulation models (GCMs) to study the changes in forest fire potential in Russian and Canadian boreal forests between $1 \times CO_2$ and $2 \times CO_2$ climates and showed significant increases in the area experiencing high–extreme fire danger in both countries during June and July. Williams et al. (2001) studied the possible impact of climate change on fire regimes in Australia by examining the changes in daily and seasonal fire danger for the present and a doubled-CO_2 climate simulated by a GCM and found an increase in the number of days of very high and extreme fire danger. For the United States, Spracklen et al. (2009) used a regression model to investigate the potential impacts of climate change from 2000 to 2050 on wildfire activity and smoke emissions for the western United States and predicted a 54% temperature-related increase of annual mean area burned by 2050 relative to present. Liu et al. (2012) examined future wildfire potential in the continental United States with the Keetch–Byram drought index (KBDI) and predicted an increase of fire potential in the Southwest, Rocky Mountains, northern Great Plains, Southeast, and Pacific Coast.

Given the tremendous impact of wildfires over the western United States in the past, the question is whether future climate and its manifestation in regional weather patterns will provide more favorable atmospheric conditions for wildfires to become erratic and spread rapidly in the region. To answer this question, this study selects the Haines index (HI) (Haines 1988; Potter et al. 2008; Heilman and Bian 2010, 2012). The HI is one of many indices that have been developed to help to assess the potential for dangerous wildfires, such as KBDI, burning index (Bradshaw et al. 1984; Schlobohm and Brain 2002), energy release component (Bradshaw et al. 1984), fire potential index (Burgan et al. 1998), spread component (USDA 1968), and 1000-h fuel moisture (Bradshaw et al. 1984). This paper presents an analysis of the changes in the climatological distribution of HI between the current and possible future climates. The HI is selected for several reasons. It was designed to assess the potential for wildfire growth by measuring the stability and dryness of the air over a fire (Haines 1988). It is one of the indices used operationally by the U.S. Forest Service to assess fire danger across the continental United States on a day-to-day basis. Although the original calculation of the HI was based on temperature and humidity information from radiosonde observations at 0000 and 1200 UTC, a climatological database of the HI over the continental United States was developed by Winkler et al. (2007) that is based on the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996), and it was then later improved by Lu et al. (2011) using the higher-resolution North American Regional Reanalysis (NARR) data (Mesinger et al. 2006).

The Haines index consists of a stability component (A) and a humidity component (B). The A component reflects the lower-atmosphere lapse rate, and the B component accounts for the dewpoint depression for a specific pressure level in the lower atmosphere. Each component is converted to an ordinal value of 1, 2, or 3 on the basis of prescribed threshold values. The two components are then summed together to yield the HI (Haines 1988). Three variants of the HI were developed for different regions in the United States to account for the differences in surface elevation (Haines 1988). Over the high-elevation regions in the western United States, the index is calculated using a 700–500-hPa environmental lapse rate and the dewpoint depression at 700 hPa. The HI values range from 2 to 6, with 5–6 indicating higher potential for erratic fire behavior as a result of a dry unstable lower atmosphere. Under such conditions, wildfires could rapidly get out of control and cause catastrophic damages and possibly large burned area. Historical wildfire events such as the 1988 Yellowstone fires were evidently associated with higher HI values as demonstrated in Fig. 1, which shows the distribution of the spatially averaged HI in a region near Yellowstone National Park (43°–47.5°N, 113°–106°W) at 0000 UTC (1700 local time) during every August from 1979 to 2012 from the NARR data. It is clear that the HI was generally higher during August of 1988 and 2012, which corresponds very well to the large wildfire activities over the region during those two periods. Other studies (Werth and Ochoa1993; Goodrick et al. 2000) have also linked high HI values to large fire activities. Therefore, by evaluating changes in the climatological distribution of the HI between the current and future climate, we hope to understand whether future climate may favor

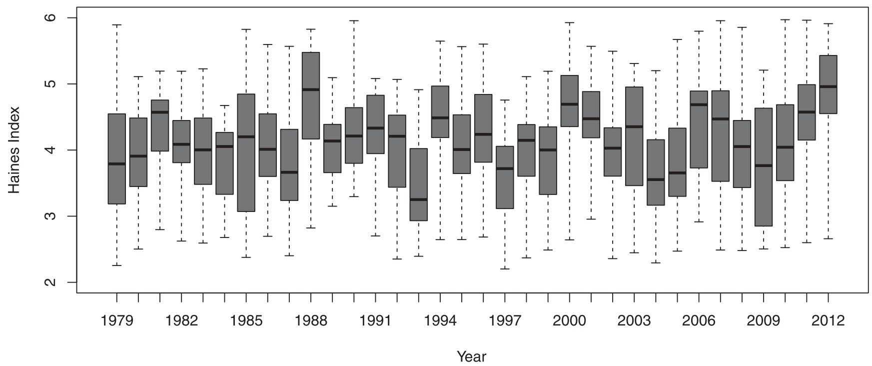

FIG. 1. Distribution of NARR-based spatially averaged HI at 0000 UTC of each day in August from 1979 to 2012. At each 0000 UTC, the HI values at each grid point are spatially averaged over the Wyoming, Idaho, and Montana border region (43°–47.5°N, 113°–106°W), and then the distribution of the 31 daily values within each August is summarized with one box-and-whisker plot. The bar in each box is the monthly mean, the upper and lower bounds of the box are the upper and lower quartiles, and the whiskers extend to the extreme values.

erratic wildfire behavior, thus posing additional challenges to wildfire management in the western United States.

2. Data and method

To estimate the changes in the climatological distribution of the HI, we used regional climate model data from the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP is an international program to produce high-resolution climate-change simulations with regional climate models (RCMs) to investigate uncertainties in regional-scale projections of future climate and to generate climate-change scenarios for use in impact research (Mearns et al. 2009, 2012). Four atmosphere–ocean general circulation models (AOGCMs) with different equilibrium climate sensitivities were chosen by the NARCCAP team to simulate the current climate (1971–2000) and the future climate (2041–70) under the ‘‘A2’’ emissions scenario described by Nakicenovic et al. (2000). Six RCMs were then nested within the AOGCMs to dynamically downscale both the current and future climates depicted by the four AOGCMs over North America. All RCMs were run using a horizontal grid spacing of 50 km, and output data are available at 3-hourly intervals. As compared with the coarser-resolution AOGCM projections, these RCM runs make it possible to better resolve the spatial variability in the mountainous western United States. The RCMs were also driven with the NCEP–U.S. Department of Energy reanalysis data (R-2; Kanamitsu et al. 2002) for the period of 1979–2004 to serve as the baseline for evaluating the performance of the RCMs over North America.

In this study, we used the temperature and humidity data from these RCM simulations at 0000 UTC for each day to assess the climatological distributions of the high-elevation variant of the HI at each grid point over the western United States for which the elevation is above 1000 m. This is also consistent with the 0000 UTC HI used operationally within the U.S. Forest Service’s Wildland Fire Assessment System (Burgan et al. 1997). In this paper, we only present the result for August over the western United States because August has historically been the most active month for wildfires in this region and the changes in HI distributions in August will have more significant implications for wildfire management. A more comprehensive analysis of the changes in HI distribution in NARCCAP model simulations for each month of the year and the entire United States is currently under way.

3. Results

Before examining changes in HI distributions between current (1971–2000) and future (2041–70) climate conditions, we first examined how effectively the RCMs simulate the HI distribution for the current climate, especially for HI $\geq$ 5 when fire-growth potential is high. Figure 2 shows the percentage of days in August for which the 0000 UTC HI $\geq$ 5 (or frequency of high-risk days) in nine simulations. The three RCMs are the Canadian Regional Climate Model (CRCM; Caya 1996; Caya and Laprise 1999), the Weather Research and Forecasting model (WRF; Skamarock et al. 2005), and the Regional Climate Model, version 3 (RCM3; Pal et al. 2007). They are driven by the R-2, the NCAR Community Climate System Model, version 3 (CCSM3; Collins

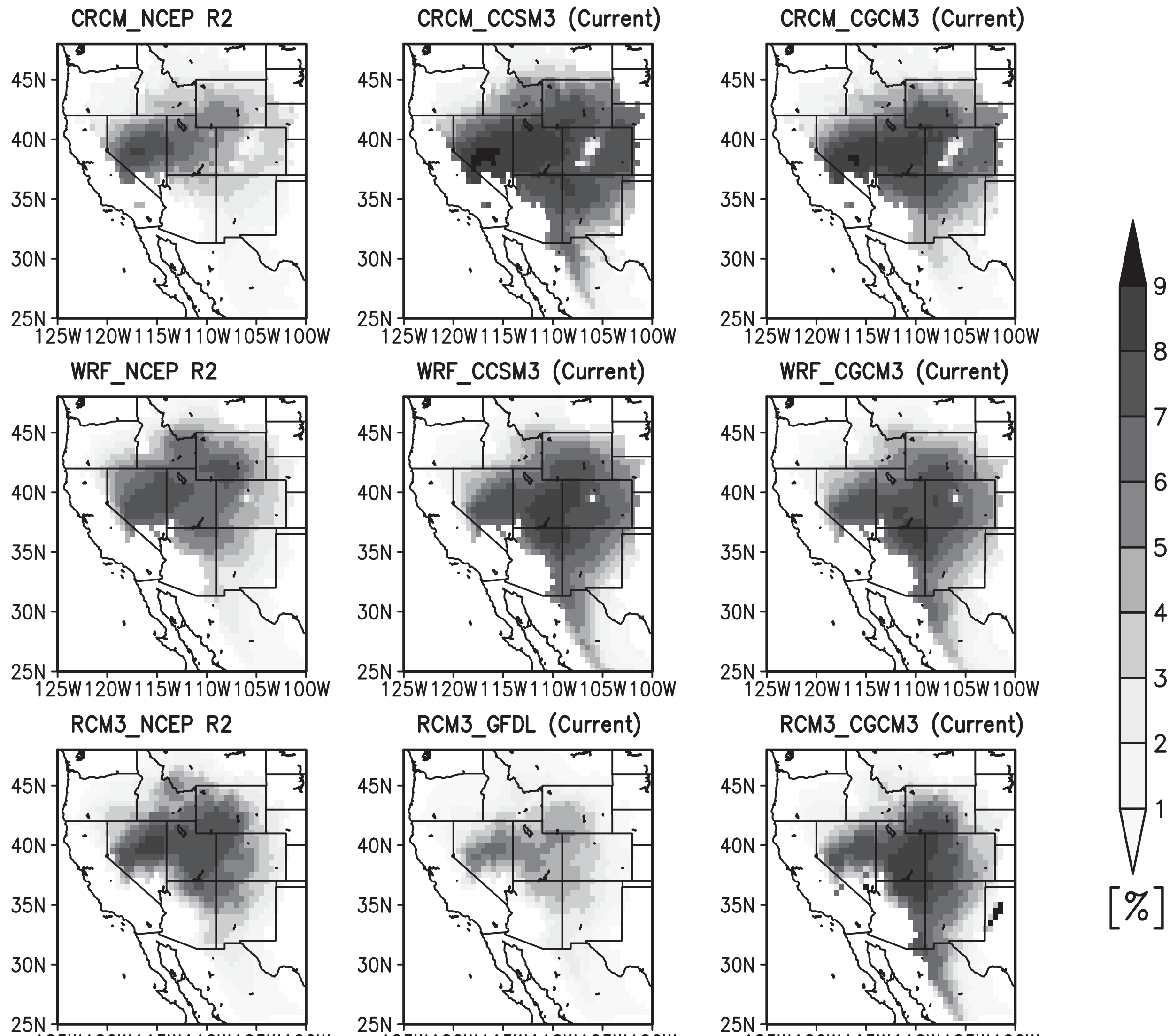

FIG. 2. Percentage of days during August for which HI ≥ 5 over the high-elevation regions in the western United States as simulated by the (top) CRCM, (middle) WRF, and (bottom) RCM3 models driven by (left) R-2, (center) CCSM3, and (right) CGCM3 fields. For RCM3, CCSM3 is replaced by the GFDL model. The HI is calculated using information at 0000 UTC of each day in August for the current (1971–2000) climate.

et al. 2006), and the Canadian Global Climate Model, version 3 (CGCM3; see online at http://www.ec.gc.ca/ccmac-cccma/default.asp?n=1299529F-1) and/or the Geophysical Fluid Dynamics Laboratory (GFDL) GCM (Delworth et al. 2006). Overall, the spatial patterns from these simulations are very similar. Large values are mainly found in regions of the Intermountain West, and the values then decrease both southward and northward. Differences among these simulations can be attributed to the RCMs, the AOGCMs, or both. For example, when driven with the R-2 (left column of Fig. 2), the WRF and RCM3 simulations show a much larger area with HI ≥ 5 than what is found in the CRCM simulation, which illustrates the differences caused by RCMs. For CRCM and WRF (top two rows of Fig. 2), the AOGCM-driven runs (center and right column of Fig. 2) show much larger areas of high HI when compared with the results driven by R-2 (left column of Fig. 2). This result demonstrates the differences caused by AOGCMs and suggests that both the CCSM3 and the CGCM3 tend to make the lower atmosphere drier and less stable when dynamically downscaled by these RCMs.

Despite these differences, a comparison between the RCM simulations driven by the same AOGCMs for the

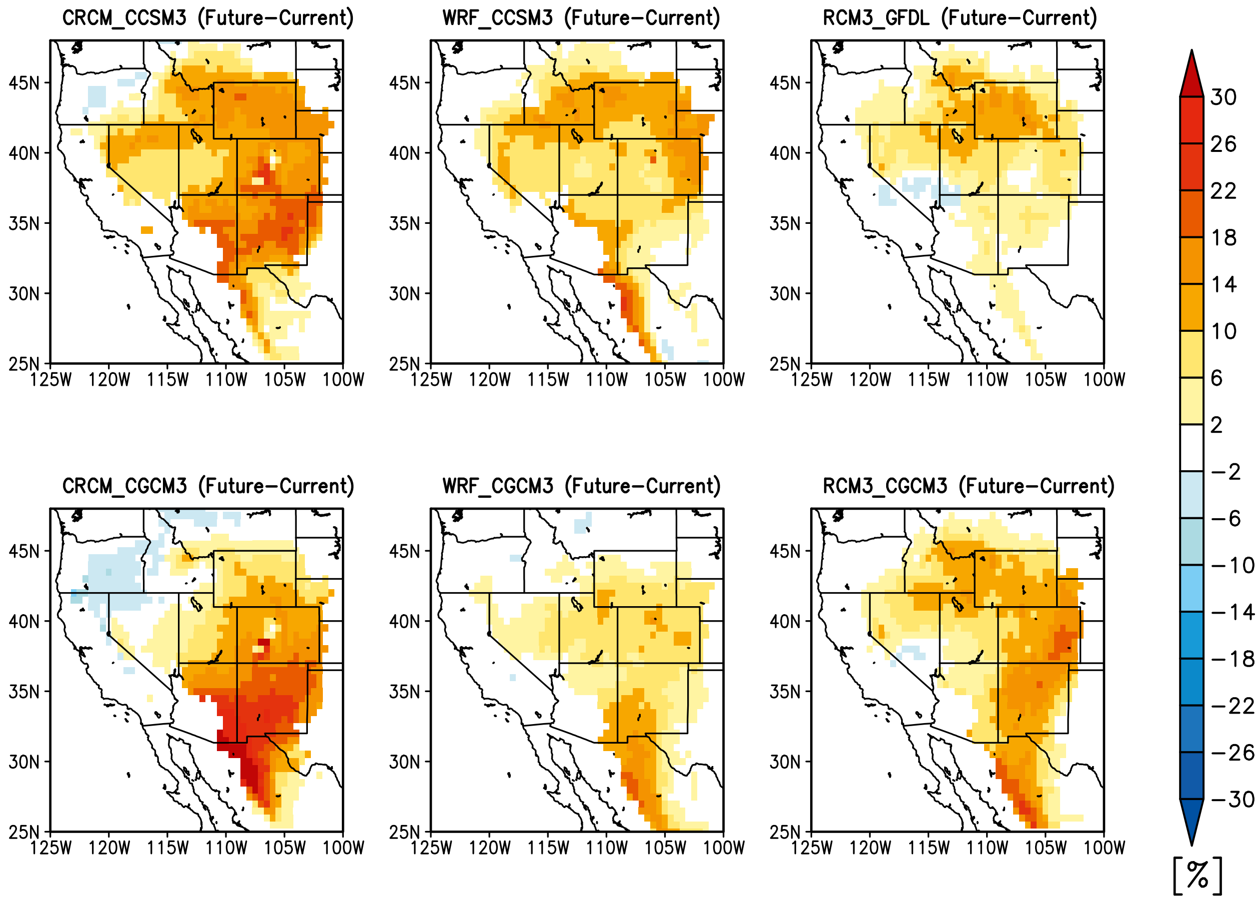

FIG. 3. Changes in the percentage of days for which HI ≥ 5 during August between the current and the future climate as simulated by the (left) CRCM, (center) WRF, and (right) RCM3 models driven by the (top) CCSM3 and (bottom) CGCM3 fields. For RCM3, CCSM3 is replaced by the GFDL model. The HI is calculated using information at 0000 UTC of each day in August for the current (1971–2000) and future (2041–70) climates.

current and future climate may provide a good basis for examining the changes in the climatological distribution of the HI in a projected future climate. Figure 3 shows the changes in the frequency of high-risk days during August between the current and future climate. All six RCM–AOGCM combinations show an increase in frequency over most of the study domain. The CRCM simulations (left column in Fig. 3) show large increases in frequency over Wyoming, Colorado, and New Mexico, whereas the WRF simulations (center column in Fig. 3) show moderate increases across the entire high-elevation area in the western United States. The RCM3 simulations (right column in Fig. 3) also show a general increase, but the magnitude of the increase and the geographic distribution change with the change of driving AOGCM. The general consensus on the increase of frequency of high-risk days among all six projections suggests that favorable lower-atmospheric conditions for wildfire growth may become more frequent over the western United States in the future as a result of global climate change. The exact magnitude of the changes is not easy to ascertain given the differences among the projections. For example, the CRCM driven with the CGCM3 shows a considerable increase in the frequency of HI ≥ 5 over the eastern side of the Rocky Mountains in Arizona, New Mexico, and northern Mexico, whereas other RCM–AOGCM combinations show only moderate increases over the same area. These disparities emphasize the importance of understanding the uncertainties associated with climate projections and how such uncertainties should be treated properly in decision making. It is also worth mentioning that the increase in HI is more due to the moisture component (B) than to the temperature component (A) in most of the models (not shown).

While individual days with HI ≥ 5 suggest moderate to high risk of rapid wildfire growth, consecutive days with HI ≥ 5 would indicate a potentially more alarming situation. We examined the changes in the average number

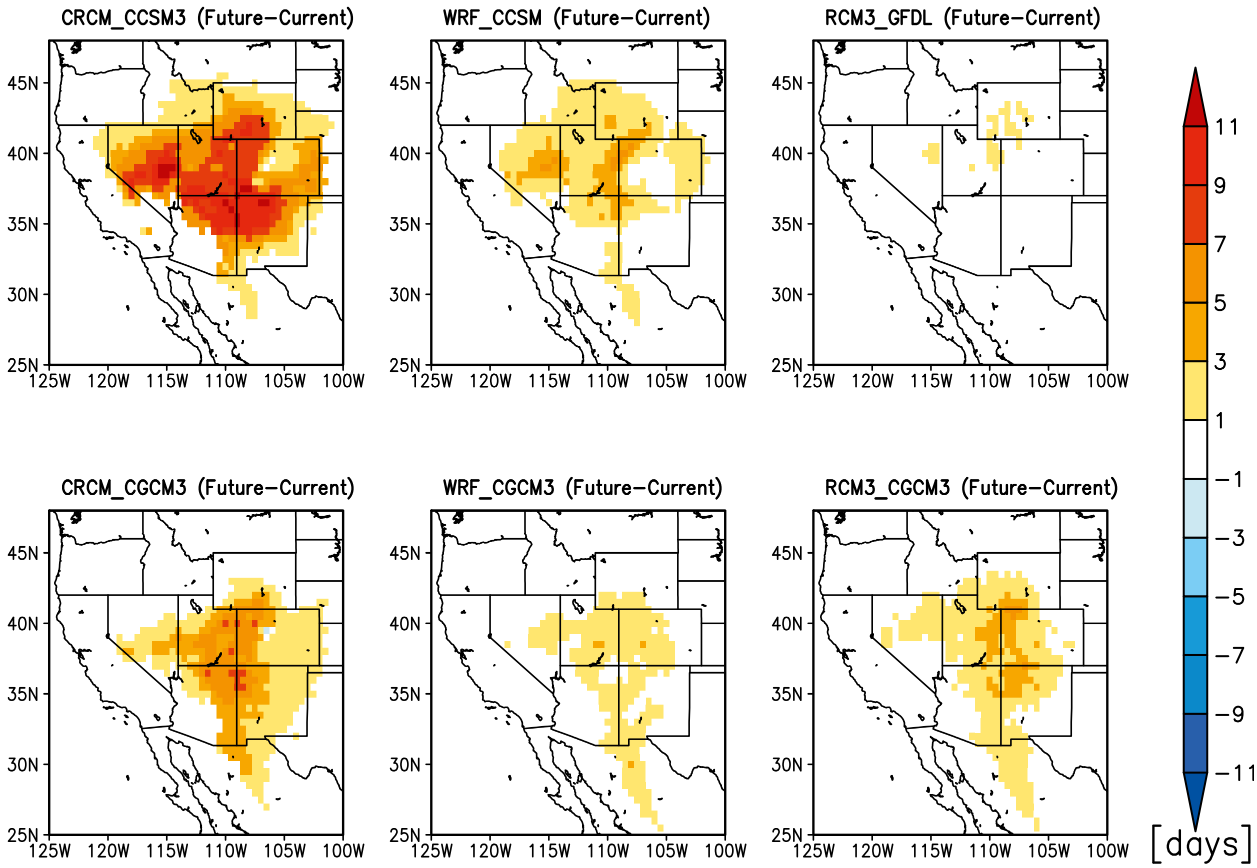

FIG. 4. As in Fig. 3, but for changes in the average length of consecutive days with HI ≥ 5.

of consecutive days when HI ≥ 5 (or the persistence of a high-risk episode) in the RCM simulations, and five of the six projections show increases in the duration of events with HI ≥ 5 (Fig. 4), and only RCM3 driven with the GFDL model shows little or no change. The CRCM driven with the CCSM3 shows a large increase in the length of high-risk episodes by 7–9 days in Utah, Colorado, and Wyoming, and the WRF model driven with the CCSM3 shows an increase of only 1–3 days over most of the regions. Despite the differences among the six projections, the result still suggests that the average duration of episodes with HI ≥ 5 may increase in the future, leading to an increased risk of rapid wildfire growth.

4. Summary and discussion

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change has shown the likely changes in temperature and precipitation over midlatitude regions as a result of global climate change driven by the increase in CO_2 concentration in the atmosphere. In this study, we further focus on the potential changes in lower-atmospheric conditions resulting from global climate change that could affect wildfire growth in the high-elevation regions over the western United States. We selected the Haines index as the metric and studied the changes in the climatological distribution of the HI between the current and projected future climates as simulated by RCMs driven with multiple AOGCMs produced by the NARCCAP project. By examining the changes in the total number of days and number of consecutive days when HI ≥ 5, we find that future climate conditions would likely result in more dry and less-stable days in August, which is the most active month for wildfires in the western United States. As a result, the potential risk of erratic large wildfires could increase greatly.

As with other climate-change studies, there are always uncertainties associated with projections. The six RCM–AOGCM combinations presented here clearly demonstrate these uncertainties, which can be attributed to the RCMs and the AOGCMs, as well as their interactions. NARCCAP has employed multiple RCMs to dynamically downscale multiple AOGCMs with different equilibrium climate sensitivity; a full analysis of all these RCM–AOGCM combinations will yield a better understanding on the uncertainties. Another paper is currently planned to provide more comprehensive analyses and discussion on this topic over the entire United States using all available NARCCAP model combinations.

We recognize that all RCMs and AOGCMs have their inherent biases in almost all fields; thus the HI, which is a derived index from multiple raw model variables, will inevitably suffer some errors and biases. Studying the bias in the NARCCAP models and developing a proper bias-correction scheme is beyond the scope of this paper. The purpose of this study is to better understand the relative changes in HI distributions between the current and potential future climate rather than to try to project the exact HI distribution in the future. Various methods that were developed to reduce systematic biases in model simulations might modify the magnitude of the changes to some degree but will unlikely affect the sign of the change.

Of course, lower-atmospheric conditions are not the only factor to consider when evaluating the risk of large and extreme wildfires. Fuel availability, hydrological conditions, lightning occurrence, and fire-suppression activities all need to be considered. Westerling et al. (2006) found that the length of the fire season in the western United States was 78 days longer on average from 1987 to 2003 than it was from 1970 to 1986. Compounding the adverse effect of a lengthening fire season, the findings from this study suggest that future atmospheric conditions may also favor larger and more extreme wildfires in the western United States, posing an additional challenge to fire and forest management in the future.

Acknowledgments. This research is supported by the USDA Forest Service Northern Research Station (Agreement 11-JV-11242306-065) and by Michigan State University AgBioResearch. We thank the NARCCAP team for conducting regional climate model simulations and making data available to this research. We also thank Julie Winkler and Lisi Pei for reviewing an early version of the manuscript, Joseph Charney for useful discussions, and the three anonymous reviewers for their insightful and constructive comments.

REFERENCES

Bradshaw, L. S., J. E. Deeming, R. E. Burgan, and J. D. Cohen, 1984: The 1978 National Fire Danger Rating System: Technical documentation. U.S. Dept. of Agriculture Forest Service General Tech. Rep. INT-169, 44 pp. [Available online at http://www.fs.fed.us/rm/pubs_int/int_gtr169.pdf.]

Burgan, R. E., R. W. Klaver, and J. M. Klaver, 1998: Fuel models and fire potential from satellite and surface observations. *Int. J. Wildland Fire,* **8,** 159–170.

——, P. L. Andrews, L. S. Bradshaw, C. H. Chase, R. A. Hartford, and D. J. Latham, 1997: WFAS: Wildland fire assessment system. *Fire Manage. Notes,* **57,** 14–17.

Caya, D., 1996: Le modèle régional de climat de l'UQÀM (The UQAM regional climate model). Ph.D. thesis, Université du Québec à Montréal, Canada, 134 pp.

——, and R. Laprise, 1999: A semi-implicit semi-Lagrangian regional climate model: The Canadian RCM. *Mon. Wea. Rev.,* **127,** 341–362.

Christensen, N. L., and Coauthors, 1989: Interpreting the Yellowstone Fires of 1988. *Bioscience,* **39,** 678–722.

Collins, W. D., and Coauthors, 2006: The Community Climate System Model version 3: CCSM3. *J. Climate,* **19,** 2122–2143.

Delworth, T. L., and Coauthors, 2006: GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics. *J. Climate,* **19,** 643–674.

Flannigan, M. D., M. A. Krawchuk, W. J. de Groot, B. M. Wotton, and L. M. Gowman, 2009: Implications of changing climate for global wildland fire. *Int. J. Wildland Fire,* **18,** 483–507.

Gillett, N. P., A. J. Weaver, F. W. Zwiers, and M. D. Flannigan, 2004: Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.,* **31,** L18211, doi:10.1029/2004GL020876.

Goodrick, S., D. Wade, J. Brenner, G. Babb, and W. Thomson, 2000: Relationship of daily fire activity to the Haines index and the Lavdas dispersion index during 1998 Florida wildfires. Florida Division of Forestry, 13 pp.

Haines, D. A., 1988: A lower atmosphere severity index for wildland fires. *Natl. Wea. Dig.,* **13,** 23–27.

Hardy-Short, D. C., and C. B. Short, 1995: Fire, death, and rebirth: A metaphoric analysis of the 1988 Yellowstone Fire debate. *West. J. Commun.,* **59,** 103–125.

Heilman, W. E., and X. Bian, 2010: Turbulent kinetic energy during wildfires in the north central and northeastern US. *Int. J. Wildland Fire,* **19,** 346–363.

——, and ——, 2012: Climatic variability of near-surface turbulent kinetic energy over the United States: Implications for fire-weather prediction. *J. Appl. Meteor. Climatol.,* **52,** 753–772.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.,* **83,** 1631–1643.

Liu, Y.-Q., S. Goodrick, and J. Stanturf, 2012: Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. *For. Ecol. Manage.,* **294,** 120–135.

Lu, W., J. Charney, S. Zhong, X. Bian, and S. Liu, 2011: A North American Regional Reanalysis climatology of the Haines index. *Int. J. Wildland Fire,* **20,** 91–103.

Mearns, L. O., W. J. Gutowski, R. Jones, L.-Y. Leung, S. McGinnis, A. M. B. Nunes, and Y. Qian, 2009: A regional climate change assessment program for North America. *Eos, Trans. Amer. Geophys. Union,* **90,** 311–312.

——, and Coauthors, cited 2012: The North American Regional Climate Change Assessment Program dataset. National Center for Atmospheric Research Earth System Grid data portal. [Available online at http://www.earthsystemgrid.org/project/NARCCAP.html.]

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.,* **87,** 343–360.

Nakicenovic, N., and Coauthors, 2000: *Special Report on Emissions Scenarios.* Cambridge University Press, 599 pp.

National Climatic Data Center, cited 2012: State of the climate: Wildfires—August 2012. [Available online at http://www.ncdc.noaa.gov/sotc/fire/2012/8.]

Pal, J. S., and Coauthors, 2007: The ICTP RegCM3 and RegCNET: Regional climate modeling for the developing world. *Bull. Amer. Meteor. Soc.,* **88,** 1395–1409.

Potter, B. E., J. A. Winkler, D. F. Wilhelm, R. P. Shadbolt, and X. Bian, 2008: Computing the low-elevation variant of the Haines index for fire weather forecasts. *Wea. Forecasting,* **23,** 159–167.

Rothermel, R. C., R. A. Hartford, and C. H. Chase, 1994: Fire growth maps for the 1988 greater Yellowstone area fires. USDA Forest Service General Tech. Rep. INT-304, 64 pp.

Schlobohm, P., and J. Brain, 2002: Gaining an understanding of the National Fire Danger Rating System. National Wildfire Coordinating Group Publication NFES 2665, 72 pp. [Available online at http://www.nwcg.gov/var/products/gaining-an-understanding-of-the-national-fire.]

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF version 2. NCAR Tech. Note TN-468+STR, 88 pp.

Spracklen, D. V., L. J. Mickley, J. A. Logan, R. C. Hudman, R. Yevich, M. D. Flannigan, and A. L. Westerling, 2009: Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *J. Geophys. Res.,* **114,** D20301, doi:10.1029/2008JD010966.

Stocks, B. J., and Coauthors, 1998: Climate change and forest fire potential in Russian and Canadian boreal forests. *Climatic Change,* **38,** 1–13.

USDA, 1968: The wildland fire-danger rating system. U.S. Dept. of Agriculture Forest Service Rep., 108 pp.

Werth, P., R. Ochoa, 1993: The evaluation of Idaho wildfire growth using the Haines index. *Wea. Forecasting,* **8,** 223–234.

Westerling, A. L., A. Gershunov, T. Brown, D. Cayan, and M. Dettinger, 2003: Climate and wildfire in the western United States. *Bull. Amer. Meteor. Soc.,* **84,** 595–604.

——, H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science,* **313,** 940–943.

Williams, A. A. J., D. J. Karoly, and N. Tapper, 2001: The sensitivity of Australian fire danger to climate change. *Climatic Change,* **49,** 171–191.

Winkler, J. A., B. E. Potter, D. F. Wilhelm, R. P. Shadbolt, K. Piromsopa, and X. D. Bian, 2007: Climatological and statistical characteristics of the Haines index for North America. *Int. J. Wildland Fire,* **16,** 139–152.