Wildfire, Weather and Climate Change in the Canadian Prairie Provinces

M. Flannigan and X. Wang

University of Alberta

March 2012

1. Introduction:

Fire activity responds dynamically to the weather/climate, fuels, and people. Recently, our climate has been warming as a result of increases of radiatively active gases (carbon dioxide, methane etc.) in the atmosphere from human activities. Such warming is likely to have a rapid and profound impact on fire activity, as will potential changes in precipitation, atmospheric moisture, wind, and cloudiness. Vegetation patterns, and thus fuels for fire, will change in the future due to both direct effects of climate change and indirectly as a result of changing fire regimes. Humans will continue to be a crucial element of fire activity in the future through fire management, human-caused fire ignitions, and land-use changes. In the future, changes in weather/climate, fuels, and people and the non-linear, complex and sometimes poorly understood interactions among these factors will determine fire activity.

There have been numerous studies suggesting that future fire activity will be influenced by climate change (Flannigan et al. 2009a). Also, studies have suggested that the recent increases in area burned in western Canada are due to human-caused climate change (Gillett et al. 2004). Wotton and Flannigan (1993) have suggested that the fire season length will increase in Canada due to a warming climate. Presently, there are about 8000 wildland fires a year that burn 2 million hectares. Estimates of area burned range from almost no change to increases of 5.5 times for Canada or parts of Canada (Flannigan et al. 2005; Tymstra et al.2007; Balshi et al. 2009) by the end of this century.

Wotton et al. (2010) suggests significant increases in forest fire occurrence in Canada throughout this century. If these estimates of the future reflect what will happen then fire management will be even more challenging in the future (Flannigan et al. 2009b).

For the purposes of this study we will address three topics related to wildland fire and climate change including fire season length, wind speed and atmospheric moisture. Using a temperature based approach for fire season start and end we will determine the fire season length that has been observed and whether there are any trends. Using GCM data we will estimate fire season length in the future. A similar procedure will be carried out for wind speed and atmospheric moisture.

The objectives for this report include:

1. Calculation of historical values of fire season length, wind speed and atmospheric moisture.
2. Determination of trends in historical fire season length, wind speed and atmospheric moisture.
3. Estimates of future fire season length, wind speed and atmospheric moisture and compare these estimates with current observations.

2. Data and Methods

2.1 Data source and data description

Climate data used in this project mainly comes from three sources: NCEP/NCAR Reanalysis I and II dataset (Kalnay et al., 1996); three weather stations with a long period

of record; and the general circulation model (GCM) projections from the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) (IPCC 2000).

The NCEP/NCAR Reanalysis I and II dataset contains historical climate surfaces that are publicly available and is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). These Gaussian Grids are global scale climate datasets downscaled to ~1.875° for Reanalysis II (available for 1979~2010) and ~2.5° for Reanalysis I (available for 1948~2010). In this study, we used the global scale climate variables including daily and monthly mean and maximum temperature (2m), precipitation, wind (uwind and vwind), and specific humidity.

The three long term local weather station data were from three Canadian Prairie Provinces (hereafter Prairie Canada), Alberta, Manitoba, and Saskatchewan. They are Calmar in Alberta, Cypress River in Manitoba, and Muenster in Saskatchewan. These weather stations all have more than 100 years of continuous weather observation records. Due to their limited observation variables (maximum and minimum temperatures), these three weather station data were later used to portray the temperature and fire season length changes in the Prairie Canada.

The general circulation model (GCM) projections were obtained from the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) (IPCC 2000) as part of the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (WCRP CMIP) multi-model dataset [https://esg.llnl.gov:8443/home/publicHomePage.do] (Meehl et al. 2007). Historical

projections were taken from the 20th century simulation, which were generally initiated between 1850 and 1880 and run through 1999 or 2000. Future projections were taken from three emission scenarios (IPCC 2000)—SRESA2 (high), SRESA1B (intermediate), and SRESB1 (low)—run from 2000 or 2001 through at least 2099 or 2100. A total of 3 GCMs were used, including the Canadian Centre for Climate Modelling and Analysis (CGCM3.1), the Hadley Centre for Climate Prediction (HadCM3), and the Institut Pierre Simon Laplace (IPSL cm4). Only monthly climate variables were available for the GCM projections.

2.2 Generating daily and monthly climate variables for 30-year periods

Daily Climate Variables: Because the future daily climate projections were not readily available we had to rely on monthly data for the future and the daily weather streams from the Reanalysis II to generate the future daily climate variables. For different combinations of future time periods, climate change scenarios (A1B, A2, and B1), and GCMs (CGCM3.1, HadCM3, and IPSL), we used the historical daily mean weather streams (1979~2010 for Reanalysis II, and 1948~2010 for Reanalysis I) as the base, and superimposed the monthly anomalies of each GCM (see below) on the daily climate bases to generate the future daily weather streams. Due to the resolution discrepancy between the projected monthly climates and daily historical measurements, this process has to take a few steps as described below.

To generate monthly anomalies, we first calculated the monthly mean temperature, precipitation, wind speed (uwind and vwind), and humidity (specific humidity or relative humidity) for the following thirty year periods: 1970-1999 (back-projections of each GCM), 2001-2030 (2020s), 2031-2060 (2050s), and 2061-2090 (2080s). We converted temperature values from Kelvin to Celsius and precipitation values from precipitation rate (prate) to millimeters. We then subtracted the back-projections from each of the future projection periods to generate the monthly climate variable anomalies surfaces. These anomalies surfaces were then clipped to North America (USA and Canada) and downscaled to both Reanalysis II and I resolution using a thin-plate spline interpolation (Green and Silverman 1994.). "The smoothing parameter is chosen by generalized cross-validation (standard GCV). The assumed model is additive $Y = f(X) + e$ where $f(X)$ is a d dimensional surface." {Cited from the help file in R} Reanalysis I resolution downscaled data was only used for relative humidity which is only available for Reanalysis I. Finally, the Reanalysis II (or I for relative humidity) resolution downscaled anomalies were superimposed onto the daily Reanalysis II (or I) -resolution variables averaged between 1979 ~ 2010 (hereafter 7910s) for North America. Maximum temperature was generated by imposing the mean temperature anomalies on daily maximum temperatures in 7910s. The results were daily future climate surfaces for North America.

Monthly Climate Variables: Instead of direct downscaling the GCM monthly climate variables to Reanalysis II resolution surfaces, we decided to calculate the future monthly climates based on the future daily climate surfaces that were generated in the previous step. We averaged the daily values within each month for temperature, wind, and humidity, and summed up the daily values within the month for precipitation.

We generated two monthly humidity variables, the specific humidity (*shum*), and the relative humidity (*rhum*) when *shum* is not available. Specific humidity variables were converted to relative humidity values in the summary. We also generated precipitation, wind, mean and maximum temperature to reflect fire condition changes in the future under different climate change scenarios. All climate variables were generated as monthly surfaces at Reanalysis II spatial resolution except for relative humidity (rhum), which was in Reanalysis I resolution.

2.3 Calculating fire season length and wind speed

Fire Season Length: Following Wotton and Flannigan (1993), we define that fire season starts when daily maximum temperature (tmax) is greater than 12°C for three consecutive days, and the fire season ends when three consecutive daily maximum temperatures are less than 5°C. Based on the daily maximum temperature variable, we calculated the fire season length by counting the number of days between fire season start and end dates for each spatial location (cell) under all combinations of time periods (7910s (Reanalysis II), 2020s, 2050s, and 2080s), climate change scenarios (A1B, A2, and B1), and global climate change models (CGCM3.1, HadCM3, and IPSL). We also calculated the fire season length values for the three weather stations; these values cover all the past years where daily maximum temperature data are available.

Wind Speed: Wind speed data includes two variables, vwind and uwind, representing the latitudinal and longitudinal wind speeds respectively. We used a simple formula to calculate the overall wind speed and wind directions.

$$wdrt = \arctan(uwind / vwind)$$

$$wsp = uwind / \sin(wdrt)$$

where *wdrt*=wind direction, *wsp*=wind speed.

Both monthly and daily mean values of these three variables were generated as spatial surfaces for various time periods (7910s (Reanalysis II), 2020s, 2050s, and 2080s) under various climate change scenarios (A1B, A2, and B1) and GCMs (CGCM3.1, HadCM3, and IPSL).

2.4 Data summary

2.4.1   Mapping the changes of fire season length and fire weather variables

In order to showcase the changes of the fire season length and fire weather variables, we generated the map of changes between the 7910s and the future projections in 2020s, 2050s, and 2080s. These changes were calculated by subtracting the 7910s values from each of the future projections for all variables in the study. In order to show the fire weather variable variations at a finer scale, changes of all fire weather variables were calculated and mapped by month from April to September, which covers most of the fire season length in Canada. Fire season length, on the other hand, was calculated by year.

With these maps, we want to demonstrate the spatial distribution of both fire season length and fire weather variable changes.

2.4.2   Fire season length and fire weather changes

We summarized the fire season length and fire weather variable changes over the continent, Prairie Canada, the boreal portion of prairie Canada (i.e. boreal prairie Canada), and the individual Prairie Provinces of Canada, respectively. Based on the Reanalysis II resolution results, we calculated the mean and standard deviation of fire season length changes (anomalies) for all the future projections relative to the 7910s time period. We also calculated the proportional cells with increased wind speed (positive anomalies), and proportional cells with decreased relative humidity (negative anomalies) over the continental and provincial (Alberta) scales. These summaries provide the extents of changes over certain focal areas (e.g. continental or provincial). We expect that the scale effects would be reflected in these summaries.

2.4.3   Three point data visualization

Although the significant spatial pattern shifts of fire season length and fire weather variables can be illustrated with the mapping approaches, visualizing changes at a single location would provide a very different perspective on both the scale and variation of these changes. We chose three center points at similar latitude for the three Canadian Prairie Provinces (Alberta, Saskatchewan, and Manitoba) (Figure 1) to illustrate the

changes of fire season length and fire weather variables. We expect these three locations would show some general trends of the focal variable changes. The coordinates for these three points are: AB (-112.50, 56.19), SK (105.00, 56.19), and MB (-97.50, 56.19).

We plotted the mean fire season length and fire weather variables including temperature, precipitation, wind, and moisture variables over the following four time periods: 7910s, 2020s, 2050s, and 2080s. We plotted fire season length and fire weather variables changes by using the mean monthly data. We plotted the fire weather variations within fire seasons using a boxplot method based on the mean daily fire weather measurements and fire season length data at each time period. In order to test whether the fire weather variables change significantly, we fitted the simple linear regression model taking the four time periods as predict variable, and the within fire season fire weather variables as response variables. We consider significant linear regression model ($\alpha = 0.05$) as an indicator of significant change of the fire weather variables over time.

2.4.4   Fire season length and temperature changes based on the local weather stations

We scatter plotted the fire season length changes over the years with a fitted linear regression line for each weather station. We evaluate whether fire season length has a significant change over time by evaluating whether the linear regression model has a significant p-value ($\alpha = 0.05$). For the temperature, we calculated the seasonal mean temperature and mean maximum temperature for months between March and September, and for three seasons: spring (April and May), summer (June, July, and August), and fall

(September). We then scatter plot both the monthly and seasonal temperature values throughout the observation years to illustrate temporal temperature changes. We fitted the simple linear regression lines to these plots, and evaluate whether the temperatures have significant changes by the p-values ($\alpha = 0.05$) as well.

2.4.5   Consensus

In order to fully illustrate the model variations and robustness of the future fire weather change direction and strength, we used a consensus approach to summarize the changes of the future fire season length and weather climate variables. Within each climate change scenario (A1B, A2, B1), if all three GCM predictions are in the same direction (all positive or all negative anomalies) for the same location (cell), the mean value of the focal variable was calculated and assigned to the cell; otherwise, an 0 will be assigned. The results shown as grid maps will show the extent of changes as well as the spatial distribution of discrepancy among GCM projections (i.e. 0 values). Because only three GCMs were considered, it is not necessary to count how many GCMs agree or disagree for uncertain cell change directions. These consensus results were mapped for the whole study area and plotted for the three points we chose to represent the three Prairie Provinces in Canada.

All climate data manipulations and part of the mappings were performed using the program R, version 2.13.0 (R Development Core Team, 2010).

3. Results

3.1 Future fire season length changes

With the global climate getting warmer in the future, the fire season lengths increase in the major continental area, but stay stable or change very little in the North Pole area (e.g. Figure 2). The extents of fire season length changes are higher in the southwestern than in the northeastern continent. This trend was shown in all consensus results. Fire season length increase also varies among different future climate change projections, at a range between 12 ~ 28 days in average (Table 1). For example, fire season length in average can be extended for 13 ~ 22 more days during 2020s and 2080s under A1B climate change scenario predicted by CGCM3.1 model. Under a more pronounced climate change scenario, A2, these extended numbers would vary between 15 ~ 25 days predicted by the same model (Table 1). There are small areas that the fire season lengths decrease with the increase of climate warming. These pixels are mostly found in areas close to the oceans which could be the result of downscaling effect.

These summaries are also scale dependent that if we consider only the Prairie Canada, the fire season length change in average would be 18~25 days increase under A1B for CGCM3.1 projections, and 19~28 days more under scenario A2 with the same GCM projections (Table 2). Considering only the boreal prairie Canada, the fire season length would increase at a similar rate as that in the Prairie Canada (Table 3).

For the three point visualizations, we found the same fire season length increase patterns. For example, fire season lengths in the three locations may prolong for 20 ~ 30 days by 2080 under A2_IPSL model. The same trend could be found for all GCMs and under all three climate change scenarios considered in this study.

As expected, both mean and maximum monthly temperature increases in the future under all model projections. We found that the temperature increase most in the arctic area and the areas close to the equator. The temperatures at middle latitude areas change the least. This pattern of changes are consistent in all fire season months (April ~ September) and model projections. The temperature increase can also be found in the three central points of the Prairie Canada in Canada with the monthly measurements. But for the within fire season variations, both temperature measurements, the daily mean and maximum temperatures, show significant increase over the time periods considered in two of the central points, Saskatchewan and Manitoba (p ≤ 0.05), but not in Alberta.

3.2 Future wind speed changes

Wind speed changes (increase and decrease) with a high spatial variation at different time periods. For example, Figure 3 shows the spatial pattern of wind speed changes in May. All three models agreed that the averaged wind speeds increase only in the southern central areas, but the locations of this increase are not fixed during the three time periods. There is no clear spatial pattern of changes that can be found in other months either. Based on our results, to most of the study area (e.g. more than 70%), especially the

central middle to the south of the continent, the three GCM predictions of wind speed changes do not agree with each other in the changing directions (i.e. increase and decrease) (Figure 3).

For the monthly mean wind speeds at the three Canadian prairie provincial center locations, we found that the changes vary month by month and location by location among all model projections. For example, in Manitoba and Saskatchewan, wind speeds tend to increase in the spring months, drop in the summer, and increase again in the fall, but the trends are not consistent.

Less than 50% of the continent would experience wind speed increase in all fire season months under any future climate change projections (Table 4). In prairie Canada and in the boreal prairie Canada, the changes vary much more (Table 5 & 6). There are cases that the whole area experiences wind speed increase (100% of the area), and other cases show that the whole area would have wind speed decrease. Averaged over the three climatic projection models, the proportional area of wind increases are much higher in the prairie Canada (>55% of the projected monthly wind speeds would increase in > 50% of the area (Table 5)) and the boreal prairie Canada (>73% of the projected monthly wind speed would increase in > 50% of the area (Table 6)) than that summarized over the continent. Temporally, proportional wind speed increase area increases with the time periods, i.e. more land area in the continent would experience wind speed increase in the 2080s than in the 2020s and 2050s (Table 4, 5 & 6).

Even though wind speed change over time doesn't show significant trends in the three central points of the three Canadian Prairie Provinces, we found the wind speed

variations within the fire seasons increase significantly between 7910s and 2080s at all three locations (e.g. Figure 4). Typically, we found that the higher wind speeds appear more often in the future projections. These wind speed change patterns can be found among all three wind speed measurements (vwind, uwind, and wind speed) and in all model predictions considered in this study.

3.3 Projected moisture and precipitation changes

Relative humidity is increasing over the majority of the continent in the spring (April and May in Table 7); this also applies to the three Prairie Provinces in Canada (e.g. May in Figure 5 A~C) under the changing climate. However, for the rest fire season, more than 50% (up to >90% in July and August) of the study area is getting drier (Table 7), especially in the southeastern United States (Figure 5 D~F). The northern parts of the continent, especially the coastal area around Hudson Bay in Canada, is getting a little bit moister (< 2%) in September; but the rest is getting as much as 5% drier. This overall continent is getting drier pattern is seen in most of the projections (Table 7). These seasonal changing patterns are also reflected in the three central points of the prairie Canada by months (results not shown).

Summarized by Prairie Canada and boreal Prairie Canada, we found a similar pattern of moisture changes (Table 8 & 9) as that of the continental summaries; although the spring and fall are moister than averaged based on the continent (Table 7). Between prairie Canada and boreal prairie Canada, we found that summarized over the boreal

forests, the spring is on average moister, but summer and fall are drier (Table 8 & 9). The differences are more significant in 2020s, where the majority (>50%) of the boreal prairie Canada would experience drier summer and fall; while for the prairie Canada, only about half of the cases the majority of the area would experience drier summers and falls.

Within the fire seasons, relative humidity doesn't show significant decrease over time at the three central points based on the linear regression models; however, we found that at the central points of AB and MB, the variation of the relative humidity becomes bigger under the changing climates in the future projections (Figure 6). There are lower relative humidity values in the future projections in comparison to that of the 7910s, which may indicate more frequent extreme dry days. For the central point of SK, the moisture values are quite consistent among the four time periods under consideration.

Monthly mean precipitations showed slightly decrease over time for the whole continent measured by the anomalies between the projected precipitations and that of the 7910s (results not shown). But the within fire season precipitation doesn't show significant changes over time.

Prairie Canada

3.4 Fire season length and temperature changes

Based on the fitted linear regression models, we find no significant changes in fire season lengths in all three long-term weather stations for the last about 100 years. For the temperature variables, we found significant mean temperature increases in the spring and

summer for all three weather stations (e.g. Figures 7-9). Figure 10 shows the fire season

length changes over time for the three long term stations. There is no statistically

significant trend though the Alberta station and the Manitoba station do suggest and

increase in fire season length over time. Figures 11 and 12 show more recent

observations using the Reanalysis I data for mean relative humidity and wind speed by

season for the Prairie Provinces. There are significant trends in all the seasons for the

relative humidity; relative humidity has been decreasing since 1948 especially in the

spring (Figure 11). Wind speed shows no significant trend except a significant trend in

spring showing decreasing wind speed (Figure 12).

4. Discussion

4.1 Fire season lengths

The definitions of fire season start and end may have major influences on fire season

lengths. The criteria used in this study are widely applied in Canada (e.g. Wotton and

Flannigan 1993). Choosing more conservative criteria (i.e. lower threshold maximum

temperatures) may result in different results, but shouldn't have changed the overall

pattern of fire season length changes. Because the increase of fire season length may raise

the risk of forest fire in the spring and fall, it is one of the key elements in understanding

the influence of climate change on forest fires. Estimating the increments of fire season

length in the future provides us an additional quantitative perspective on how much more

efforts needed to be taken if the same forest fire management strategy is to be performed.

With the projected global climate changes, fire season length increases more in locations closer to the equator and along the coastal areas as shown in Figure 2. This pattern of increase may mainly due to the originally higher spring / fall maximum temperatures in the south and coastal areas that, with a slightly increase of temperature change, the originally non-fire-prone days in the spring and fall would become fire risky days.

Fire season length would stay stable under two conditions: in the arctic areas where the maximum temperatures never pass the criteria we used in this study, and areas that fire season length have already been year round (365 days or 366 days in a leap year). Global climate change may turn more areas into year-round fire risk areas, which might be a major threat in southern USA.

4.2 Fire weather changes

Wind speed changes do not have a clear pattern in terms of their spatial distributions and magnitudes at different time periods in the future. Our results showed that only relatively small portion of the continent (< 40%) will see increased wind speeds (Table 4). This is consistent with other published work (e.g., Greene et al. 2010) and additional work on trends in observed wind speed data over the USA depended on what data set was used (Pryor et al. 2009). The most significant aspect of the wind is that we may see more extreme wind speed values in the future (e.g. Figure 4). Increases in the extreme wind speed values during the fire season may have some important implications for forest fires.

In addition to the increased temperature (both mean and maximum temperature), the greater wind speed would increase the risk of larger and fast-growing forest fires.

Based on our results, we found that the air moisture content as determined by relative humidity decreases in the south but increases in the north, especially the Prairie Provinces of Canada, in the spring (Figure 5 and Table 7). However, this increase of moisture may not alter the overall moisture change pattern that the whole continent is getting drier, especially in the central part (Figure 5) and in the summer and fall (Table 7). In addition, future drier summers and falls in the boreal prairie Canada (e.g. Table 8 and 9) are more significant and will pose a greater threat of forest fires to the area. Because relative humidity depends on both air temperature and precipitation, even with an increase of temperature in the north in the spring, because of the increment of spring precipitation, we may still see the increases in the relative humidities. In the summer and fall, the temperature increases while the precipitation remains unchanged meaning the whole continent would be getting drier.

4.3 Scale effect

The summary statistics based on the continent (USA and Canada) were supposed to be quite different compared to that based on Prairie Canada and other smaller units; however, we found that the fire season length and fire weather variable changing trends in the smaller scales are very well reflected in the continental summaries. There are certainly some differences reflecting the scale effects, especially the extent of variations

in all variables considered. For example, we found even though the fire season length

changes over the continent (Table 1) are similar in patterns to that over prairie Canada

and boreal prairie Canada (Table 2 and 3), the variations of the measurements over the

continent is much larger than that summarized over the smaller units. This type of

differences can also be found in the other variables, e.g. wind speed and relative humidity

anomalies.

We found the summary statistics of the fire season length and some fire weather

variables over Prairie Canada and over the boreal Prairie Canada are either insignificant

(Table 2~3), or failed to show a clear pattern (e.g. Table 5 and 6). Choosing boreal Prairie

Canada as a summary unit was to address the difference between forest cover land and

the prairie that is more than 50% of the prairie Canada area, the clear pattern shown in

relative humidity changes (Table 5 and 6) confirmed this concern. Therefore, in order to

have more accurate estimate of the changes of any fire weather variables, summarize

them over a smaller and relatively uniform unit would be necessary. We believe that

using ecozone (boreal plains, boreal shield, etc.) as the summary unit would reflect better

the fire weather changes, and would be more meaningful to understand the fire weather

change patterns.

4.4 Fire season length changes at the weather stations

Fire season length hasn't shown a significant increase over the last ~100 years at the

three long-term weather stations. This is out of expectation since global climate warming

has been reported as being significant over the last two decades in North America. One possible explanation is based on the definition of fire season start and end used in this study, daily maximum temperature is the determinant of fire season length of a specific year. As we have shown that even though the mean temperature has significant increase over the spring and summer at these weather stations, the maximum temperature, on the other hand, doesn't show significant changes. With the future climate warming, the balance may most likely be tipped, and the fire season length would start to change as what has been projected for other areas (e.g. Figure 2).

5 Summary

At first glance there does not appear to be any significant trends in fire season length in the Canadian Prairie Provinces. There are significant warming trends in average temperature throughout the fire season and there are indications for some locations for an increase in fire season length (Figure 10). Other researchers using different approaches have found a significant increase in the fire season length using ignitions as the variable rather than a temperature based measure to define the fire season (D. Woolford, personal communication). There is a significant trend in relative humidity for all three seasons in the Prairie Provinces showing decreasing relative humidities especially in the spring. This is particularly concerning since Alberta has a pronounced spring fire season. All three GCMs for all three emission scenarios suggest increases in fire season length, decreases in relative humidity in summer and autumn. Of particular note is the indication of increasing extreme wind events and if these events occur at the same time as a fire it

could cause serious problems for fire management activities in the future. Despite the lack of a trend in some of the variables investigated we have already seen increases in area burned that have been attributed to changes in the weather among other factors (Podur et al. 2002: Gillett et al 2004) despite increases in fire management effectiveness and area of coverage during the last 30-40 years. One possible avenue for future work is to investigate changes in the extremes as most of the area burned is a result of a relatively small number of fires (Stocks et al. 2002) that occur over a few days of extreme fire weather (Amiro et al. 2001). If the GCMs are anywhere close to estimating the future fire weather we should see longer fire seasons, with lower relative humidity and increasing extreme wind speed values. These factors would all contribute to increasing the challenges for fire management agencies in the future.

References:

Amiro, B.D., Todd, J.B., Wotton, B.M., Logan, K.A., Flannigan, M.D., Stocks, B.J.,Mason, J.A.,Skinner, W.R., Martell, D.L. and Hirsch, K.G. 2001. Direct carbon emissions from Canadian forest fires, 1959 to 1999. Canadian Journal of Forest Research. 31:512-525.

Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J. 2009. Modeling historical and future area burned of western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biology. 15: 578-600. DOI: 10.1111/j.1365-2486.2008.01679.x.

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

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

Flannigan, M.D., Stocks, B.J., Turetsky, M.R. and Wotton, B.M. 2009b. Impact of climate change on fire activity and fire management in the circumboreal forest. Global Change Biology. 15:549-560. DOI: 10.1111/j.1365-2486.2008.01660.x.

Gillett, N.P., Weaver, A.J., Zwiers, F.W. and Flannigan, M.D. 2004. Detecting the effect of climate change on Canadian forest fires. Geophysical Research Letters. 31(18), L18211, doi:10.1029/2004GL020876.

Green, P.J. and B.W. Silverman. 1994. Nonparametric regression and generalized linear models: a roughness penalty approach. Volume 58 of Monographs on statistics and applied probability. Chapman & Hall. London.

Greene, J.S., M. Morrissey, M. and S. E. Johnson. 2010.Wind Climatology, Climate Change, and Wind Energy. Geography Compass, 4:1592-1605. doi:10.1111/j.1749-8198.2010.00396.x

IPCC. 2000. Special Report on Emissions Scenarios. Summary for Policymakers. A Special Report of IPCC Working Group III.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-Year Reanalysis Project., Bull. Amer. Meteor. Soc., 77, No. 3, 437-470.

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. B. Mitchell, 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bull. Amer. Meteor. Soc., 88, 1383–1394.

Podur, J., Martell, D. L., and K. Knight. 2002. Statistical quality control analysis of forest fire activity in Canada". Canadian Journal of Forest Research 32:195-205.

Pryor SC, Barthelmie RJ, Young DT, Takle ES, Arritt RW, Flory D, Gutowski WJ, Nunes A, Roads J (2009) Wind speed trends over the contiguous United States. J Geophys Res 114:D14105. doi:10.1029/2008jd011416

R Development Core Team. 2010. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L. and Skinner, W.R.

2002. Large forest fires in Canada, 1959-1997. Journal of Geophysical Research. 107, 8149, doi:10.1029/2001JD000484.

Tymstra, C., Flannigan, M., Armitage, B. and Logan, K. 2007. Impact of climate change on area burned in Alberta's boreal forest. International Journal of Wildland Fire. 16:153-160.

Wotton, B. M. and M.D. Flannigan. 1993. Length of the fire season in a changing climate. The Forestry Chronicle. 69 (2): 187~192.

Wotton, B.M., Nock, C.A. and Flannigan, M.D. 2010. Forest fire occurrence and climate change in Canada. International Journal of Wildland Fire. 19:253-271.
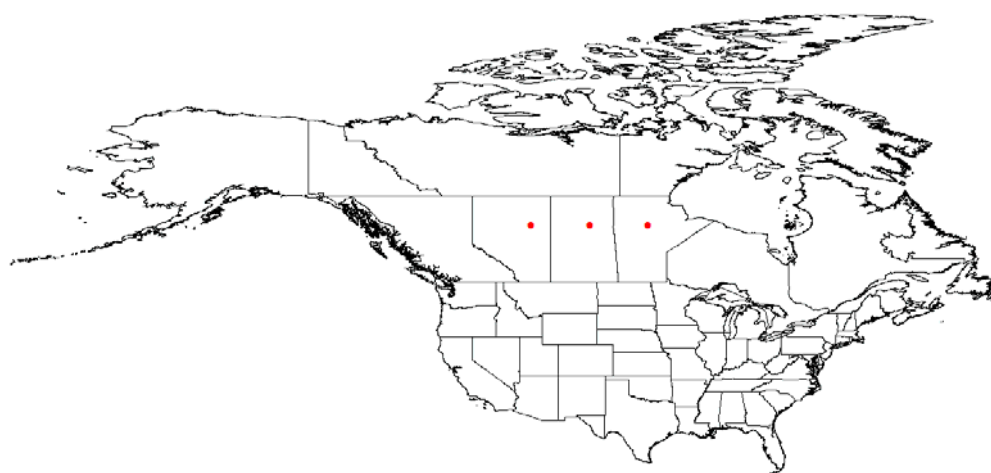
Figure 1. Locations of the three points representing Alberta, Saskachwan, and Manitoba for climate changes.
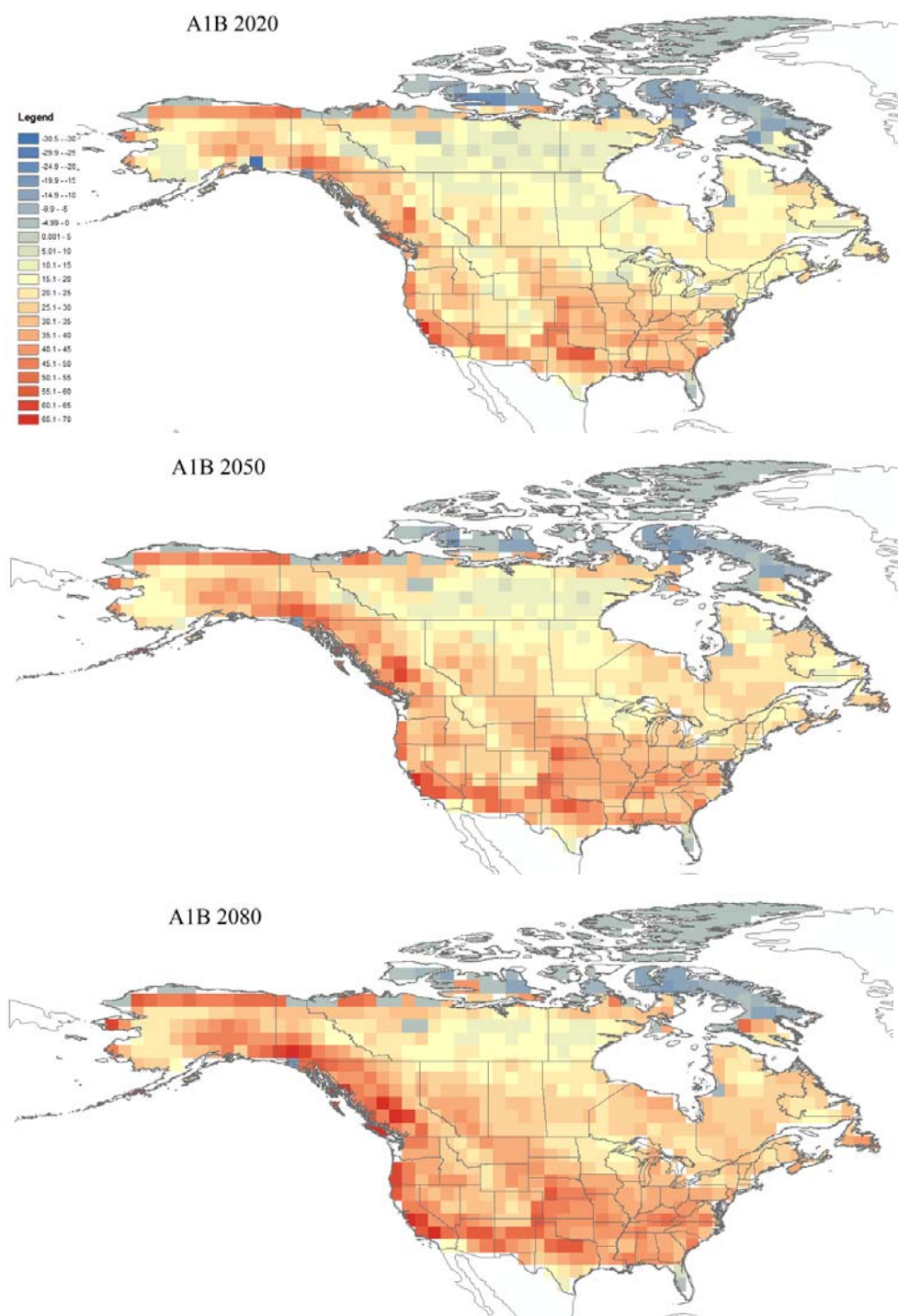
Figure 2. Fire season length variations in days compared with the baseline (7910s).
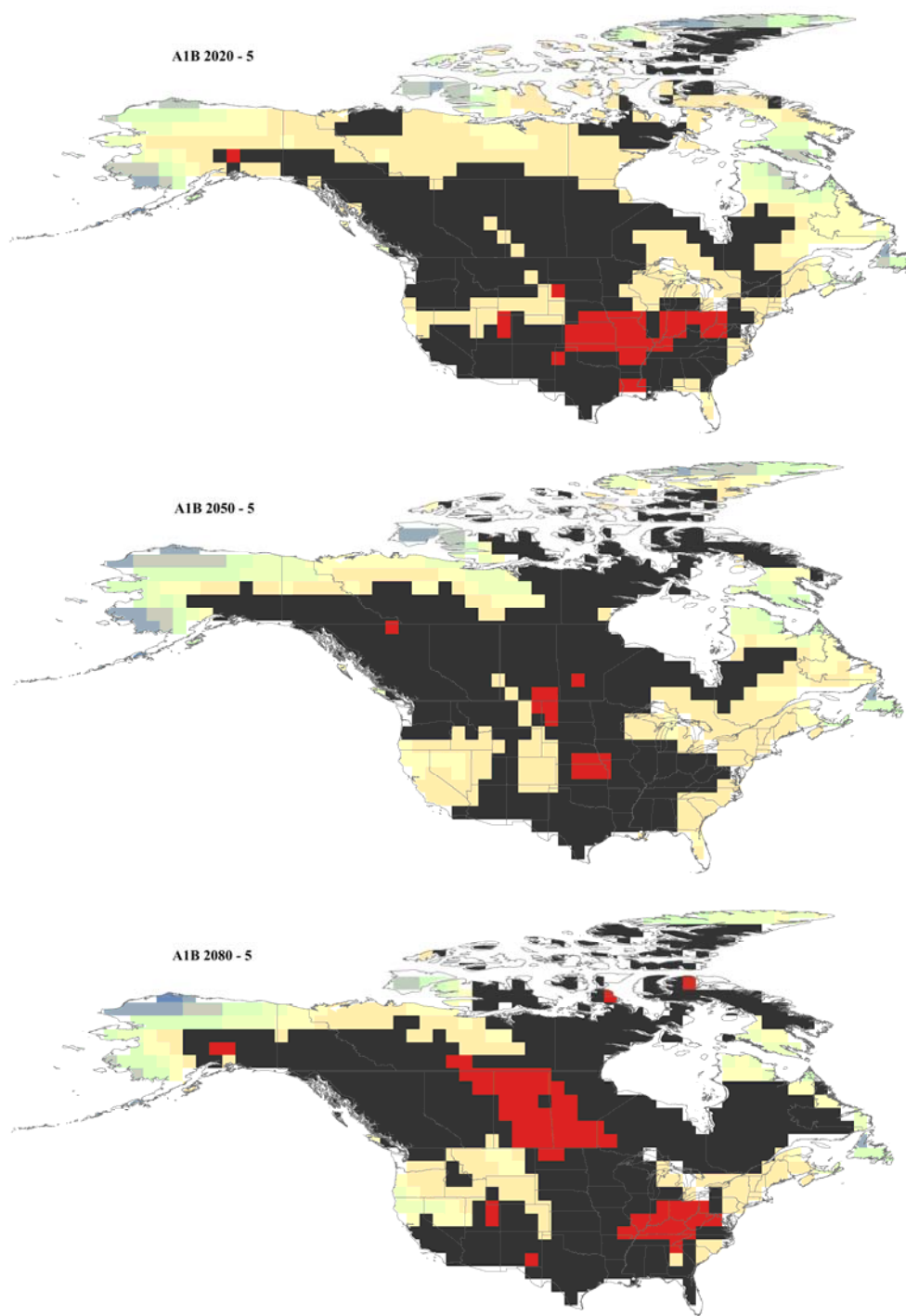
Figure 3. Wind speed changes in May for A1B. Color from blue to light green, and light brown indicate negative changes, and color in red represents positive changes. Black indicates 0 that the three GCMs do not agree with the wind speed change directions.
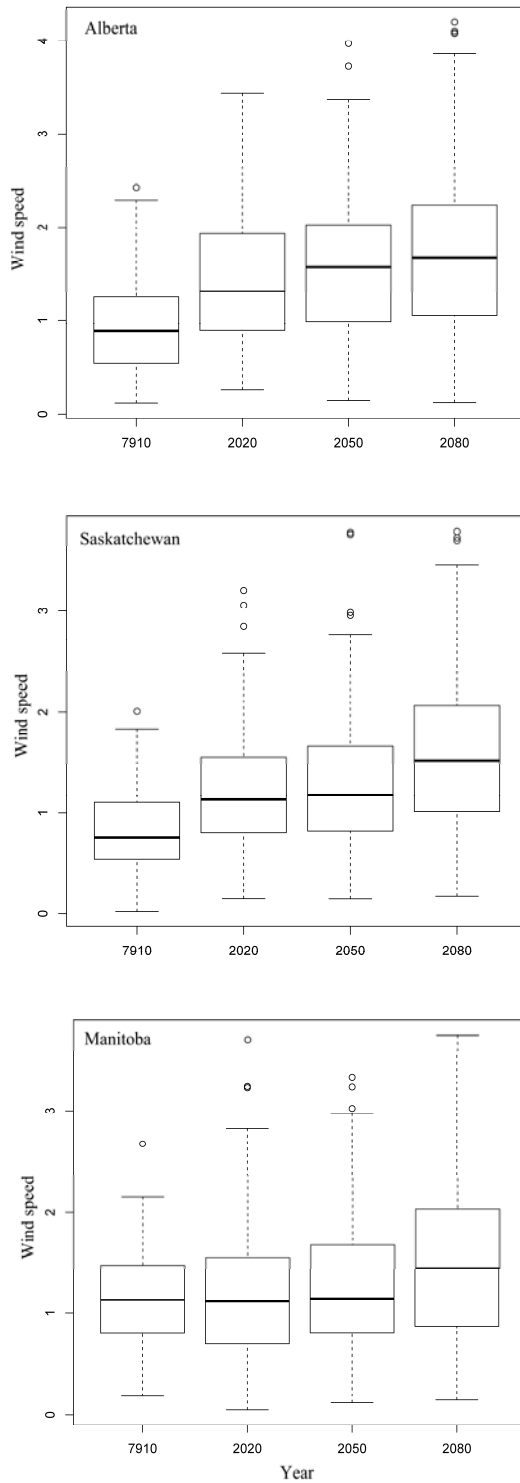
Figure 4. Fire season wind speed variations projected by CGCM3.1 and under A1B climate change scenario in the three Canadian prarire provincial central points, Alberta (AB), Saskatchewan (SK), and Manitoba (MB).

(A)

(D)

(B)

(E)

(C)

(F)
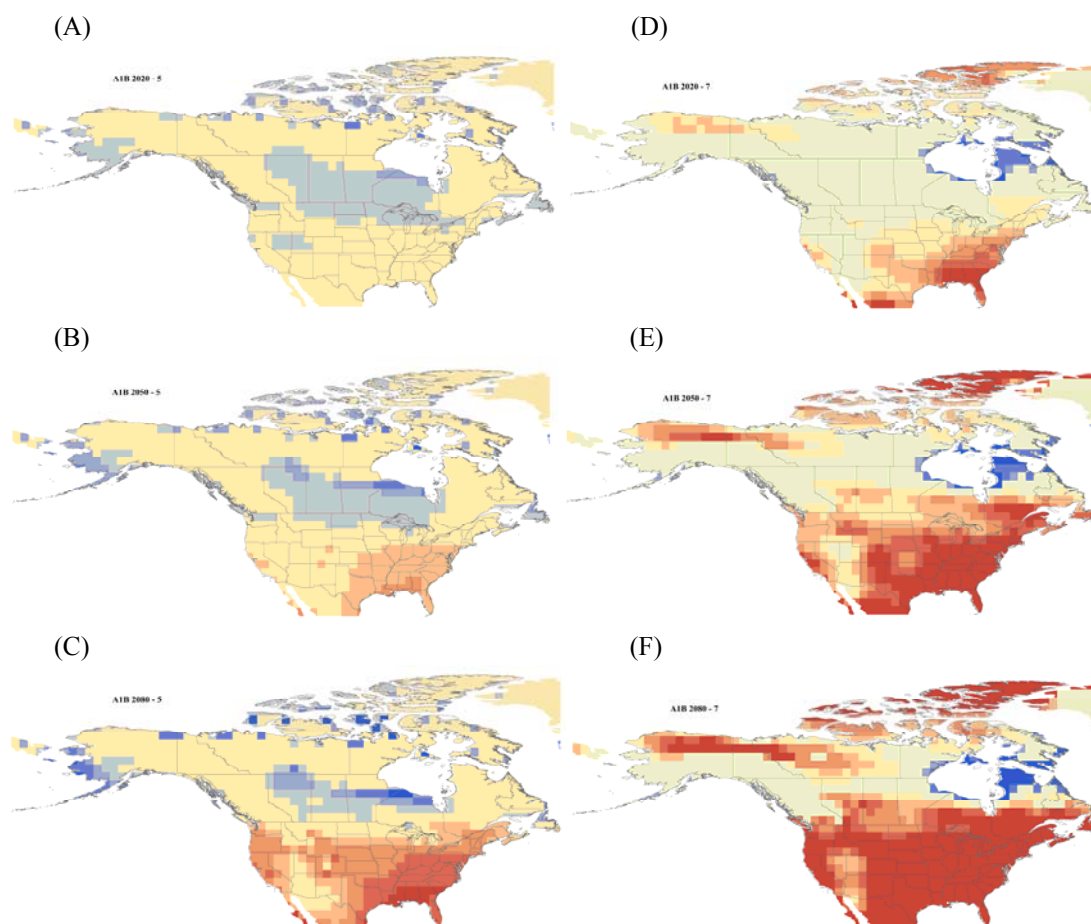
Figure 5. Relative humidity changes of May and July in the future averaged among the three GCMs under A1B climate change scenario. Blue color indicates increases relative humidities and yellowish and red colors indicates decreases in relative humidity. The values range between -10% ~ 11%.
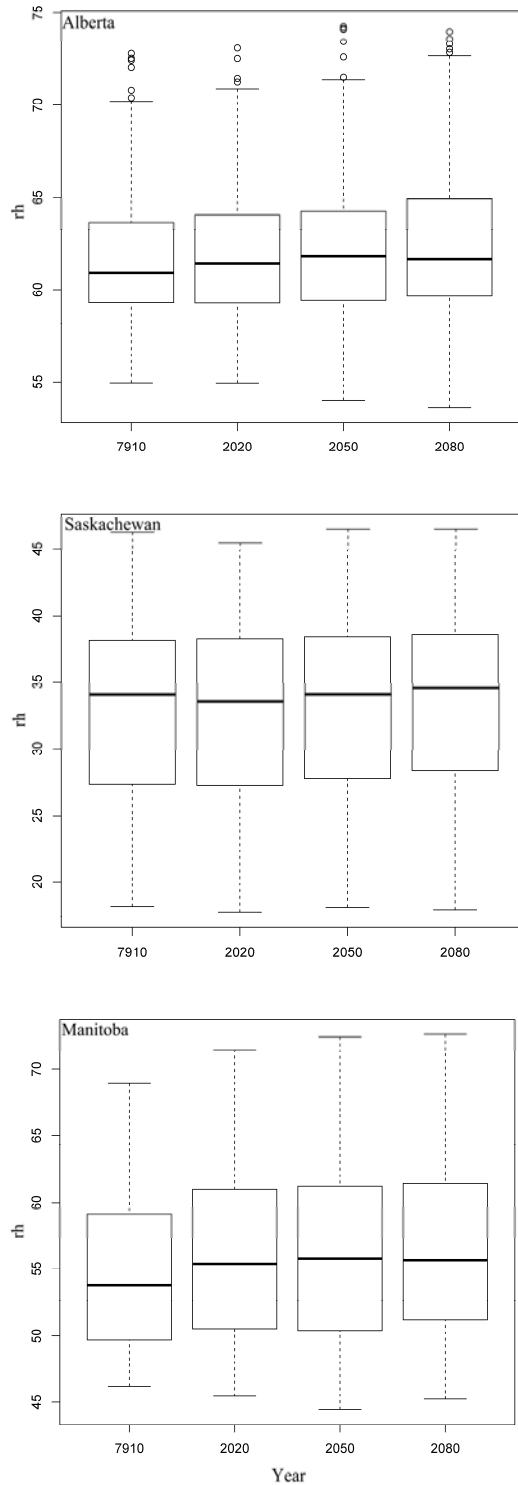
Figure 6. Relative humidtiy variations during fire seasons projected by A1B – Hadley model for three central points in Alberta, Saskatchewan, and Manitoba.
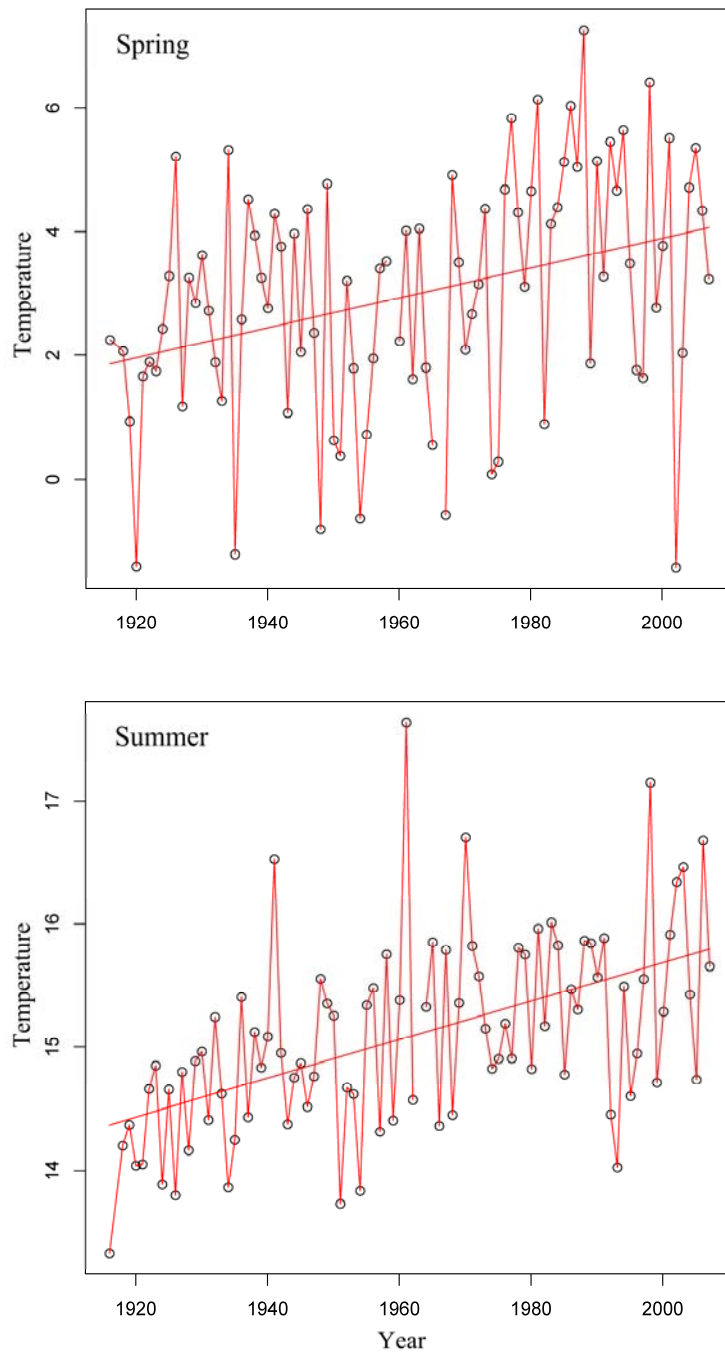
Figure 7. Spring and summer seasonal mean temperature (°C) changes in the last ~100 years in Calmar, Alberta. Temperatures in both seasons increase significantly based on the linear regression model estimates.
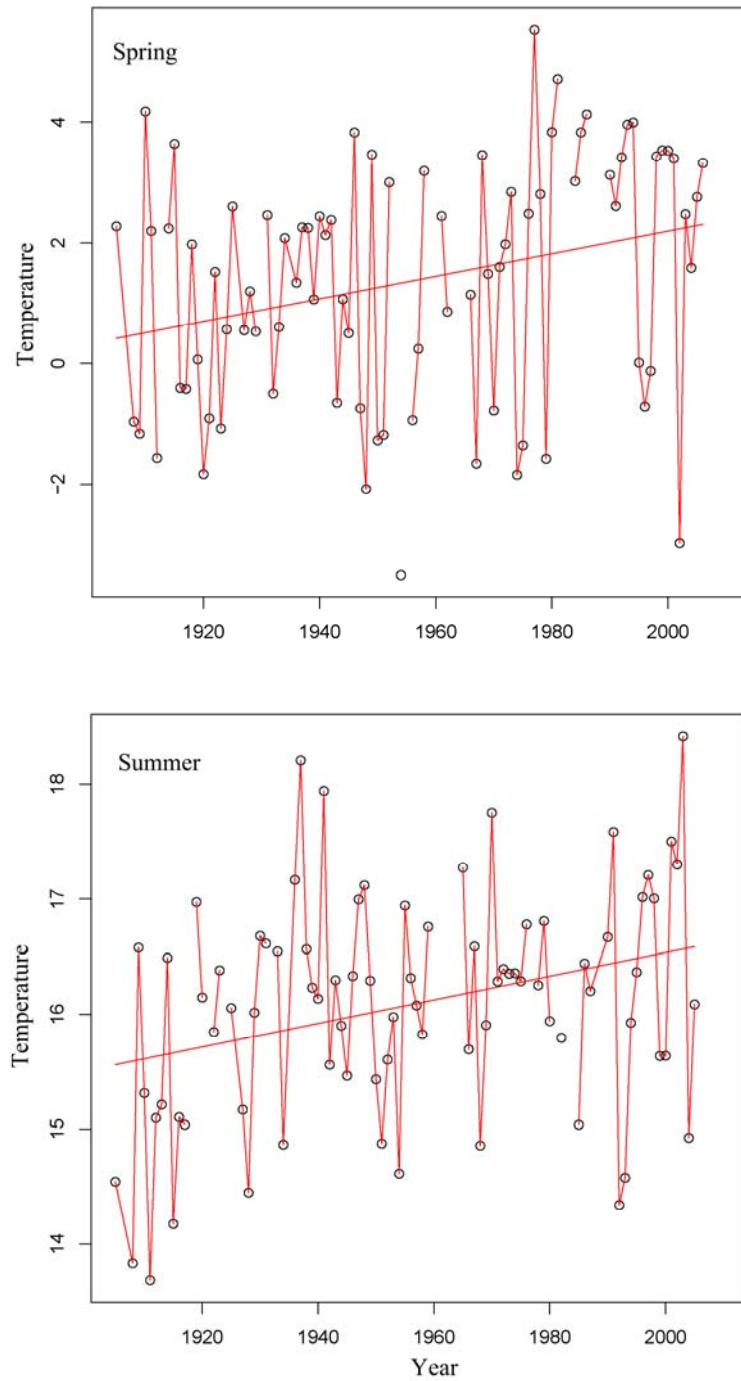
Figure 8. Spring and summer seasonal mean temperature changes (°C) in the last ~100 years in Muenster, Saskachewan. Temperatures in both seasons increase significantly based on the linear regression model estimates.
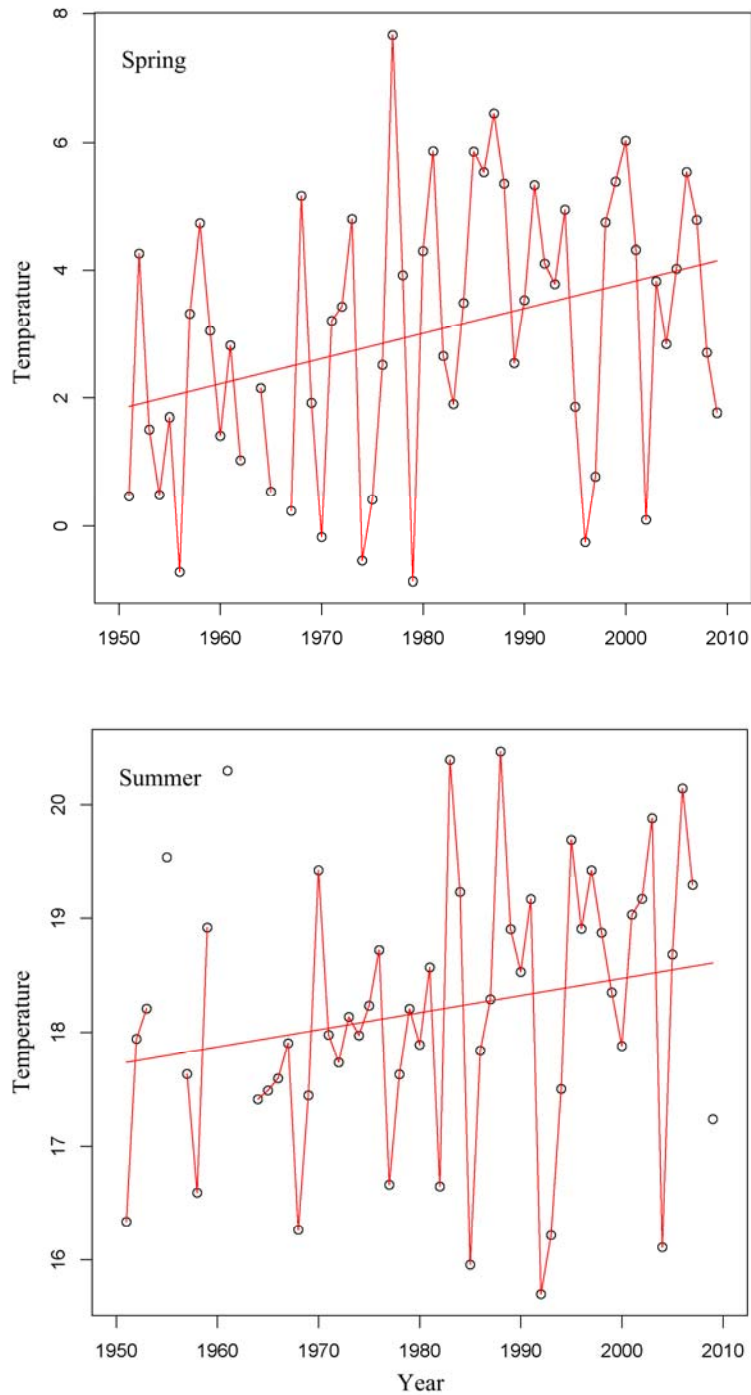
Figure 9. Spring and summer seasonal mean temperature changes (°C) in the last ~60 years in Cypress River, Manitoba. Temperatures in both seasons increase significantly based on the linear regression model estimates.
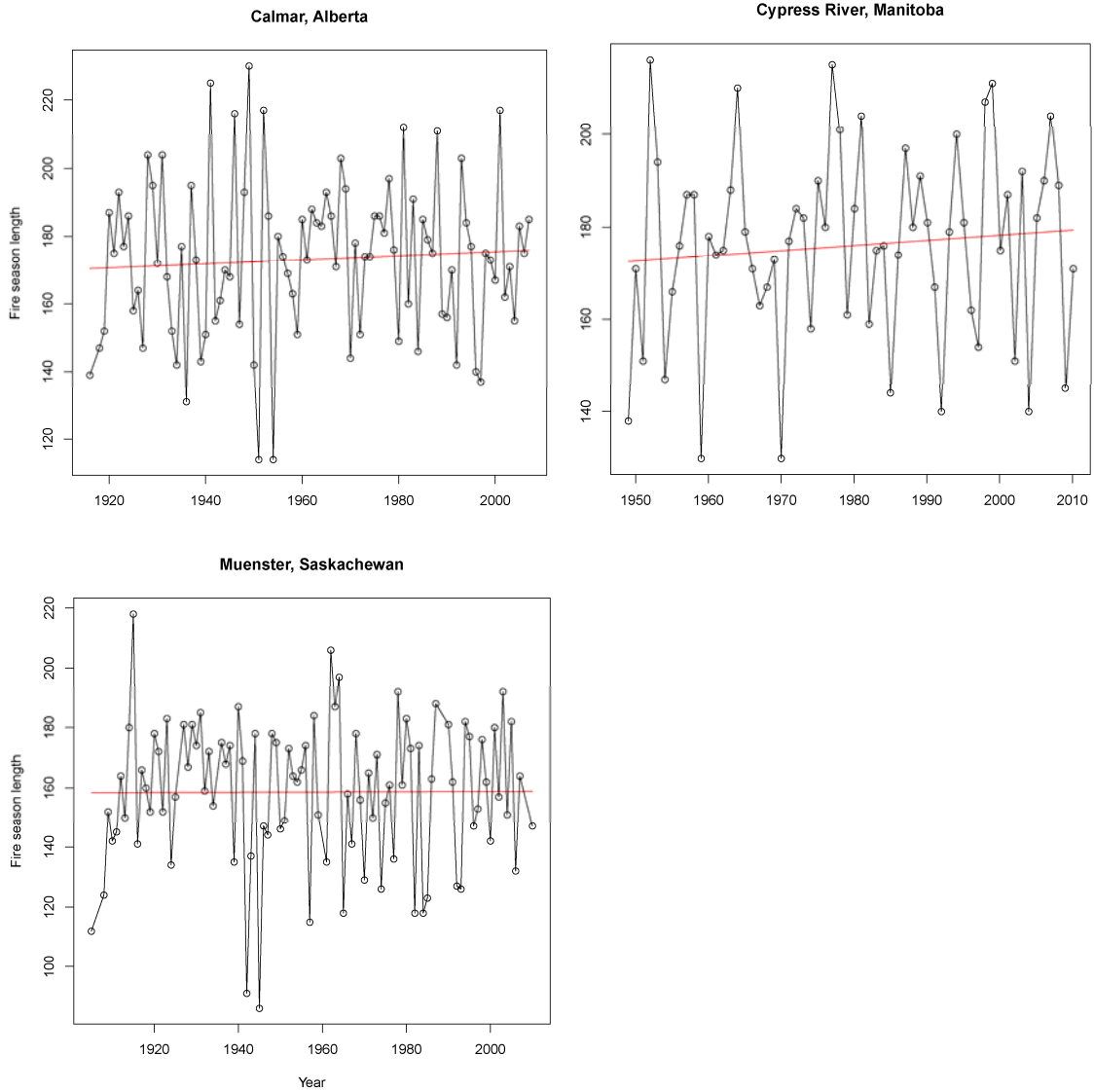
Figure 10. Recent fire season length changes at three long term weather stations of the prairie provinces, Calmar in Alberta, Cypress River in Manitoba, and Muencher in Saskachewan.
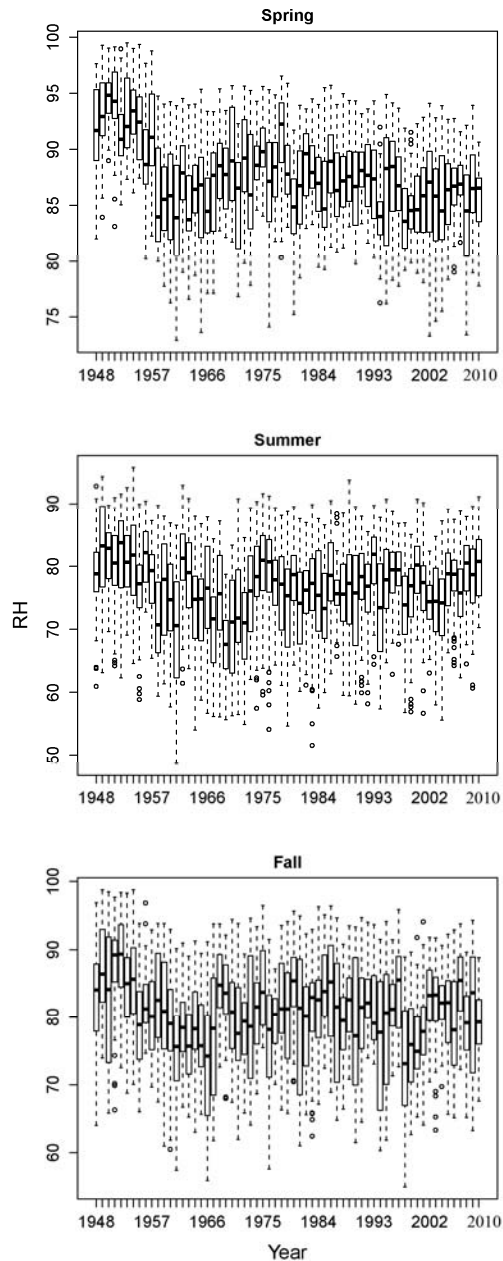
Figure 11. Boxplot of seasonal relative humidity variations in the boreal Prairie Provinces during 1948 ~ 2010 based on Reanalysis I data. Spring include April and May, summer includes June, July, and August, and fall includes September and October.
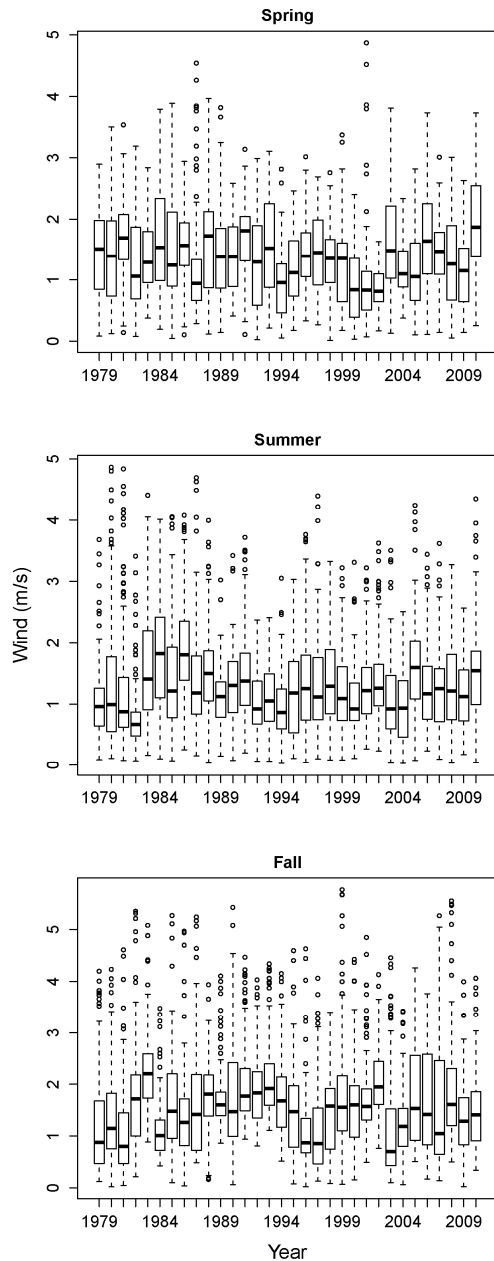
Figure 12. Boxplot of seasonal wind speed variations in the boreal Prairie Provinces during 1979 ~ 2010 based on Reanalysis II data. Spring include April and May, summer includes June, July, and August, and fall includes September and October.

Table 1. Fire season length increments (mean±standard deviation) in days for North America.

Scenario	Model	2020s	2050s	2080s
A1B	CGCM	13.6±21.8	18.8±27.1	22.5±30.4
	Hadley	13.5±21.5	17.6±25.6	22.6±30.3
	IPSL	15.6±24.2	20.4±28.4	26.1±33.8
A2	CGCM	14.7±23.3	18.6±27.0	24.6±32.5
	Hadley	12.2±19.7	18.0±26.2	24.4±32.1
	IPSL	15.2±23.3	18.8±26.2	27.4±34.9
B1	CGCM	12.5±19.6	16.3±24.1	20.0±28.3
	Hadley	13.0±21.1	16.2±24.8	19.5±27.6
	IPSL	15.5±24.4	18.5±26.2	22.4±30.1

Table 2. Fire season length increments (meant±standard deviation) in days for

Prairie Canada

Scenario	Model	2020s	2050s	2080s
A1B	CGCM	18.0±5.2	21.5±5.7	24.5±6.0
	Hadley	18.1±5.5	21.3±5.4	25.4±6.3
	IPSL	18.9±4.8	23.1±5.5	28.0±6.8
A2	CGCM	18.0±5.2	21.0±5.3	26.2±6.6
	Hadley	17.8±5.6	21.4±5.3	26.5±6.8
	IPSL	19.1±4.9	22.9±5.4	29.3±6.4
B1	CGCM	17.6±5.0	19.7±5.4	22.0±5.3
	Hadley	17.9±5.8	20.1±5.3	23.5±5.8
	IPSL	18.8±5.0	22.2±5.3	24.8±6.0

Table 3. Fire season length increments (meant±standard deviation) in days over boreal Prairie Canada

Scenario	Model	2020s	2050s	2080s
A1B	CGCM	17.6±4.9	20.8±5.4	23.5±5.0
	Hadley	17.6±5.2	21.1±5.3	25.1±6.1
	IPSL	18.1±4.6	22.7±5.3	27.7±6.5
A2	CGCM	17.5±4.6	20.6±5.3	25.6±6.0
	Hadley	17.2±5.2	21.0±5.0	26.5±6.6
	IPSL	18.4±4.8	22.7±5.3	28.8±6.2
B1	CGCM	17.2±4.7	19.3±5.4	21.2±5.1
	Hadley	17.4±5.6	19.8±5.0	23.1±5.6
	IPSL	18.2±4.8	22.0±5.2	24.5±5.9

Table 4. Proportional area of future wind speed increase (%) during April ~ September
in North America.

scenario	time periods	Model	April	May	June	July	Aug	Sept	mean
A1B	2020s	CGCM	17.7	15	25.6	25.5	22.1	11	19.5
		Hadley	10.7	10.9	10.9	19.1	30.4	10.2	15.4
		IPSL	9.5	18.2	15.8	23.3	15.9	21.8	17.4
		mean	12.6	14.7	17.4	22.6	22.8	14.3	17.4
	2050s	CGCM	30.7	26.9	33.3	14.8	31.2	16.2	25.5
		Hadley	5.9	3.9	14.9	20.7	32.7	11.2	14.9
		IPSL	27.9	13.2	12.9	28	30	19.5	21.9
		mean	21.5	14.7	20.4	21.2	31.3	15.6	20.8
	2080s	CGCM	36.2	23.1	44	27.3	43.6	26.6	33.5
		Hadley	20.9	9	24.7	22.3	31.5	11.6	20
		IPSL	32.4	36.2	23.1	38.2	46	22.8	33.1
		mean	29.8	22.8	30.6	29.3	40.4	20.3	28.9
A2	2020s	CGCM	16.9	12.9	23.1	23.9	31	8.3	19.4
		Hadley	23.7	4.4	10.7	20.8	26.8	6.5	15.5
		IPSL	21.7	24.8	25.2	26	30.4	21.8	25
		mean	20.8	14.0	19.7	23.6	29.4	12.2	20.0
	2050s	CGCM	28.9	17.6	25.6	21.6	33.2	16.3	23.9
		Hadley	17.7	9.3	29.9	17.2	26.7	10.1	18.5
		IPSL	19.9	16.3	13.5	34.7	41.9	16	23.7
		mean	22.2	14.4	23.0	24.5	33.9	14.1	22.0
	2080s	CGCM	40.4	42.6	49.2	38.7	46.1	23.6	40.1
		Hadley	28.3	9.7	27.2	21	37.8	12.8	22.8
		IPSL	37.4	30.4	50.8	53	38	23.2	38.8
		mean	35.4	27.6	42.4	37.6	40.6	19.9	33.9
B1	2020s	CGCM	16.3	7.5	26.4	29.1	28.1	7.5	19.2
		Hadley	5.2	4.5	16.9	11.7	33.1	7	13.1
		IPSL	5.4	4.6	15.6	20	49.8	10.8	17.7
		mean	9.0	5.5	19.6	20.3	37.0	8.4	16.7
	2050s	CGCM	16.4	7.2	28.7	20.2	32.9	12.5	19.7
		Hadley	8.6	7.4	29.3	18.3	30.4	7.9	17
		IPSL	14	23.2	13.4	28.5	26.7	10.4	19.4
		mean	13.0	12.6	23.8	22.3	30.0	10.3	18.7

2080s	CGCM	31.2	43.5	39.4	28.7	32.4	10.4	30.9
	Hadley	11.4	6.7	19.5	20.2	22.5	10.2	15.1
	IPSL	31.5	31.1	23.1	31.5	44.8	28	31.7
	mean	24.7	27.1	27.3	26.8	33.2	16.2	25.9

Table 5 Proportional area of future wind speed increase (%) during April ~ September in Prairie Canada.

scenario	time periods	Model	April	May	June	July	Aug	Sept	mean
A1B	2020s	CGCM	45.6	82.3	48.1	44.3	46.8	6.3	53.4
		Hadley	16.5	57	46.8	21.5	32.9	0	34.9
		IPSL	7.6	12.7	38	68.4	34.2	84.8	32.2
		mean	23.2	50.7	44.3	44.7	38.0	30.4	40.2
	2050s	CGCM	88.6	87.3	92.4	15.2	74.7	26.6	71.6
		Hadley	7.6	17.7	32.9	31.6	50.6	27.8	28.1
		IPSL	58.2	21.5	25.3	75.9	94.9	84.8	55.2
		mean	51.5	42.2	50.2	40.9	73.4	46.4	51.6
	2080s	CGCM	81	79.7	91.1	63.3	100	86.1	83
		Hadley	60.8	49.4	70.9	24.1	45.6	27.8	50.2
		IPSL	94.9	98.7	64.6	93.7	98.7	98.7	90.1
		mean	78.9	75.9	75.5	60.4	81.4	70.9	74.4
A2	2020s	CGCM	45.6	63.3	57	62	98.7	6.3	65.3
		Hadley	84.8	19	51.9	20.3	35.4	0	42.3
		IPSL	32.9	53.2	79.7	73.4	92.4	88.6	66.3
		mean	54.4	45.2	62.9	51.9	75.5	31.6	58.0
	2050s	CGCM	73.4	74.7	49.4	38	97.5	25.3	66.6
		Hadley	51.9	26.6	91.1	12.7	31.6	1.3	42.8
		IPSL	24.1	43	35.4	97.5	100	62	60
		mean	49.8	48.1	58.6	49.4	76.4	29.5	56.5
	2080s	CGCM	86.1	86.1	94.9	88.6	100	65.8	91.1
		Hadley	82.3	34.2	69.6	13.9	59.5	38	51.9
		IPSL	98.7	97.5	94.9	100	97.5	100	97.7
		mean	89.0	72.6	86.5	67.5	85.7	67.9	80.2
B1	2020s	CGCM	38	54.4	55.7	73.4	63.3	0	57
		Hadley	0	15.2	50.6	6.3	63.3	6.3	27.1
		IPSL	7.6	8.9	64.6	51.9	100	12.7	46.6
		mean	15.2	26.2	57.0	43.9	75.5	6.3	43.6
	2050s	CGCM	41.8	50.6	87.3	25.3	64.6	16.5	53.9
		Hadley	6.3	24.1	62	10.1	51.9	3.8	30.9
		IPSL	24.1	43	30.4	57	82.3	19	47.4
		mean	24.1	39.2	59.9	30.8	66.3	13.1	44.1
	2080s	CGCM	84.8	92.4	89.9	60.8	77.2	6.3	81

Hadley	13.9	21.5	69.6	16.5	16.5	1.3	27.6
IPSL	96.2	100	81	92.4	100	100	93.9
mean	65.0	71.3	80.2	56.6	64.6	35.9	67.5

Table 6. Proportional area of future wind speed increase (%) during April ~ September in the boreal Prairie Canada.

scenario	time periods	Model	April	May	June	July	Aug	Sept	mean
A1B	2020s	CGCM	43.8	95.8	50	43.8	43.8	0	46.2
		Hadley	16.7	66.7	62.5	10.4	29.2	0	30.9
		IPSL	0	8.3	39.6	75	41.7	93.8	43.1
		mean	20.2	56.9	50.7	43.1	38.2	31.3	40.1
	2050s	CGCM	97.9	95.8	100	8.3	75	29.2	67.7
		Hadley	10.4	16.7	33.3	22.9	33.3	35.4	25.3
		IPSL	56.2	16.7	18.8	87.5	100	95.8	62.5
		mean	54.8	43.1	50.7	39.6	69.4	53.5	51.8
	2080s	CGCM	85.4	87.5	100	70.8	100	97.9	90.3
		Hadley	75	56.2	93.8	16.7	43.8	14.6	50
		IPSL	100	100	68.8	100	100	100	94.8
		mean	86.8	81.2	87.5	62.5	81.3	70.8	78.4
A2	2020s	CGCM	47.9	72.9	62.5	58.3	100	2.1	57.3
		Hadley	91.7	16.7	70.8	20.8	29.2	0	38.2
		IPSL	33.3	52.1	93.8	83.3	97.9	95.8	76
		mean	57.6	47.2	75.7	54.1	75.7	32.6	57.2
	2050s	CGCM	77.1	83.3	52.1	41.7	100	31.2	64.2
		Hadley	64.6	29.2	100	8.3	27.1	2.1	38.6
		IPSL	25	43.8	45.8	100	100	68.8	63.9
		mean	55.6	52.1	66.0	50.0	75.7	34.0	55.6
	2080s	CGCM	93.8	93.8	100	89.6	100	79.2	92.7
		Hadley	89.6	39.6	89.6	10.4	43.8	45.8	53.1
		IPSL	100	100	100	100	100	100	100
		mean	94.5	77.8	96.5	66.7	81.3	75.0	81.9
B1	2020s	CGCM	41.7	64.6	56.2	70.8	64.6	0	49.7
		Hadley	0	14.6	58.3	4.2	50	10.4	22.9
		IPSL	0	4.2	68.8	52.1	100	8.3	38.9
		mean	13.9	27.8	61.1	42.4	71.5	6.2	37.2
	2050s	CGCM	43.8	62.5	97.9	25	52.1	20.8	50.4
		Hadley	10.4	25	75	2.1	27.1	4.2	24
		IPSL	25	43.8	35.4	70.8	85.4	8.3	44.8
		mean	26.4	43.8	69.4	32.6	54.9	11.1	39.7
	2080s	CGCM	93.8	100	97.9	70.8	75	2.1	73.3

Hadley	18.8	20.8	89.6	12.5	10.4	0	25.4
IPSL	100	100	87.5	100	100	100	97.9
mean	70.9	73.6	91.7	61.1	61.8	34.0	65.5

Table 7. Mean proportional relative humidity decrease (%) area over the three GCM projections for the future during April ~ September in North America.

scenario	time periods	Model	April	May	June	July	Aug	Sept	mean
A1B	2020s	CGCM	15	33.8	62	88.2	88.3	54.1	56.9
		Hadley	1.8	58.2	49.6	45.3	55.5	63.3	45.6
		IPSL	31.2	43.8	85.9	92.5	93.2	70.6	69.5
		mean	16.0	45.3	65.8	75.3	79.0	62.7	57.4
	2050s	CGCM	29.4	41.4	75.1	87.7	91.4	71	66.0
		Hadley	5.2	33.8	42.9	59.2	69.7	74.9	47.6
		IPSL	33.8	44.5	80	93.3	94.2	76.1	70.3
		mean	22.8	39.9	66.0	80.1	85.1	74.0	61.3
	2080s	CGCM	26.5	46.9	70.4	87.6	90.1	69.1	65.1
		Hadley	9.8	10.6	31.1	33.2	65.4	64.2	35.7
		IPSL	32.7	48.1	76.4	92.5	94.3	69.3	68.9
		mean	23.0	35.2	59.3	71.1	83.3	67.5	56.6
A2	2020s	CGCM	21	51.2	73	89.1	93.1	68.1	65.9
		Hadley	38	47.1	79.9	45.8	95.1	77.2	63.9
		IPSL	37.3	48.6	84.6	93.1	93	76	72.1
		mean	32.1	49.0	79.2	76.0	93.7	73.8	67.3
	2050s	CGCM	24.8	41.1	71.8	88.9	90.4	71	64.7
		Hadley	16.5	18.8	58.2	55.4	76	84	51.5
		IPSL	34	46.4	78.3	90.8	92.7	75.4	69.6
		mean	25.1	35.4	69.4	78.4	86.4	76.8	61.9
	2080s	CGCM	27.3	45.5	73.3	90.6	91.1	70.8	66.4
		Hadley	24.8	14.9	54.1	45.2	63.1	56.8	43.2
		IPSL	32.7	45.8	76.4	93.1	94.8	72.1	69.2
		mean	28.3	35.4	67.9	76.3	83.0	66.6	59.6
B1	2020s	CGCM	12.1	47.1	53.1	81.9	87.9	57.8	56.7
		Hadley	7.2	40.3	15.5	2.5	99.5	64.1	38.2
		IPSL	36.2	36.5	80.4	93.7	91.5	69.8	68.0
		mean	18.5	41.3	49.7	59.4	93.0	63.9	54.3
	2050s	CGCM	21.6	39.6	72.5	87.5	83.3	76.5	63.5
		Hadley	55.2	66	56.7	41	84.6	58.5	60.3
		IPSL	33.6	40.3	77.6	91.8	92.5	71.4	67.9
		mean	36.8	48.6	68.9	73.4	86.8	68.8	63.9

2080s	CGCM	22.1	42.1	69.6	86.3	90.6	57.8	61.4
	Hadley	17.8	57.8	53.6	44.8	70.6	60.9	50.9
	IPSL	33.1	45.3	77	92	92.2	72.1	68.6
	mean	24.3	48.4	66.7	74.4	84.5	63.6	60.3

Table 8. Mean proportional relative humidity decrease (%) area over the three GCM projections for the future major fire season months in Prairie Canada.

scenario	time periods	Model	April	May	June	July	Aug	Sept	mean
A1B	2020s	CGCM	0	0	59.5	94.9	97.5	55.7	51.3
		Hadley	0	45.6	48.1	22.8	12.7	12.7	23.7
		IPSL	0	11.4	93.7	97.5	97.5	60.8	60.2
		mean	0.0	19.0	67.1	71.7	69.2	43.1	45.0
	2050s	CGCM	0	0	75.9	94.9	97.5	53.2	53.6
		Hadley	0	13.9	16.5	36.7	36.7	35.4	23.2
		IPSL	0	20.3	89.9	98.7	98.7	73.4	63.5
		mean	0.0	11.4	60.8	76.8	77.6	54.0	46.8
	2080s	CGCM	0	12.7	74.7	96.2	98.7	57	56.6
		Hadley	0	0	1.3	8.9	39.2	19	11.4
		IPSL	0	40.5	87.3	98.7	100	70.9	66.2
		mean	0.0	17.7	54.4	67.9	79.3	49.0	44.7
A2	2020s	CGCM	0	24.1	79.7	94.9	97.5	55.7	58.7
		Hadley	29.1	50.6	79.7	21.5	86.1	39.2	51.0
		IPSL	0	34.2	92.4	97.5	97.5	81	67.1
		mean	9.7	36.3	83.9	71.3	93.7	58.6	58.9
	2050s	CGCM	0	0	70.9	96.2	98.7	58.2	54.0
		Hadley	0	12.7	41.8	31.6	45.6	72.2	34.0
		IPSL	0	24.1	87.3	97.5	98.7	73.4	63.5
		mean	0.0	12.3	66.7	75.1	81.0	67.9	50.5
	2080s	CGCM	0	1.3	79.7	97.5	98.7	53.2	55.1
		Hadley	0	0	2.5	16.5	16.5	7.6	7.2
		IPSL	0	31.6	89.9	98.7	100	69.6	65.0
		mean	0.0	11.0	57.4	70.9	71.7	43.5	42.4
B1	2020s	CGCM	0	22.8	67.1	89.9	97.5	63.3	56.8
		Hadley	0	41.8	15.2	0	100	15.2	28.7
		IPSL	0	0	89.9	97.5	97.5	81	61.0
		mean	0.0	21.5	57.4	62.5	98.3	53.2	48.8
	2050s	CGCM	0	0	81	94.9	96.2	79.7	58.6
		Hadley	13.9	43	12.7	0	54.4	41.8	27.6
		IPSL	0	0	87.3	97.5	98.7	69.6	58.9
		mean	4.6	14.3	60.3	64.1	83.1	63.7	48.4

2080s	CGCM	0	0	68.4	96.2	98.7	51.9	52.5
	Hadley	1.3	25.3	1.3	12.7	49.4	13.9	17.3
	IPSL	0	20.3	87.3	98.7	98.7	69.6	62.4
	mean	0.4	15.2	52.3	69.2	82.3	45.1	44.1

Table 9. Mean proportional relative humidity decrease (%) area over the three GCM projections for the future during April ~ September in the boreal Prairie Canada.

scenario	time periods	Model	April	May	June	July	Aug	Sept	mean
A1B	2020s	CGCM	0	0	75	97.9	97.9	60.4	54.2
		Hadley	0	54.2	70.8	22.9	4.2	20.8	30.4
		IPSL	0	6.2	97.9	97.9	97.9	68.8	60.0
		mean	0.0	20.1	81.2	72.9	66.7	50.0	48.2
	2050s	CGCM	0	0	91.7	97.9	97.9	56.2	57.5
		Hadley	0	22.9	22.9	39.6	56.2	54.2	28.3
		IPSL	0	10.4	97.9	100	100	83.3	61.7
		mean	0.0	11.1	70.8	79.2	84.7	64.6	49.2
	2080s	CGCM	0	8.3	87.5	97.9	100	62.5	58.7
		Hadley	0	0	2.1	14.6	41.7	20.8	11.7
		IPSL	0	39.6	97.9	100	100	85.4	67.5
		mean	0.0	16.0	62.5	70.8	80.6	56.2	46.0
A2	2020s	CGCM	0	12.5	93.8	97.9	97.9	60.4	60.4
		Hadley	29.2	54.2	95.8	8.3	87.5	39.6	55.0
		IPSL	0	29.2	97.9	97.9	97.9	93.8	64.6
		mean	9.7	32.0	95.8	68.0	94.4	64.6	60.0
	2050s	CGCM	0	0	87.5	97.9	100	64.6	57.1
		Hadley	0	20.8	50	31.2	47.9	62.5	30.0
		IPSL	0	14.6	97.9	97.9	100	85.4	62.1
		mean	0.0	11.8	78.5	75.7	82.6	70.8	49.7
	2080s	CGCM	0	2.1	93.8	100	100	56.2	59.2
		Hadley	0	0	4.2	20.8	8.3	12.5	6.7
		IPSL	0	25	97.9	100	100	83.3	64.6
		mean	0.0	9.0	65.3	73.6	69.4	50.7	43.5
B1	2020s	CGCM	0	22.9	93.8	95.8	97.9	68.8	62.1
		Hadley	0	54.2	16.7	0	100	18.8	34.2
		IPSL	0	0	97.9	97.9	97.9	93.8	58.7
		mean	0.0	25.7	69.5	64.6	98.6	60.5	51.7
	2050s	CGCM	0	0	95.8	97.9	97.9	91.7	58.3
		Hadley	10.4	50	8.3	0	68.8	52.1	27.5
		IPSL	0	0	97.9	97.9	100	83.3	59.2
		mean	3.5	16.7	67.3	65.3	88.9	75.7	48.3

2080s	CGCM	0	0	83.3	97.9	100	54.2	56.2
	Hadley	0	27.1	2.1	10.4	54.2	12.5	18.8
	IPSL	0	10.4	97.9	100	100	83.3	61.7
	mean	0.0	12.5	61.1	69.4	84.7	50.0	45.6