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Global wildland fire season severity in the 21st century ☆

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ABSTRACT

We used Cumulative Severity Rating (CSR), a weather-based fire danger metric, to examine the potential influence of climate change on global fire season severity. The potential influence of climate change on fire season length was also addressed. We used three General Circulation Models (GCMs) and three emission scenarios to calculate the CSR and fire season length for mid-century (2041–2050) and late century (2091–2100) relative to the 1971–2000 baseline. Our results suggest significant increases in the CSR for all models and scenarios. Increases were greatest (more than three times greater than the baseline CSR) for the Northern Hemisphere at the end of the century. Fire season length changes were also most pronounced at the end of the century and for northern high latitudes where fire season lengths will increase by more than 20 days per year. The implications from this study are that fire seasons will be more severe in future and that conventional fire management approaches may no longer be effective.

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1. Introduction

Wildland fire is a widespread and critical aspect of the earth system (Bond and Keeley, 2006). Estimates of annual area burned range between 300 and 450 Mha (van der Werf et al., 2006) which is comparable to the size of India. Over 80% of the global area burned occurs in grasslands and savannas, primarily in Africa and Australia but also in South Asia and South America. Globally fires are frequent over most of the earth except in areas of sparse vegetation (e.g., North Africa) and near the poles (Mouillot and Field, 2005). Wildland fires are a continuous and global feature with fire occurring all year long in the northern or southern or both hemispheres. We do not know how many fires are started each year but human activities are responsible for the vast majority; lightning is the other common ignition cause for wildland fires. Many billions of dollars are spent on fire management and fire suppression every year.

Fire activity is strongly influenced by four factors: fuels, climate-weather, ignition agents and people (Flannigan et al., 2005). Fuel amount, type, continuity, structure, and moisture level are critical elements of fire occurrence and spread. For fires to spread there needs to be fuel continuity; some suggest that at least 30% of the landscape needs to have fuel for a fire to spread (Hargrove et al., 2000). This is important in many drier parts of the world where a certain amount of precipitation is required prior to the fire season for plant growth to provide sufficient fuel buildup that allows continuous fire spread on the landscape (Swetnam and Betancourt, 1998; Meyn et al., 2007). Fuel structure can also be important in fire dynamics. For example, understory trees and shrubs in a forest can act as ladder fuels that carry a surface fire up into tree crowns and thereby generate a faster moving and much more intense fire. Although the amount of fuel, or fuel load, affects fire activity because a minimum amount of fuel is required for fire to start and spread, fuel moisture largely determines fire behaviour, and has been found to be an important factor in the amount of area burned.

Weather and climate – including temperature, precipitation, wind, and atmospheric moisture – are critical aspects of fire activity (Flannigan and Harrington, 1988; Swetnam, 1993). Some examples that highlight the role of weather and climate include Cary et al. (2006) who found that weather and climate best explained the amount of area burned using landscape fire models, as compared with variation in terrain and fuel pattern. Carcaillet et al. (2001) found that climate was the key process triggering fire over the eastern boreal forest during the Holocene. Prasad et al. (2008) found that mean annual temperature and average precipitation of the warmest quarter of the year were among the variables that best explained fire occurrence in southern India.

The global climate is warming and this may have a profound and immediate impact on wildland fire activity. Some suggest that wildland fire activity has already increased due to climate change.

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Gillett et al. (2004) suggest that the increase in area burned in Canada over the past four decades is due to human-caused increases in temperatures. Flannigan et al. (2009a) in a review of global wildland fire activity found numerous research papers that suggests area burned and fire occurrence will increase with a warmer climate and fire seasons will be longer. The results were more mixed with respect to fire severity and intensity with some studies suggesting increase and some suggesting no changes or decreases. The objective of this paper is to examine future global fire season severity using the Daily Severity Rating (DSR) of the Canadian Forest Fire Danger Rating System (CFFDRS). These results provide insights into future fire intensity, which is important in terms of fire management. For example, as average fire intensity increases, wildfire suppression resource requirements will exceed available resource levels with greater frequency, resulting in greater area burned. Additionally, we will calculate future fire season length for the globe as an additional indicator of future fire management challenges since longer fire seasons will translate into more fire starts and more opportunities for fires to escape control.

2. Data and methods

This study used components of the Canadian Forest Fire Weather Index (FWI) System. The FWI System is used by many countries around the world, and the FWI component itself (of the FWI System) is commonly used as a general indicator of fire danger and fire intensity at the landscape level (Van Wagner, 1987). The FWI System is a weather-based system that models fuel moisture using a dynamic bookkeeping system that tracks the drying and wetting of distinct fuel layers in the forest floor. There are three moisture codes that represent the moisture content of fine fuels (Fine Fuel Moisture Code, FFMC), loosely compacted organic material (Duff Moisture Code, DMC) and a deep layer of compact organic material (Drought Code, DC). The drying time lags for these three fuel layers are 2/3 of a day, 15 days and 52 days respectively for the FFMC, DMC and DC under normal conditions (temperature 21.1 °C, relative humidity 45%). These moisture indexes are combined to create a generalised index of the availability of fuel for consumption (Buildup Index, BUI); the FFMC is combined with wind to estimate the potential spread rate of a fire (Initial Spread Index, ISI). The BUI and ISI are combined to create the FWI which is an estimate of the potential intensity of a spreading fire. The daily severity rating (DSR) is a simple power function of the FWI intended to increase the weight of higher values of FWI in order to compensate for the exponential increase in area burned with fire diameter (Williams, 1959; Van Wagner, 1970).

The FWI was designed as a scaled analogue of Byram (1959) fireline intensity. Fireline intensity is used operationally in many jurisdictions around the world to evaluate the potential effectiveness of different resources to contain and control wildland fire for the environmental conditions on a given day. It was recognised early in the development of fire danger rating that the appropriate scale of operationally useful fire danger indexes (i.e. the FWI) did not reflect the difficulty of control or work required for suppression of a fire under given conditions (Williams, 1959). The Daily Severity Rating (DSR) was conceived to indicate fire suppression difficulty in the Canadian danger rating system and is essentially a simple power function of the FWI (with an exponent of 1.77). With this scaling, the DSR is intended to reflect the non-linear increase in difficulty of control as the fire grows (Van Wagner, 1970) and as such is the index used when seasonal summaries of fire severity are generated.

Typically, the average DSR over an entire fire season (the Seasonal Severity Rating, SSR) is used to provide a general summary of the potential difficulty of fire control over an entire season. It is used when regionally contrasting potential fire control difficulty for seasons over multiple years. A simple seasonal average, however, may not be the best relative indicator of changes in control difficulty in scenarios where a trend to a lengthening of the fire season exists. In such scenarios, increased number of days of high and extreme potential suppression difficulty may be obscured in the average by increased number of days overall; days which, in the shoulders of the season, are likely to be more benign. For this study, to try to capture the changes in control difficulty across fire seasons with potentially changing lengths, we chose to rely on the sum of DSR values over the season as our indicator of fire season severity (the Cumulative Severity Rating, CSR). In a region with an unchanging fire season duration, SSR and CSR are essentially the same (CSR simply being SSR unscaled by the number of days in the fire season). By not scaling the CSR by season length, however, it provides what can be thought of as a weighted count of number of severe days in the fire season, and thus will be a better indicator of the absolute numbers of challenging (in terms of fire

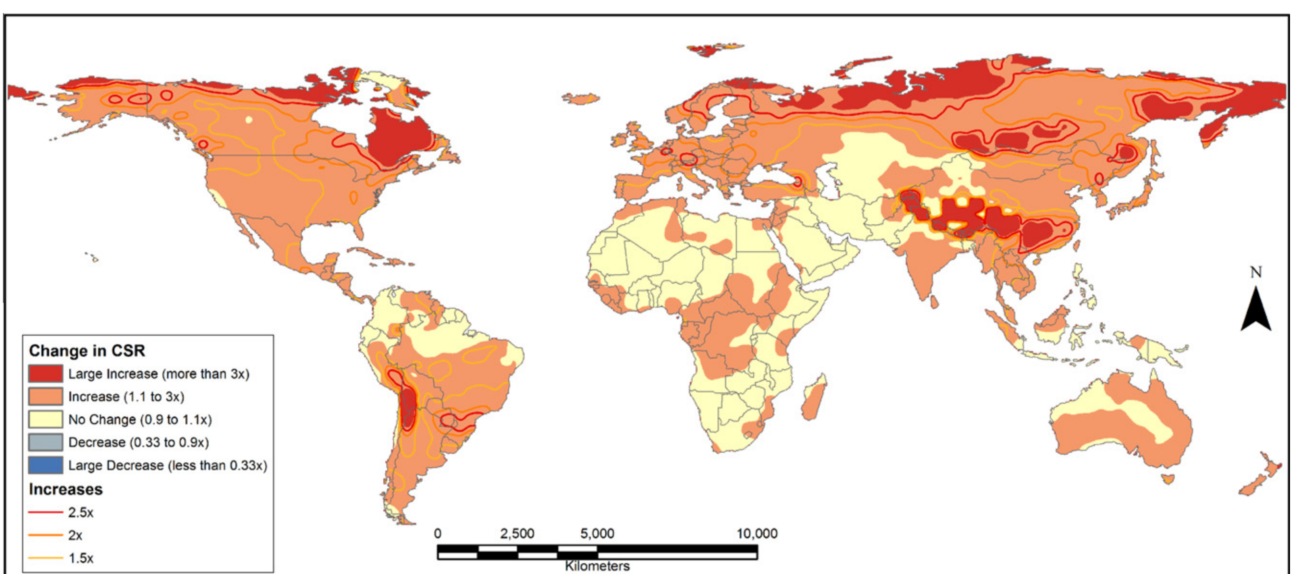

Fig. 1. CSR anomalies for the IPSL-CM4 A2 for 2041–2050 relative to the 1971–2000 base period.

control) days across fire seasons. The fire season length was calculated using a straightforward temperature approach similar to that used by Wotton and Flannigan (1993). The beginning of the season was defined as 3 consecutive days of 9 °C or greater, and the end of the fire season was defined as three consecutive days of 2 °C or lower. These values are lower than what Flannigan and Wotton used but this study used mean temperature as opposed to 1200 LST temperature in the previous study.

For the observational weather data required to calculate the CSR, we used the NCEP Reanalysis I data from 1971 to 2000, which was provided by NOAA/OAR/ESRL PSD, in Boulder Colorado. The raw data was analysed using a $2.5° \times 2.5°$ grid for daily mean surface RH, air temperature, U-wind vector and V-wind vector. Wind speed was calculated as the magnitude of the sum of these two vectors. The 6 h precipitation rate was analysed on T63 Gaussian grid then interpolated to the $2.5° \times 2.5°$ grid and assumed to fall uniformly over the 6 h interval. This hourly precipitation was then accumulated for the 24 h prior to noon local time each day, and together with the other three weather variables, was combined into one large dataset, sorted by date and grid point, and then used to calculate daily FWI System outputs.

We selected three GCMs for this study: (1) the CGCM3.1 from the Canadian Centre for Climate Modelling and Analysis, (2) the HadCM3 from the Hadley Centre for Climate Prediction in the United Kingdom, and (3) the IPSL-CM4 from France. For the Canadian model, there were two resolutions available: T47 and T63. T47 was chosen as it was more complete than T63. These three models were selected to provide us a range of warming with the Canadian model being the smallest increase in monthly mean temperatures and the Hadley having the largest increase in monthly mean temperature.

There are four families of emission scenarios to choose from for this analysis; A1, A2, B1, and B2. A1 is described by a world of very rapid economic growth, with the global population peaking

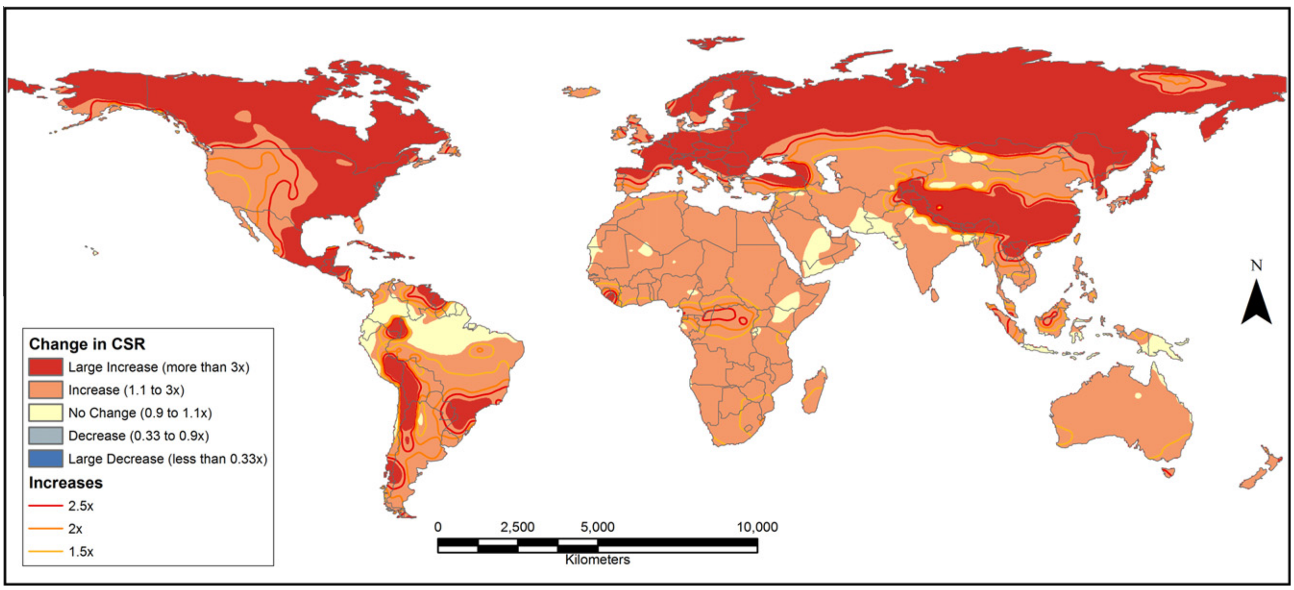

Fig. 2. CSR anomalies for the IPSL-CM4 A2 for 2091–2100 relative to the 1971–2000 base period.

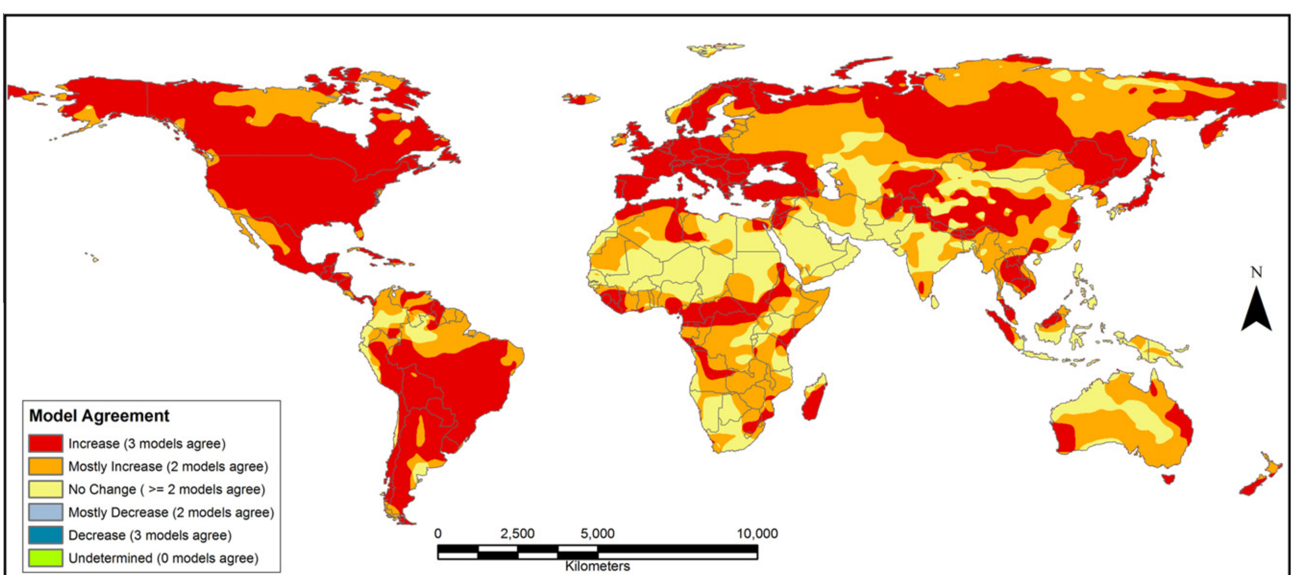

Fig. 3. Composite CSR anomaly map for the A2 scenario 2041–2050 relative to the 1971–2000 base period.

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mid-century. In this scenario, there is a rapid introduction of new and more efficient technologies. A1 is further divided into three groups. A1F1 is fossil-fuel intensive, A1T assumes non-fossil energy resource use, and A1B is a balance across all energy sources. A2 is a world with increased population growth, slow economic development and slow technological change. B1 shares the same population trend as A1, but has a more rapid change in economic structure, moving towards service and information technology. Lastly, B2 has an intermediate population and economic growth. It emphasises local solutions to economic, social and environmental sustainability. We selected three scenarios for evaluation in this study: A1B, A2 and B1.

We downloaded the historical or baseline monthly data for air temperature, precipitation rate, U-wind vector and V-wind vector variables for each GCM. For CGCM3.1 and IPSL-CM4 models, specific humidity was downloaded and converted to relative humidity; for HadCM3, relative humidity was downloaded directly. We calculated 30-year monthly averages for each variable. We then downloaded monthly data for the 21st century for all three GCMs and all three emission scenarios (A1B, A2 and B1). The CSR and fire season lengths were calculated using the modified NCEP daily data to be representative of future decades. Because the GCM grids were different from the NCEP Reanalysis, we interpolated all GCM data to the same NCEP $2.5^\circ \times 2.5^\circ$ grid. We used XConv/convsh 1.91 (Cole, 2009) which allowed us to easily interpolate from one grid format to any other grid format using an area weighted interpolation.

For all scenarios and models, we calculated the decadal monthly means for all the variables and for all decades in the 21st century (2001–2010 to 2091–2100). The GCM 30-year baseline monthly averages for air temperature, relative humidity and wind speed were subtracted from the future decadal monthly averages and the result was added to the NCEP baseline daily data, by month. The resulting new daily weather was used to calculate the start

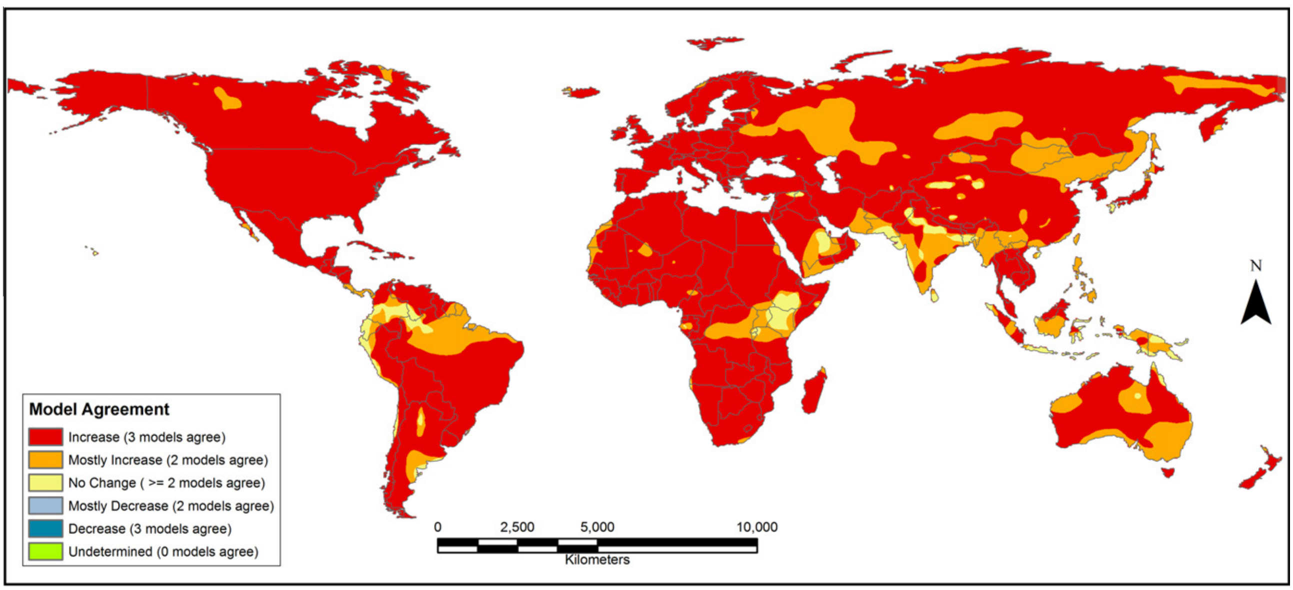

Fig. 4. Composite CSR anomaly map for the A2 scenario 2091–2100 relative to the 1971–2000 base period.

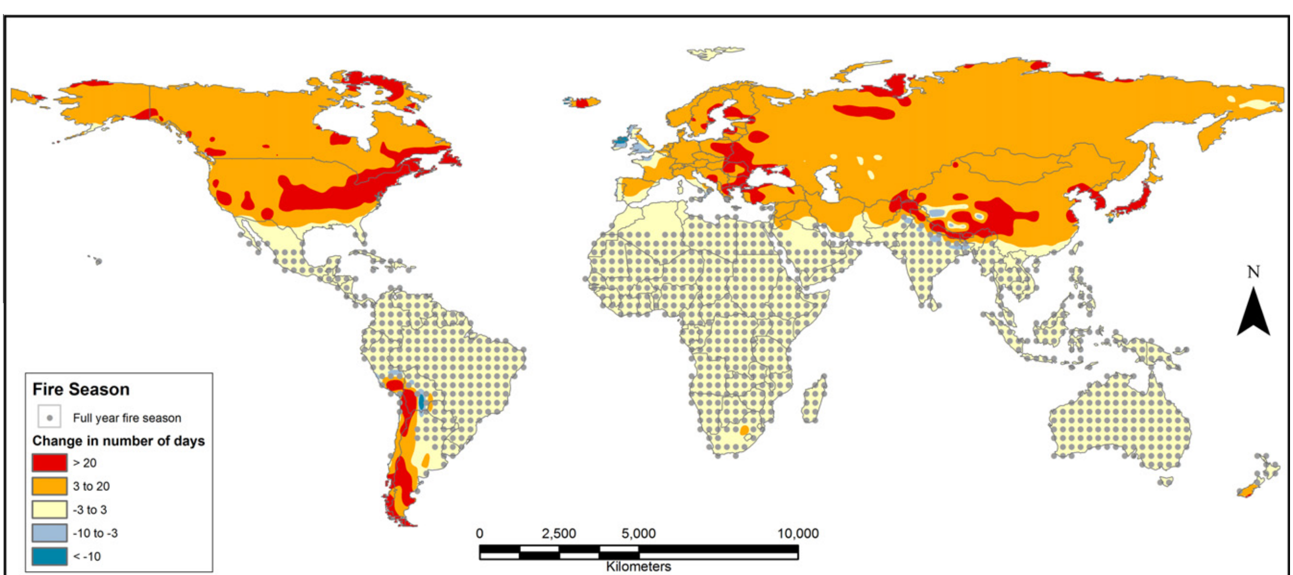

Fig. 5. Fire season length anomaly maps for 2041–2050 for Hadley CM3 B1 scenario relative to the 1971–2000 base period.

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and end dates of the fire season and calculate the FWI System components, and ultimately the CSR over the resulting fire season. For example, if the average May temperature was 2 °C warmer in a future decade than in the GCM 1971–2000 period at a particular grid point then all the daily May temperatures in the NCEP baseline data at that grid point were increased by 2 °C. For precipitation, the decadal future monthly GCM averages were divided by the 30-year GCM monthly baselines to get a ratio of future precipitation over baseline precipitation. This ratio was used as a multiplier to the daily precipitation amount in the NCEP baseline. Thus the CSR and fire season length were calculated using the modified NCEP daily data to be representative of future decades. CSR anomaly maps (ratios of future CSR over baseline 1971–2100 CSR values) were created for the 2041–2050 and 2091–2100 periods for all GCMs and all emission scenarios. For this study, we used the entire land surface of the earth except Antarctica but there are other regions that are sparsely vegetated where fire is currently absent or infrequent. There were nine maps for each decade (3 GCMs × 3 scenarios). Fire season length anomaly maps were created for the 2041–2050 and 2091–2100 periods for each GCM and each scenario (nine maps for each decade) in the same fashion as the CSR maps.

All the analyses were conducted using R (R development Core Team, 2011).

3. Results

Figs. 1 and 2 show examples of CSR for the IPSL model and the A2 scenario for 2041–2050 and for 2091–2100. These examples (Figs. 1 and 2) are representative of all the GCMs and scenarios maps that show a significant world-wide increase in CSR especially for the northern hemisphere. The increases relative to the base period of 1971–2000 are observed across the entire world at the end

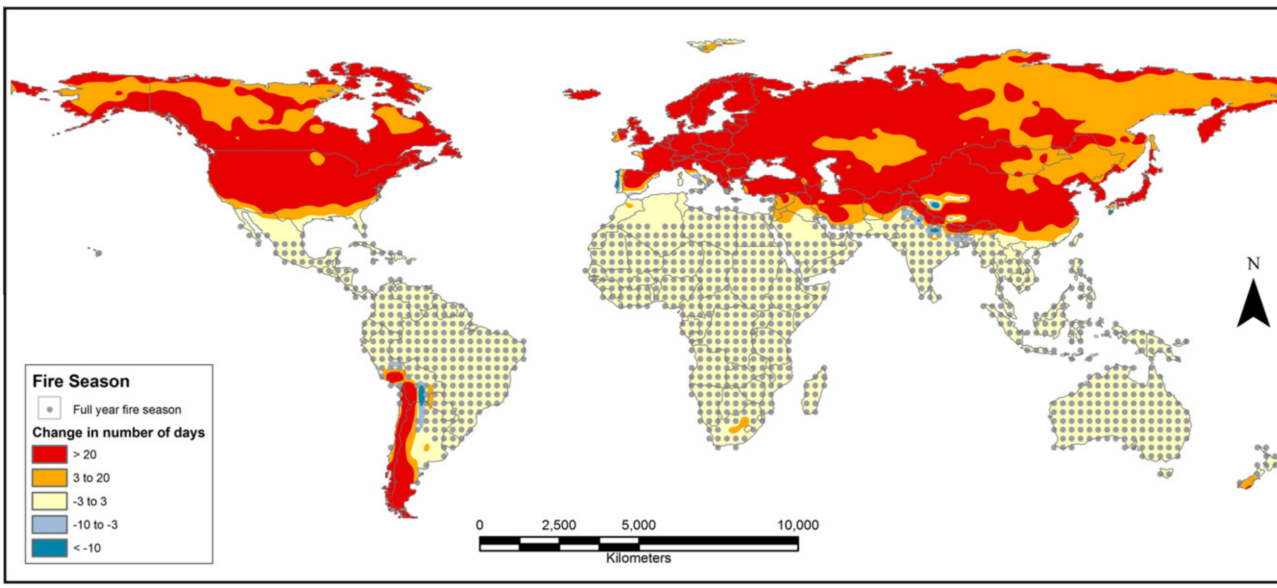

Fig. 6. Fire season length anomaly maps for 2091–2100 for Hadley CM3 B1 scenario relative to the 1971–2000 base period.

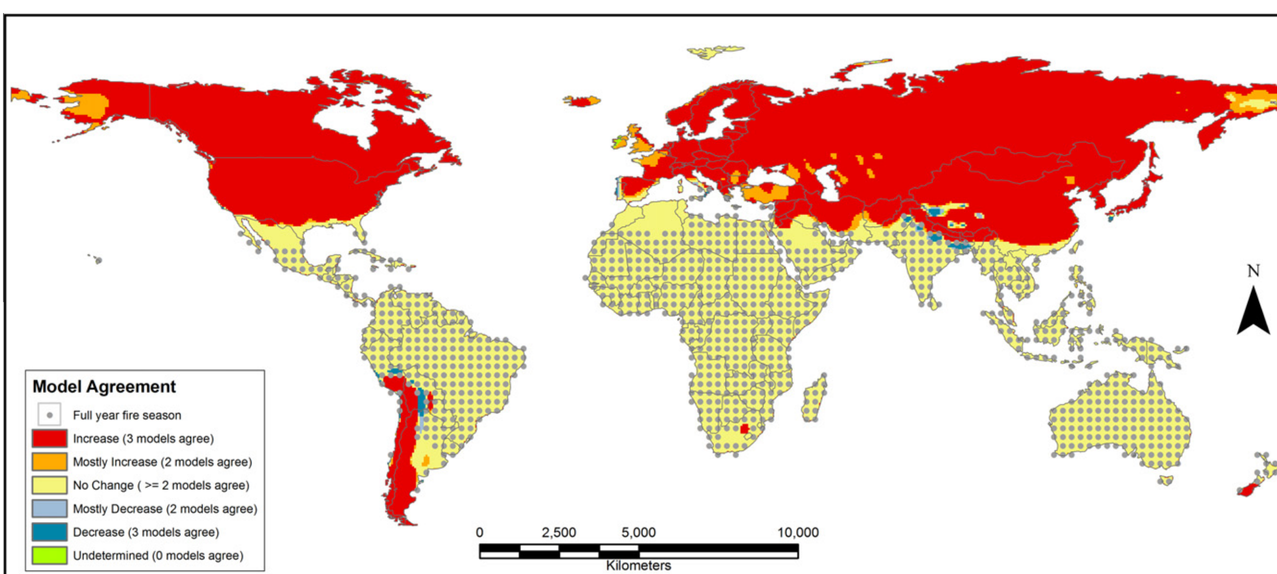

Fig. 7. Fire season length anomaly maps for the B1 scenario 2041–2050.

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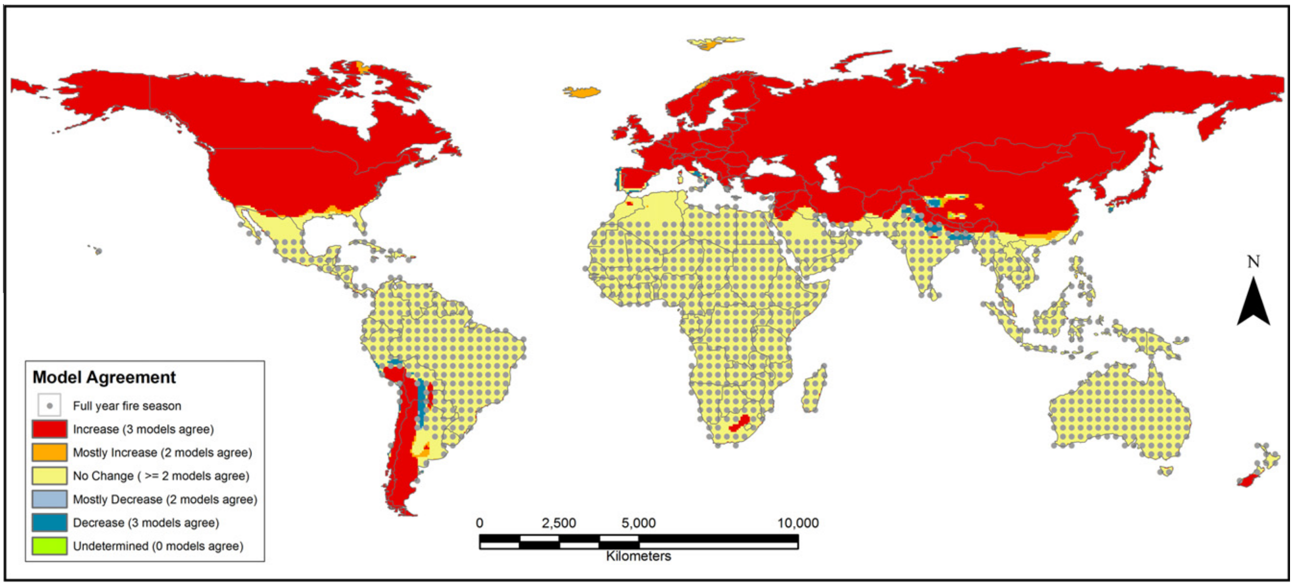

Fig. 8. Fire season length anomaly maps for the B1 scenario 2091–2100.

of the century with some of the increases exceeding three times the baseline value which are very significant.

Composite CSR anomaly maps were made for 2041–2050 and 2091–2100 that show how well GCMs agreed for each emission scenario (Figs. 3 and 4 show the A2 scenario which is very similar to A1B and B1 that are not shown). In these maps, agreement was made on whether it was in the same category; we used three categories, decrease, no change and increase. These figures highlight that there is good agreement across the models and there is good agreement across scenarios (not shown). Large parts of the earth are showing increases in CSR for all three GCMs for mid-century and the increases are even more pronounced at the end of the century. There are no areas where models suggest a decrease in CSR. There are some regions where the consensus is no change but these areas are not large and become almost insignificant by the end of the century.

The anomaly maps showed the change in number of days in fire season per year. Figs. 5 and 6 show examples of fire season length for the Hadley model and the B1 scenario for 2041–2050 and 2091–2100. These maps were combined to show how well the models agreed across scenarios for each time period (Figs. 7 and 8 for the B1 scenario but these are very similar to A1B and A2 that are not shown).

These results suggest significant increases in CSR across most of the earth with very pronounced increases initially at high northern latitudes but encompassing most of the earth by the end of the century. With these increases we expect more area burned, increased fire occurrence, and greater fire intensity that will result in more severe fire seasons and increased fire control difficulty. The fire season length shows significant parts of the globe such as tropical areas and the Mediterranean region have a full year fire season already. The increases in fire season length are modest overall, and are largest at higher latitudes and later in the century.

4. Discussion

Our climate is warming and this may have a dramatic and rapid impact on wildland fire activity. The consistency in the results suggesting significant increases over most of the earth may be attributed to the role temperature plays in fire activity. Almost the entire globe is expected to warm over this century and our results may be a reflection of this temperature increase. Numerous studies suggest that temperature is the most important variable affecting annual wildland fire activity, with warmer temperatures leading to increased fire activity (Parisien et al., 2011). Gillett et al. (2004) suggest that the increase in area burned in Canada over the past four decades is due to human-caused increases in temperatures. The reason for the positive relationship between temperature and wildland fire is threefold. First, warmer temperatures will increase evapotranspiration, as the ability for the atmosphere to hold moisture increases rapidly with higher temperatures, thereby lowering water table position and decreasing fuel moisture unless there are significant increases in precipitation. Second, warmer temperatures translate into more lightning activity that generally leads to increased ignitions (Price and Rind, 1994). Third, warmer temperatures may lead to a lengthening of the fire season (Westerling et al., 2006). While testing the sensitivity of landscape fire models to climate change and other factors, Cary et al. (2006) found that area burned increased with higher temperatures. This increase was present even when precipitation was increased, although the increase in area burned was greatest for the warmer and drier scenario. The bottom line is that we expect more fire in a warmer world. Precipitation also has an important influence on fire activity but timing of precipitation during the fire season rather than the amount is usually the most important aspect (Flannigan and Harrington, 1988). In this study, we did not change the timing of the precipitation but only the amount and this probably does have some bearing on our results. If some regions have fewer days of precipitation in the future, this would probably enhance the predicted increases in fire activity; alternatively, if some regions have greater precipitation frequency, this could offset some of the predicted fire activity increases. Our results are somewhat similar to Liu et al. (2010) who found potentially significant increases in future wildfire potential in many parts of world using the Keetch–Byram Drought Index. Our results differ from Liu et al. (2010) in the circumboreal region (Russia, Canada, Alaska) where we found very significant increases. The results from this study do not agree with the findings from Krawchuk et al. (2009) who suggest that there may be many regions of the world with decreasing fire activity. However, most of the research suggests that we should expect increases in area burned and number of fires in a warmer world

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(Flannigan et al., 2009a). Hansen et al. (2012) show that the likelihood of extreme seasonal mean temperatures has increased significantly since the 1951–1980 base period and suggests that the extreme anomalies in Russia 2010 and Texas and Oklahoma in 2011 are a consequence of global warming. It is interesting to note that extreme fire activity was associated with this period of extreme heat in Russia and central USA. Also, Dai (2012) demonstrates that increasing drought has been observed, and some models suggest more severe and widespread droughts in the future under global warming. As mentioned earlier, fuels, ignitions, weather and people are key factors affecting fire activity but in many regions it is weather, and in particular temperature, that is the primary factor explaining much of the variance in regional area burned (Balshi et al., 2009; Parisien et al., 2011). In many parts of the world, ignitions are not limiting as people are widely distributed across the landscape. The fuel factor is more complicated and may indeed be a constraint for fire activity in extremely sparsely vegetated parts of the world during some time periods. However, many fire-prone biomes like the circumboreal (de Groot et al., this issue) have little or no fuel constraints. The bottom line is that a warmer world will have more fire over most of the earth according to the simulations in this study.

If fire activity is determined by fuels, ignitions and weather, then this influences our response to the potential impact of climate warming on wildland fire activity. We can't change the weather and we can't modify lightning activity in any significant way. Our remaining options are to reduce human-caused ignitions and to modify fuels. Human-caused ignitions can be reduced through education programs, restricting or excluding the use of fire, and through proper enforcement of existing policies. Treating fuels at the global scale is not possible but treating fuels at the local scale near areas of high value can be done. A number of programs already exist that promote the fuel reduction or modification approach as one way to help protect communities and other values at risk.

Using three GCMs and three emission scenarios, our results suggest an increase in fire season length in regions where the fire season is not a full year already. Wotton and Flannigan (1993) found that the fire season length in Canada increased by an average of 22% or 30 days using the Canadian GCM $2 \times CO_2$ scenario. Our results suggest similar numbers by the end of the century rather than mid-century. In a study of wildfire in the western USA, Westerling et al. (2006) found that the fire season length has increased by over 2 months since 1980s. These results suggest a more dramatic change than our results are showing but this could be due to coarse spatial scale in our global study and the influence of snow and mountains in the Westerling study.

The substantial CSR predicted across climate change scenarios by the end of this century are truly noteworthy for wildland fire managers. Increases of up to 300% in cumulative DSR, particularly in the northern circumpolar region, will place unprecedented demands on fire suppression resources. Some of the CSR increase is due to longer fire seasons (about 20–30 days); however the DSR on low and even moderate days (the most frequent days in the fire season) is quite small relative to DSR values on high and extreme days and thus the vast majority of the increase is due to the increase in potential fire intensity and subsequent control difficulty. Fire suppression action most often fails during high intensity crown fires (Stocks et al., 2004), and the climate change scenarios of this study indicate that this type of fire behaviour will occur with greater frequency in the future. Many countries of the world operate highly efficient fire management organisations that have a high fire control success rate. However, climate change may cause a disproportionate increase in uncontrolled fires because it is thought that most modern fire management organisations already operate at near to optimum efficiency; thus any further increase in fire control difficulty will force many more fires beyond a threshold of suppression capability (cf Flannigan et al., 2009b; Podur and Wotton, 2010). Perhaps we are already experiencing what is to come with recent disastrous fires in Australia in 2009, Russia in 2010 and Texas and other states in the USA in 2011. Increased wildland fire on the landscape in the future will force fire management agencies to re-assess policy and strategy. All wildland areas cannot be protected from fire, and many high value areas managed with a policy of fire exclusion will be threatened by wildfire. To protect those key areas, early warning systems based on fire danger will be critical to prevent or mitigate disaster fires (de Groot et al., 2010). The international fire community recognises that greater demands will be placed on fire management as fire season severity increases in the future. Fire early warning systems, one component of A Strategy to Enhance International Cooperation in Fire Management (FAO, 2006), will assist in pre-suppression preparedness and support greater international resource-sharing during periods of extreme fire activity.

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References

Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., Melillo, J., 2009. Assessing the response of area burned to changing climate in western boreal North America using a multivariate adaptive regression splines (MARS) approach. Global Change Biol. 15, 578–600. http://dx.doi.org/10.1111/j.1365-2486.2008.01679.x.

Bond, W.J., Keeley, J.E., 2006. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. Trends Ecol. Evol. 20, 387–394.

Byram, G.M., 1959. Combustion of forest fuels. In: Davis, K.P. (Ed.), Forest Fire: Control and Use. McGraw-Hill, New York, pp. 61–89.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S., Prairie, Y.T., 2001. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? J. Ecol. 89, 930–946.

Cary, G.J., Keane, R.E., Gardner, R.H., Lavorel, S., Flannigan, M.D., Davies, I.D., Li, C., Lenihan, J.M., Rupp, T.S., Mouillot, F., 2006. Comparison of the sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather. Landscape Ecol. 21, 121–137.

Cole, J., 2009. Xconv/Convsh (Version 1.91). Software. <http://badc.nerc.ac.uk/help/software/xconv/>.

Dai, A., 2012. Increasing drought under global warenubg ub observations and models. Nat. Climate Change. http://dx.doi.org/10.1038/NCLIMATE1633.

de Groot W.J., Goldammer, J.G., Justice, C.O., Lynham, T.J., Csiszar, I.A., San-Miguel-Ayanz, J., 2010. Implementing a global early warning system for wildland fire. In: Viegas, D.X. (Ed.), Proceedings of the VI International Conference on Forest Fire Research, ADAI/CEIF, Univ. Coimbra, Portugal (CD ROM).

de Groot, W.J., Cantin, A.S., Flannigan, M.D., Soja, A.J., Gowman, L.M., Newbery, A., this issue. A Comparison of Canadian and Russian Boreal Forest Fire Regimes. For. Ecol. Manage.

FAO, 2006. Fire Management Review: International Cooperation. Fire Management Working Paper 18. Food and Agriculture Organization, United Nations. Rome.

Flannigan, M.D., Harrington, J.B., 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953–80. J. Appl. Meteorol. 27, 441–452.

Flannigan, M.D., Krawchuk, M.A., de Groot, W.J., Wotton, B.M., Gowman, L.M., 2009a. Global wildland fire and climate change. Int. J. Wildland Fire 18, 483–507.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., Stocks, B.J., 2005. Future area burned in Canada. Climatic Change 72, 1–16.

Flannigan, M.D., Stocks, B.J., Turetsky, M.R., Wotton, B.M., 2009b. Impacts of climate change on fire activity and fire management in the circumboreal forest. Global Change Biol. 15, 549–560.

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

Hansen, J., Sato, M., Ruedy, R., 2012. Perception of climate change. In: Proceedings of the National Academy of Sciences. http://dx.doi.org/10.10732/pnas.1205276109.

Hargrove, W.W., Gardner, R.H., Turner, M.G., Romme, W.H., Despain, D.G., 2000. Simulating fire patterns in heterogeneous landscapes. Ecol. Model. 135, 243–263.

Krawchuk, M.A., Moritz, M.A., Parisien, M.-A., Van Dorn, J., Hayhoe, K., 2009. Global pyrogeography: macro-scaled models for understanding the current and future distribution of fire. Public Libr. Sci. (PLOS One) 4. http://dx.doi.org/10.1371/journal.pone.0005102.

Liu, Y., Stanturf, J., Goodrick, S., 2010. Trends in global wildfire potential in a changing climate. Forest Ecol. Manage. 259, 686–697.

Meyn, A., White, P.S., Buhk, C., Jentsch, A., 2007. Environmental drivers of large, infrequent wildfires: the emerging conceptual model. Prog. Phys. Geogr. 31, 287–312.

Mouillot, F., Field, C.B., 2005. Fire history and the global carbon budget: A $1^\circ \times 1^\circ$ fire history reconstruction for the 20th century. Global Change Biol. 11, 398–420.

Parisien, M.-A., Parks, S.A., Krawchuk, M.A., Flannigan, M.D., Bowman, L.M., Moritz, M.A., 2011. Scale-dependent controls on the area burned in the boreal forest of Canada, 1980–2005. Ecol. Appl. 21, 789–805.

Podur, J., Wotton, B.M., 2010. Will climate change overwhelm fire management capacity? Ecol. Model. 221, 1301–1309.

Prasad, V.K., Badarinath, K.V.S., Eaturu, A., 2008. Biophysical and anthropogenic controls of forest fires in the Deccan Plateau. India J. Environ. Manage. 86, 1–13.

Price, C., Rind, D., 1994. Possible implications of global climate change on global lightning distributions and frequencies. J. Geophys. Res. 99 (D5), 10,823–10,831.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. <http://www.R-project.org/>.

Stocks, B.J., Alexander, M.E., Lanoville, R.A., 2004. Overview of the international crown fire modelling experiment (ICFME). Can. J. For. Res. 34, 1543–1547.

Swetnam, T.W., 1993. Fire history and climate change in giant sequoia groves. Science 262, 885–889.

Swetnam, T.W., Betancourt, J.L., 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American southwest. J. Clim. 11, 3128–3147.

van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Kasibhatla, P.S., Arellano Jr., A.F., 2006. Interannual variability in global biomass burning emissions from 1997 to 2004. Atmos. Chem. Phys. 6, 3423–3441.

Van Wagner, C.E., 1970. Conversion of Williams severity rating for use with the fire weather index. Can. Dep. Fish. For., Can. For. Serv., Rep. PS-X-21. Petawawa, ON.

Van Wagner, C.E., 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., For. Tech. Rep. 35, Ottawa, ON.

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

Williams, D.E., 1959. Fire Season Severity Rating. Department of Northern Affairs and National Resources, Forestry Branch, Headquarters. Forest Research Division Technical Note 73. Ottawa, ON.

Wotton, B.M., Flannigan, M.D., 1993. Length of the fire season in a changing climate. Forest. Chron. 69, 187–192.