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Trends in midlatitude cyclone frequency and occurrence during fire season in the Northern Rockies: 1900–2004

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[1] We examined changes in the timing and frequency of major midlatitude cyclones (MLCs) during August through October for eight climate stations in the Northern Rockies from 1900–2004. As MLCs can effectively diminish fire activity through both cooler temperatures and higher humidity/precipitation, we also determined if area burned by wildfires from 1940–2004 was correlated with the timing and frequency of these events. Our results indicate that: (1) significant long-term trends in MLCs exist, as the timing of the first MLC has occurred later in the year during the past century, with a marked upward shift post-mid-1980s; (2) MLC frequency has significantly declined since 1900, with a pronounced decrease also beginning in the mid-1980s; (3) the relationships between the timing of the first MLC and frequency of MLCs with forest area burned are significant; and (4) mid-tropospheric ridging upstream from the Northern Rockies that blocks MLCs has become more pronounced. **Citation:** Knapp, P. A., and P. T. Soulé (2007), Trends in midlatitude cyclone frequency and occurrence during fire season in the Northern Rockies: 1900–2004, *Geophys. Res. Lett.*, *34*, L20707, doi:10.1029/2007GL031216.

1. Introduction

[2] The area burned by wildfires in western North America has traditionally been associated with the annual variability in fuels, topography and weather conditions, yet the relative contribution of each is largely dependent upon forest type [*Agee*, 1997]. In the Northern Rockies, where nearly half of the total forested environment is classified as subalpine forest (A. C. Cilimburg and K. C. Short, Forest fire in the U. S. Northern Rockies: A primer, http://www.northernrockiesfire.org, 2005), weather conditions have been shown to be the principal determinant of area burned both prior to [*Larsen and Delavan*, 1922] and after over a half-century of fire suppression [*Romme and Despain*, 1989; *Bessie and Johnson*, 1995]. Recently, several studies [e.g., *Gillett et al.*, 2004; *Whitlock*, 2004; *Running*, 2006; *Westerling et al.*, 2006] have posited that the influence of climate on fire activity during the past several decades may be linked to the effects of global warming. There also is a strong geographical component to recent fire activity as approximately 60% of the total increase in forest fires in the western United States during the past three decades has occurred in the Northern Rockies [*Westerling et al.*, 2006]. Increased fire activity in the Northern Rockies has been attributed to the earlier onset of snowmelt and warmer spring and summer periods [*Westerling et al.*, 2006], with the latter cause also being implicated for increased Canadian forest fire activity [*Gillett et al.*, 2004].

[3] One topic that has received less attention regarding the weather hypothesis for explaining variations in fire activity has been the timing and frequency of mid-summer/early autumn (MS/EA) midlatitude cyclones (MLCs) that occur between August and October. Regionally, the characteristics of any summer season in the Northern Rockies in terms of temperature and moisture are linked to midlatitude cyclonic activity. These storms, which are capable of producing significant widespread precipitation and maximum temperature reductions >15°C below average, can occur in mid- to late-summer when cumulative fuel moisture deficits typically are highest and thus can diminish current fire activity and reduce fuel moisture deficits. Fire occurrence, spread, and size are all influenced, in part, by meteorological conditions [*Hostetler et al.*, 2005], with temperature being the primary determinant of area burned [*Flannigan and Harrington*, 1988; *Flannigan et al.*, 2005]. Therefore, the passage of MLCs that cause major temperature decreases can have a significant impact on the overall severity of the fire season. In particular, both *Skinner et al.* [1999, 2002] and *Gedalof et al.* [2005] found that wildfire activity in the American West was positively correlated with mid-tropospheric (500 mb) summertime circulation anomalies. It follows that changes in the mid-tropospheric heights during the summer in the Northern Rockies would also be associated with shifts in fire activity.

[4] Given the significance of meteorological conditions in relation to fire activity, our objective is to show that significant changes have occurred in the both the timing and frequency of major midlatitude cyclones during MS/EA in the Northern Rockies during the last 105 years (1900–2004). We then examine if these changes are correlated with interannual variability in forest fire activity in the Northern Rockies based on fire records from 1940–2004. Finally, we explore if the observed shifts in the timing and frequency of MLCs, with the resulting implications for fire-season severity, are significantly associated with changes in synoptic-scale meteorological phenomena.

2. Climate Data

[5] We used maximum temperature anomalies (MTAs) as an indicator of the presence of MS/EA MLCs. We chose to focus our study on August–October because this represents the season of increasing midlatitude cyclonic activity and it

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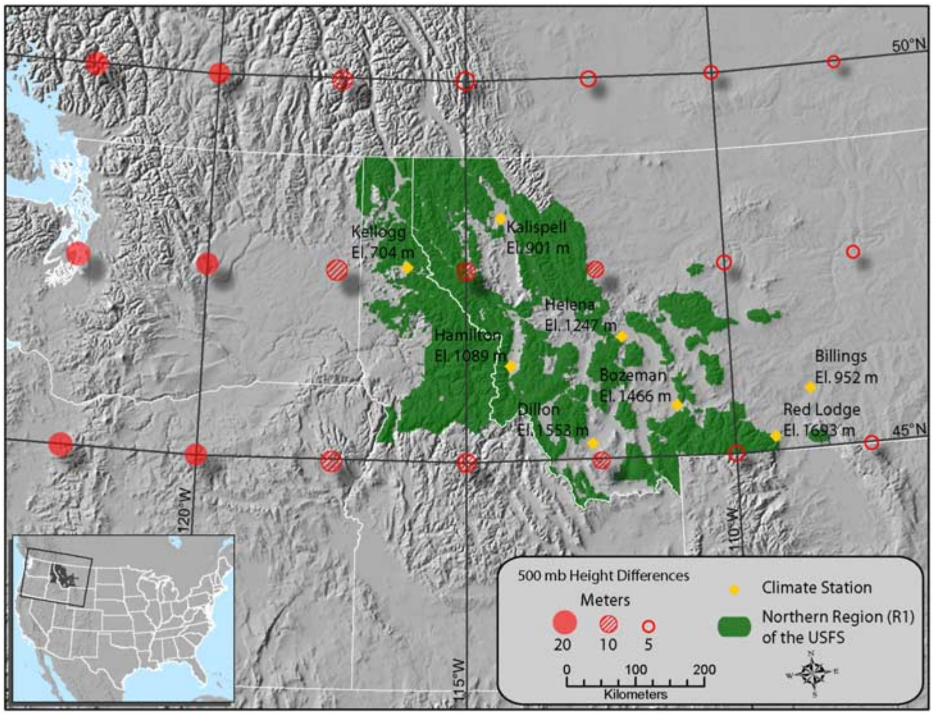

Figure 1. Climate stations with elevations, boundary of Northern Region (R1) forests, and differences in mean 500 mb heights (m) at selected grid points: 1987–2004 minus 1948–1986. Significance of graduated circles: solid, $P < 0.01$; hachured, $P < 0.05$; open, $P > 0.05$.

occurs during the middle and latter period of the fire season when fuel moisture deficits typically are greater than the earlier portion of the fire season. Thus, we focus our analysis on the period where the influence of MLC activity would be most critical.

[6] We selected eight spatially well-separated climate stations with century-long or greater records (except Kellogg, 1906–2004), coverage exceeding 90 percent, and located within Region 1 (Northern) of the United States Forest Service mapping boundaries (Figure 1). We examined the station metadata to ensure there had been no station moves of a magnitude great enough to bias the temperature record. We extracted the daily data directly from the National Climatic Data Center *Summary of the Day* data files [*National Climate Data Center*, 2004] and made no attempt to correct the data for any inhomogeneities that might have been caused by changes in time of observation or instrumentation. Further, we made no attempt to fill in data gaps with data from nearby stations. If any day had missing data we examined the day before and the day after to determine if it was possible that it would have contributed to a MTA. If it did, we then examined data from nearby stations to determine whether the missing data day would have likely been included in a MTA. If a missing day would have, we then eliminated that entire year from consideration for that given station. A station with missing data for a given day was thus not used in the calculation of the mean.

[7] To identify MTAs across study sites we standardized the maximum temperature data for each of the 92 Julian days (Julian day 1 = August 1st to avoid problems with leap years) over the study period (thus, $n = 105$ if no missing years for 1900–2004). Before standardizing the data we tested for normality and found that the majority of days had distributions that were not significantly different ($P < 0.01$) from a normal distribution. We converted the maximum daily temperatures for August, September, and October for each station into standardized scores (z-scores). We defined a MTA as any sequence of two consecutive days with a combined z-score ≤ -4.0, or three consecutive days ≤ -5.0; four days ≤ -6.0; and five days ≤ -7.0. We used the Julian day of the first day for each MTA sequence in our analyses. By using a definition based on a multi-day criteria with high thresholds, we both reduce the potential of non-frontal events (e.g., isolated thunderstorms) causing a MTA and ensure that some multi-day synoptic feature, typically a cold-frontal passage associated with an early season mid-latitude cyclone, was the cause.

[8] For each site and for each year that there were available data (1900–2004) we recorded both the Julian date of the first MTA and the total MTAs during the 3-month study period. If no MTA occurred, the Julian date was recorded as a value of 93 (i.e., later than October 31, which would be the end of the fire season), and we used this value in the calculation of the mean. For the determination of multiple MTAs, the daily z-score in a multi-day sequence had to rise to ≥ -0.5 for one MTA to end and another to begin. For both first MTAs and total MTAs, we calculated yearly averages using data from all available sites. For first MTAs, the fewest sites comprising the average in any given year were five; for total MTAs it was four. While we recognize the possible statistical complications of using the mean when the averages are impacted by non-MTA years, we determined that the means and medians were highly correlated for both the first MTAs (r = 0.94, $P < 0.01$) and total MTAs (r = 0.96, $P < 0.01$).

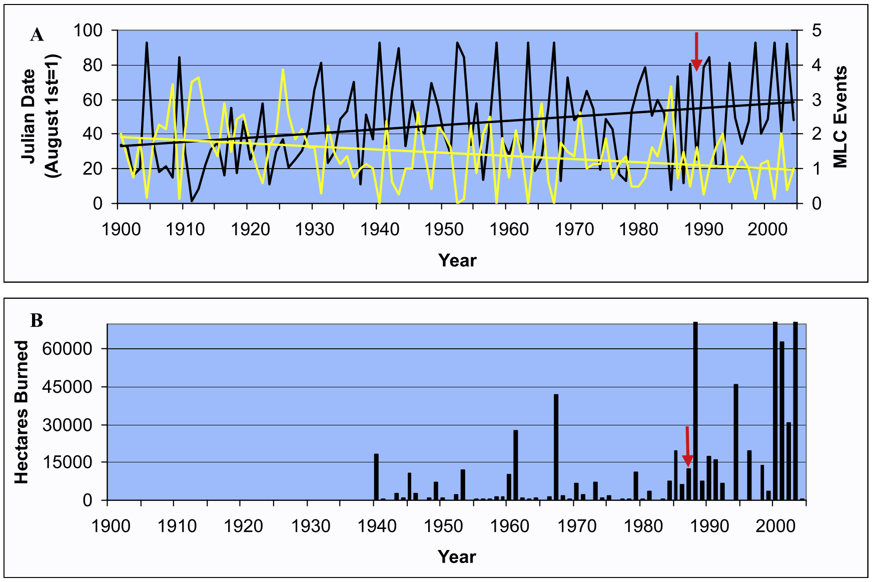

Figure 2. (a) The timing (increasing trend) and frequency (decreasing trend) of major midlatitude cyclones. (b) Hectares of Northern Region (R1) forests burned between 1940 and 2004. Arrows indicate the approximate period where *Westerling et al.* [2006] noted abrupt changes in forest wildfire activity in the western United States. Extreme values for 1988, 2000, and 2003 (in text) have been truncated.

[9] We explored if geographical differences existed either latitudinally or longitudinally in the timing and frequency of MLCs. We separated the data into northern (Kalispell, Kellogg, Hamilton, and Helena) and southern (Bozeman, Billings, Dillon, and Red Lodge) groups, which also separated the stations into sites west and east of the Continental Divide (except Helena, so we did not create additional groups). We averaged the annual data for each group and generated trend lines using bivariate regression and the MLC data as the dependent variable.

[10] We obtained seasonal (August–September) mean 500 mb data from the NCEP/NCAR Reanalysis data set [*Kalnay et al.*, 1996] for 21 points on a 2.5° latitude by 2.5° longitude grid (Figure 1). Our coverage area ranged from 50°N, 122.5°W to 45°N 107.5°W to include Region 1 plus the area west of the forest boundaries as changes in 500 mb geopotential heights upstream of the study area would affect the tracking of midlatitude cyclones.

3. Fire Data

[11] We obtained fire data for the number of hectares burned annually for the period 1940–2004 for Region 1 of the United States Forest Service (Northern Region Geospatial Library Regional Office Data, Fire history for region 1 (1940–2001) and fire history for region 1 (1985–2005 polygons), http://www.fs.fed.us/r1/gis/ThematicTables.htm#Fire, 2006, hereinafter referred to as NRGL, http://www.fs.fed.us/r1/gis/ThematicTables.htm#Fire, 2006) excluding data for the Custer National Forest as these eastern Montana and South Dakota forests are outside of our study area. Our complete data set was created using two files, one from 1940–2001, and a second from 1985–2004 where we used the years 1988, 2000, 2001 (incomplete from the other file) and 2002, 2003, 2004 (absent from the other file). Area burned for both data sets was based on the use of polygons as opposed to point data, and fires of less than approximately 40 ha were excluded. Thus, this data set slightly underestimates total area burned, but is consistent throughout the time frame. We used total hectares burned as opposed to the commonly used large wildfire frequency because the practice of fire herding that became widely used in the 1990s (i.e., causing multiple fires to merge) may have artificially increased frequency values. We included area burned in our analysis regardless of ignition source, either lightning- or human-caused, because we wished to analyze the linkage between area burned and climatic conditions where the importance of anthropogenic activities is included. Further, fire suppression has been employed in the Northern Region since the early 20th century, but these activities are unlikely to have affected the subalpine forests in the Northern Rockies [*Schoennagel et al.*, 2004].

4. Statistical Tests

[12] After examining a suite of curve estimates and finding no meaningful differences in significance or explanatory power between non-linear and linear models, we used simple regression and Pearson's correlation to test for the significance of temporal trends in the timing of first MTAs, total MTAs, and hectares burned. We examined the relationships between hectares burned and the first MTAs/total MTAs using cubic regression models after removing the outlier years of 1988, 2000, and 2003.

[13] We tested for significant increases in seasonal 500 mb heights at each of the 21 points on our grid for the time period 1987–2004 relative to 1948–1986 using 1-tailed Wilcoxon tests. These time periods were selected because 1987 marks a major transition boundary between lower and higher fire activity in the western United States [*Westerling et al.*, 2006] and specifically, the Northern Rockies region (NRGL, http://www.fs.fed.us/r1/gis/ThematicTables.htm#Fire, 2006). Additionally, we used a 1-tailed Wilcoxon test to determine if seasonal 500 mb heights were

significantly greater during the top five fire years compared to all other years.

5. Results and Discussion

[14] Our analyses establish the existence of significant long-term trends in MLCs during the past century that also may have affected fire trends. The mean date of the first MLC has occurred nearly a month later in the early 21st century relative to the early 20th century (Figure 2a), and the linear trend is significant (r = 0.30, $P < 0.01$). The frequency of MLCs is inversely related to the timing of the first MLC (r = −0.72, $P < 0.001$) and decreases through time (r = −0.31, $P < 0.01$) as values dropped from approximately 2 events/year from 1910 to 1920 to approximately 1 event/year in the early 21st century (Figure 2a).

[15] The fire records from 1940–2004 for the Northern Rockies included the exceptional fire years of 1988 (300,317 hectares burned), 2000 (437,974), and 2003 (231,339), which clearly skew the data (Figure 2b). Yet, the linear trend is significantly upward regardless if those years are retained (r = 0.33, $P < 0.01$, $n = 65$) or removed (r = 0.34, $P < 0.01$, $n = 62$). We found the relationship between timing of the first MLC and hectares burned is significant ($R^2 = 0.18$, $P < 0.01$, $n = 62$), indicating that the delayed onset of the first MLC is associated with more active fire years. Total MLCs also help explain hectares burned ($R^2 = 0.13$, $P < 0.05$, $n = 62$). For the top ten years for hectares burned since 1940 (including the outlier years), only one experienced the first MLC in August, with five years recording the first MLC in October or not at all. Further, the top five fire years had a mean total of MLCs (0.58/year) that was roughly one-third of the bottom five years (1.47/year), again suggesting that the absence/decline of MLCs has an impact of total fire activity.

[16] There are no significant geographical differences in MLC timing and frequency in Region 1, suggesting that these changes are geographically extensive. Both the northern and southern groups had similar trends for the timing ($R^2 = 0.072$, P < 0.01 northern; $R^2 = 0.073$, P < 0.01 southern) and frequency ($R^2 = 0.098$, P < 0.01; $R^2 = 0.078$, P < 0.01) of MLCs.

[17] Our analyses also show congruence between *Westerling et al.*'s [2006] observation of a dramatic increase in wildfire activity in the mid-1980s in the western U.S. with our findings of a progressively later occurrence of the first MLC and decreasing total MLCs (Figure 2a). Fire season activity is more extensive when the first MLC occurs later in the season and when the frequency of MLCs decrease, highlighting the importance of these events for dampening the extent of fires. We found significant changes in the 500 mb heights between the periods 1987–2004 and 1948–1986 over and upstream (i.e., to the west and north) of our study sites (Figure 1). Increased heights in the later period suggest a greater likelihood of blocking events that prevent MLC passage in the Northern Rockies as storms would track either northward of the ridge or weaken as they entered an area of unfavorable atmospheric conditions. Either condition would account for the changes in the timing and frequency of MLCs that are pronounced during the past two decades. Further, mean 500 mb heights were significantly greater ($P < 0.05$) during the top-five fire years (2000, 1988, 2003, 2001, and 1994) at all 21 grid points compared to all other years, suggesting the critical importance of changes to summertime steering currents for fire regimes. These findings are in accord with the observations of *Skinner et al.* [1999, 2002] and *Gedalof et al.* [2005], as they found positive correlations between 500 mb heights and area burned by forest fires throughout the summer in regions adjacent to the Northern Rockies.

[18] Several studies that have examined cyclone frequency trends in the Northern Hemisphere reveal both the spatial complexity of the trends and that midlatitude cyclonic activity has decreased during the past 40 years [*Key and Chan*, 1999; *McCabe et al.*, 2001; *Zhang et al.*, 2004] including summer activity [*Key and Chan*, 1999]. Our results for the Northern Rockies region are consistent with these findings. The causes for the decrease in cyclonic activity, however, are not fully understood, nor are the changes temporally or spatially consistent. For example, *Zhang et al.* [2004] found that Arctic midlatitude cyclone activity decreased from 1960 to approximately 1993 and then increased through 2002 with the shift associated with phase changes in broad-scale circulation indices, while *Geng and Sugi* [2001] determined that midlatitude cyclone intensity increased during the past four decades in the North Atlantic.

[19] Reduced activity of major MS/EA MLCs indicated by our analysis would correspond with a northward shift in the mean position of the storm track over the Northern Rockies, as shown by the increases in mid-tropospheric heights upstream of Region 1 (Figure 1). These findings parallel the projections of *Yin* [2005] who found that under conditions of elevated atmospheric CO_2 concentrations in the 21st century, the Northern Hemisphere storm track shifted poleward and weakened during the summer months and that tropospheric heights increased. Thus, summertime warming at higher latitudes decreases the baroclinic instabilities required for MLCs. These projections are consistent with our results as the largest changes occurred during the period of highest greenhouse gas concentrations, potentially suggesting that changes in storm position and strength have already begun in the Northern Rockies. We also explored the potential influence of PDO and ENSO shifts on MLC patterns as *Schoennagel et al.* [2005] determined that fire activity in the Northern Rockies was positively associated with warm PDO and El Niño phases. We found no significant correlations (P > 0.05) between MLC timing and frequency with annual, winter or summer PDO indices (NOAA, PDO indices, 1900–2007, http://www.beringclimate.noaa.gov/data/BCresult.php, 2007) nor with ENSO data (Western Regional Climate Center, Classification of El Niño and La Niño winters, 1933–2006, http://www.wrcc.dri.edu/enso/ensodef.html, 2007). Additional non-climatic factors could partially account for the mid-1980s change in fire activity, including more human-caused ignitions, and, because of changes in wildland fire use policy, allowing more fires to burn without attempts to extinguish [*Zimmerman and Bunnell*, 1998].

6. Conclusions

[20] The causes for changing wildfire activity in the Northern Rockies include the critically important temporal

variability in MS/EA weather patterns, which account for approximately one-fifth of the total variance in wildfire activity. We determined that later and fewer MLCs have led to an increase in area burned in the Northern Rockies. The causes for these changes are associated with elevated 500 mb geopotential heights, where a greater intensity of ridging during MS/EA has inhibited cyclonic activity and the associated maximum temperature anomalies. Changes in wildfire activity linked to climatic change may have serious ecologic and economic impacts and, as noted by *Running* [2006], are occurring now as opposed to some distant future date, and in "our own back yards." Forest wildfires are costly to suppress and/or control, and "seasonal expenditures by governmental agencies in recent years have reached $1.7 billion" [*Running*, 2006]. Thus far, trends in the timing and frequency of major MLCs in the Northern Rockies have accord with the changes expected (i.e., more hot summer days, higher maximum temperatures) with increases in greenhouse gases [*Easterling et al.*, 2000]. Projected changes during the 21st century suggest that these trends will continue [*Easterling et al.*, 2000], indicating the likelihood of more intense fire seasons in the Northern Rockies.

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References

Agee, J. K. (1997), The severe weather wildfire—Too hot to handle, *Northwest Sci. Forum*, *71*, 153–156.

Bessie, W. C., and E. A. Johnson (1995), The relative importance of fuels and weather on fire behavior in subalpine forests, *Ecology*, *76*, 747–762.

Easterling, D. R., G. A. Meehl, C. Parmesan, S. A. Changnon, T. R. Karl, and L. O. Mearns (2000), Climate extremes: Observations, modeling and impacts, *Science*, *289*, 2068–2074.

Flannigan, M. D., and J. B. Harrington (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., K. A. Logan, B. D. Amiro, W. R. Skinner, and B. J. Stocks (2005), Future area burned in Canada, *Clim. Change*, *72*, 1–16.

Gedalof, Z., D. L. Peterson, and N. J. Mantua (2005), Atmospheric, climatic, and ecological controls on extreme fire years in the northwestern United States, *Ecol. Appl.*, *15*, 154–174.

Geng, Q., and M. Sugi (2001), Variability of the North Atlantic cyclone activity in winter analyzed from NCEP-NCAR reanalysis data, *J. Clim.*, *14*, 3863–3873.

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.

Hostetler, S. W., P. J. Bartlein, A. M. Solomon, J. O. Holman, R. T. Busing, and S. L. Shafer (2005), Climatic controls of fire in the western United States: From the atmosphere to ecosystems, final report for project 01-1-6-05, 28 pp., Joint Fire Sci. Program, Boise, Idaho.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, http://www.cdc.noaa.gov/cgi-bin/Timeseries/timeseries1.pl.

Key, J. R., and A. C. K. Chan (1999), Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies, *Geophys. Res. Lett.*, *26*, 2053–2056.

Larsen, J. A., and C. C. Delavan (1922), Climate and forest fires in Montana and northern Idaho, 1909 to 1919, *Mon. Weather Rev.*, *49*, 55–68.

McCabe, G. J., M. P. Clark, and M. C. Serreze (2001), Trends in Northern Hemisphere surface cyclone frequency and intensity, *J. Clim.*, *14*, 2763–2768.

National Climate Data Center (2004), *Summary of the Day, West 2 2005* [CD-Rom], EarthInfo, Boulder, Colo.

Romme, W. H., and D. Despain (1989), Historical perspective on the Yellowstone fires of 1988, *BioScience*, *39*, 695–699.

Running, S. W. (2006), Is global warming causing more, larger fires?, *Science*, *313*, 927–928, doi:10.1126/science.1130370.

Schoennagel, T., T. T. Veblen, and W. H. Romme (2004), The interaction of fire, fuels, and climate across Rocky Mountain forests, *BioScience*, *54*, 661–676.

Schoennagel, T., T. T. Veblen, W. H. Romme, J. S. Sibold, and E. R. Cook (2005), ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subalpine forests, *Ecol. Appl.*, *15*, 2000–2014.

Skinner, W. R., B. J. Stocks, D. L. Martell, B. Bonsal, and R. Shabbar (1999), The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada, *Theor. Appl. Climatol.*, *63*, 89–105.

Skinner, W. R., M. D. Flannigan, B. J. Stocks, D. L. Martell, B. M. Wotton, J. B. Todd, J. A. Mason, K. A. Logan, and E. M. Bosch (2002), A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959–1996, *Theor. Appl. Climatol.*, *71*, 157–169.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam (2006), Warming and earlier spring increases western U. S. Forest wildfire activity, *Science*, *313*, 940–943, doi:10.1126/science.1128834.

Whitlock, C. (2004), Forests, fires, and climate, *Nature*, *432*, 28–29.

Yin, J. H. (2005), A consistent poleward shift of the storm tracks in simulations of 21st century climate, *Geophys. Res. Lett.*, *32*, L18701, doi:10.1029/2005GL023684.

Zhang, X., J. E. Walsh, U. S. Bhatt, and M. Ikeda (2004), Climatology and interannual variability of Arctic cyclone activity, *J. Clim.*, *17*, 2300–2317.

Zimmerman, G. T., and D. L. Bunnell (1998), Wildland and prescribed fire management policy: Implementation procedures reference guide, 92 pp., Natl. Interagency Fire Cent., Boise, Idaho.

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