CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire* **2011**, *20*, 479–486

Relative importance of weather and climate on wildfire growth in interior Alaska

John T. Abatzoglou[A,B] *and Crystal A. Kolden*[A]

[A]Department of Geography, University of Idaho, PO BOX 443021, Moscow, ID 83844-3021, USA.
[B]Corresponding author. Email: jabatzoglou@uidaho.edu

Abstract. Efforts to quantify relationships between climate and wildfire in Alaska have not yet explored the role of higher-frequency meteorological conditions on individual wildfire ignition and growth. To address this gap, meteorological data for 665 large fires that burned across the Alaskan interior between 1980 and 2007 were assessed to determine the respective influence of higher-frequency weather and lower-frequency climate, in terms of both antecedent and post-ignition conditions on fire growth. Antecedent climate exhibited no discernable influence on eventual fire size. In contrast, fire size was sensitive to weather in the days to weeks following ignition, particularly the post-ignition timing of precipitation. Prolonged periods of warm and dry conditions coincident with blocking that persists for several weeks after ignition enabled growth of large wildfires, whereas the return of wetting precipitation generally within a week after ignition inhibited growth of smaller wildfires. These results suggest that daily weather data are a critical predictor of fire growth and large fire potential and encourage their use in fire management and modelling.

Additional keywords: boreal forest, fire danger indices.

Introduction

Wildfire is the dominant natural disturbance regime across interior Alaska, playing a critical ecological role in defining species habitat and succession (Chapin *et al*. 2006), as well as negatively affecting human–environment systems (e.g. Chapin *et al*. 2008). Annual area burned by wildfires in Alaska often surpasses totals from the contiguous United States. The frequency of episodic, region-wide wildfire seasons across interior Alaska has increased over the past three decades (Kasischke *et al*. 2002; Kasischke and Turetsky 2006), coinciding with a period of significant warming observed regionally and across circumpolar land masses in the northern hemisphere (IPCC 2007). The association between warming and wildfire was exemplified by the 2004 fire season, during which interior Alaska experienced the warmest spring–summer temperature in the observational record (Shulski *et al*. 2005) and the greatest area burned in the historic period (2.7×10^6 ha). The observed trends, the 2004 fire season, and subsequent large fire seasons in 2005 and 2009 have fuelled findings and further hypotheses that wildfire size and annual area burned in Alaska have increased in response to warming (Duffy *et al*. 2005), and that wildfire activity will continue increasing in response to predicted warming throughout the 21st century (e.g. Balshi *et al*. 2009*a*).

To project fire activity across a spectrum of timescales relevant to research interests and fire management (e.g. short-term outlooks, seasonal forecast, climate-change predictions) necessitates predictive models that incorporate a process-based understanding of the consortium of factors contributing to fuel conditions, fire ignition potential, actual ignitions and wildfire growth. Previous work has shown climate (herein referred to as monthly and longer aggregates of weather conditions that characterise lower-frequency timescales) to influence annual area burned in interior Alaska (Duffy *et al*. 2005); however, the relative importance of weather and climate in regulating the growth of individual fires in interior Alaska, and determining whether they stay relatively small or grow relatively large, has not yet been fully resolved. Research in analogous Canadian boreal ecosystems suggests that short-term sub-monthly moisture deficits are sufficient to deplete fuel moisture and enable lightning ignition and fire growth (Flannigan and Harrington 1988; Johnson and Wowchuk 1993; Nash and Johnson 1996), leading us to posit that sub-monthly meteorological conditions likely also contribute significantly to large fire growth in interior Alaska.

The relative importance of climate (including antecedent conditions) and higher-frequency meteorology on wildfire growth and large fire potential in interior Alaska is not fully resolved. Climate data typically synthesise meteorological conditions over fixed points in the calendar year (e.g. July, June–August) and are useful in characterising antecedent conditions (e.g. drought; Westerling *et al*. 2003) and generalising conditions during fire season. However, such data are ill-suited to capture higher-frequency features such as the timing of precipitation and fluctuations in temperature and humidity, as well as critical weather situations (e.g. heat waves, dry cold fronts, dry lightning), all of which have an influence on fire ignition and subsequent fire behaviour (Bessie and Johnson 1995).

A qualitative and quantitative understanding of the influence of higher-frequency meteorological data and low-frequency climate data can be used to improve model predictions of area

10.1071/WF10046 1049-8001/11/040479

burned and aid in operational fire management planning. Fire managers utilise predictions of area burned to inform annual operations (i.e. suppression efforts) and to develop long-term management plans that cover multiple decades. In Alaska and across the circumpolar boreal forest, land managers are also developing long-term management plans for the region's vast carbon stocks, which are at risk of converting from a sink to a source (Balshi *et al*. 2009*b*) in response to projected changes in climate (Flannigan *et al*. 2005; Balshi *et al*. 2009*a*).

Here, we use a coupled approach that incorporates both low-frequency climate information and high-frequency weather information to examine the relative importance of climate and weather on wildfire growth for 665 wildfires in interior Alaska from 1980 to 2007. Specifically, we examined the role of spatially explicit (1) antecedent climate, (2) antecedent meteorological conditions, and (3) post-ignition meteorological conditions as determinants of fire growth.

Data and methods

One of the major hurdles in scientific studies at high latitudes is the paucity of data. The sparseness of long-term, high-quality meteorological instrumentation across Alaska has precluded a spatially explicit analysis of meteorological influences on Alaskan wildfire. Duffy *et al*. (2005) utilised monthly climate aggregates from seven climate stations to assess annual area burned as a product of spatially homogeneous, or large-scale, monthly climatic variability over the Alaskan interior (e.g. monthly precipitation region-wide wetter than normal). Analyses show that climate variables (e.g. temperature, precipitation) exhibit distinct regional-scale patterns that arise in response to the coupling of atmospheric and physiographic processes (e.g. Abatzoglou *et al.* 2009). A macroscale view of climate data overlooks regional-scale variations that may be important in understanding the influence of meteorology across a spectrum of timescales on wildfire ignition, growth and eventual fire size. Given the dominant influence of large wildfires in determining annual area burned, it is of particular interest in understanding processes that enable and drive growth of the largest fires.

Gridded meteorological data

To circumvent the described limitations, we derived a fine-scale, spatially and temporally consistent gridded dataset that covers the Alaskan interior at a daily resolution by integrating desirable attributes of three existing datasets, including:

1. Monthly climatological normals for the period 1961–90 from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) that account for fine-scale (2-km) geographic controls on precipitation and temperature (Daly *et al.* 1994).
2. Monthly precipitation and temperature data from Arctic RIMS (Rapid Integrated Monitoring System, http://rims.unh.edu/data/data.cgi, accessed 12 April 2011) that account for monthly variability as well as the inherent bias between the period of calculated normals in PRISM (1961–90) and that of the period of interest (1980–2007). This dataset was developed by interpolating monthly station observations from the Global Historical Climatology Network version 2 dataset (Peterson and Vose 1997) including 13 long-term climate stations within the study area and numerous stations in adjacent portions of Alaska and Canada. Anomalies of monthly temperature (°C) and precipitation (percentages of normal) from the Arctic RIMS data (native resolution 25 km) were interpolated to 2-km resolution, then respectively added to and multiplied by static climatological normals of the PRISM dataset to create a continuous monthly dataset for the 1980–2007 study period (hereafter referred to as the PRISM-RIMS dataset).
3. Daily temperature, precipitation, wind speed and relative humidity from the North American Regional Reanalysis (NARR) (Mesinger *et al.* 2006) at 32-km horizontal resolution accounted for sub-monthly timescales. NARR was interpolated to the 2-km-resolution grid of the PRISM-RIMS dataset. Estimates of daily relative humidity (maximum and minimum) and wind speed (1300 hours local time, derived from 3-hourly output) were taken directly from NARR, whereas daily temperatures (maximum and minimum) and precipitation were developed using Eqns 1 and 2:

$$T(x,y,m,d) = T_N(x,y,m,d) + T_{PR}(x,y,m) \qquad (1)$$

$$P(x,y,m,d) = \left[\frac{P_N(x,y,m,d)}{\sum\limits_{d=1}^{nd} P_N(x,y,m,d)} \right] \times P_{PR}(x,y,m) \qquad (2)$$

where x, y, m and d represent the longitudinal and latitudinal coordinates, the month and the day respectively. Daily temperature data from NARR (T_N in Eqn 1), defined as the daily deviation from the monthly NARR data, are additive to the monthly PRISM-RIMS data (denoted by T_{PR} in Eqn 1). Daily precipitation data from NARR (P_N) is defined as the percentage of monthly precipitation from NARR that falls on each day multiplied by the monthly PRISM-RIMS data (P_{PR}).

The derived dataset was validated using independent data from 36 remote automated weather stations (RAWS) during the warm season (May–September). Strong correlations (mean $r = 0.9$) were noted for daily maximum temperature, whereas relationships were weaker (mean $r = 0.4$, using the square root of precipitation to reduce skewness) for precipitation (Fig. 1*a*, *b*). Lower correlations for precipitation can be attributed to (i) representativeness of RAWS of the surrounding area; (ii) quality control issues of RAWS precipitation observations; (iii) inadequacies or inaccuracies in the derived dataset in tracking daily precipitation at sub-synoptic (<100 km) scales; and (iv) the intrinsic challenges in capturing the magnitude and location of localised convective precipitation. We found that by aggregating daily precipitation across a regional group of stations (and co-located pixels) at spatial scales of 100–300 km in an effort to reduce noise associated with the aforementioned factors, precipitation timing and amounts were well captured in the derived dataset (e.g. Fig. 1*c* considers six stations in the south-eastern Tanana Valley). We conclude that, although the derived dataset may not fully represent localised convection,

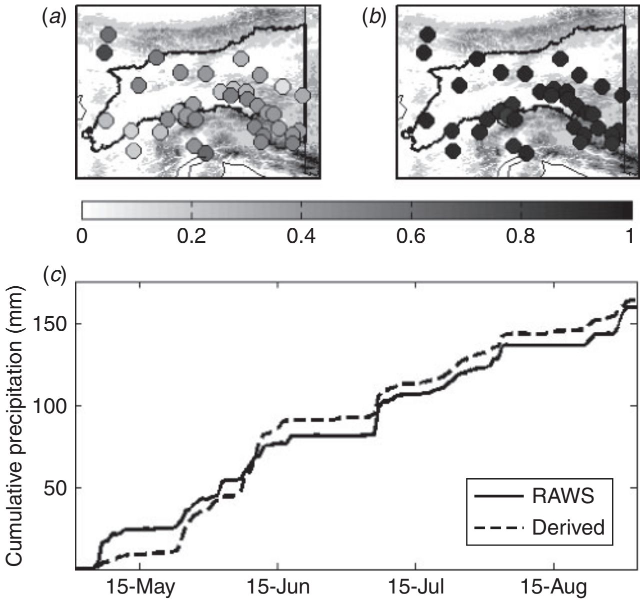

Fig. 1. Correlation of (*a*) daily precipitation (square root of precipitation), and (*b*) daily maximum temperature between remote automated weather stations (RAWS) and co-located gridded data. Observations from RAWS are for the time period 1997–2006 covering the May–August time period. The boundary of the Yukon River Basin study area is outlined in bold. (*c*) Cumulative precipitation averaged over six RAWS stations located in the south-eastern portion of the Tanana Valley (east of 145°W, south of 63°N) (solid) and co-located derived data (dashed) for May–August 2005.

it is adept at tracking widespread convection and synoptic-bearing precipitation events that are of importance in modifying regional fire activity.

Wildfire database

Previous assessments of Alaskan wildfire activity have utilised the Alaska Large Fire Database (ALFD, http://fire.ak.blm.gov/incinfo/aklgfire.php, accessed 30 September 2008) that spans seven decades (Kasischke *et al*. 2002). The ALFD, however, is incomplete before the 1980s owing to lost records and a non-standardised reporting system (Kasischke *et al*. 2002; P. Martin, pers. comm., October 2008); thus, we restricted our assessment to the post-1980 period. Wildfire perimeters were obtained from the ALFD (http://fire.ak.blm.gov/incinfo/aklgfire.php) for the Alaskan interior boreal forest study area, as defined by the boreal forest ecotype (Nowacki *et al*. 2001) within the Yukon River Basin (boundary shown in Fig. 1*a*, *b*). Our analysis was restricted to wildfires occurring between 1980 and 2007, and to fires ignited during the primary wildfire season (June–August) as reflected by the ignition date in the ALFD (i.e. the date the wildfire was first reported). Although wildfires occur outside of the primary fire season, prior analyses suggest that most early-season wildfires are human-caused, are managed (i.e. suppressed), and are not conducive to becoming large wildfires (DeWilde and Chapin 2006).

The largest wildfires in the ALFD account for most of the area burned across the Alaskan interior, with the largest 25% of fires in the ALFD dataset totalling ~85% of the area burned. The largest fires have a considerable effect on shaping the successional composition of the interior (Chapin *et al*. 2006) and occur primarily during years of increased fire activity (e.g. 2004). As a single large wildfire disturbance has more significant effects than several smaller disturbances (Turner *et al*. 1998), it is of interest to determine the atmospheric processes that foster wildfire growth and enable large fires. To accomplish this, we selected a subsample of 166 large fires (>13 000 ha), defined by the upper quartile of the ALFD dataset, and a subsample of 166 small fires (<1200 ha), defined by the lower quartile of the ALFD dataset.

Methods

Monthly climate (temperature (maximum and minimum) and precipitation) and daily weather (temperature (maximum and minimum), precipitation, relative humidity (maximum and minimum), and wind speed) datasets were spatially aggregated over all pixels that intersected or were contained within the perimeter of each fire. Geographically and temporally explicit values were assigned for each individual fire to account for spatial climatic variability as well as the temporal variability of fire ignition dates within a season. The individual fire approach differs from previous efforts that examined the collective influence of climate on total area burned (all fires inclusive) in a year (e.g. Duffy *et al*. 2005).

For each fire, we examined monthly temperature and precipitation data (both as raw variables and as anomalies from climatological normals (1980–2007, period of record)) for 21 months leading up to and including the summer of ignition (e.g. for a June 1991 fire, monthly climate data from January 1990 through September 1991 were examined). At daily time scales, meteorological variables for each fire were examined for a 181-day period relative to the ignition date, encompassing 90 days before and 90 days following the ignition date. These daily weather streams were also used to calculate the Duff Moisture Code (DMC) using the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner 1987). The DMC is a numerical means for assessing fire danger and is a proxy for fuel consumption in loosely compacted duff layers.

In addition to daily meteorological information, we addressed the influence of precipitation timing, as previous studies in Canadian boreal ecosystems (e.g. Flannigan and Harrington 1988) have shown the timing of precipitation, rather than the amount, to be a critical determinant of wildfire growth. Two different precipitation thresholds were evaluated: a 2-mm threshold and a 12.7-mm threshold. The former threshold stems from the amount of precipitation a closed canopy will absorb on a given day (1.5 mm) before any additional moisture becomes available to moisten the duff layer (Van Wagner 1987). The latter stems from guidelines describing the conditions that inhibit the spread of a fire, also called a ‘fire-slowing event’ (Alaska Fire Service Fire Ending Event Workshop, Fairbanks, AK, January, 2008). These conditions include at least 12.7 mm (0.5″) of precipitation over a 5-day period with precipitation duration (determined here from 3-hourly NARR data) of at least 25 h, indicative of widespread precipitation, as opposed to localised, convective precipitation.

To determine the relative influence of antecedent climate and meteorological conditions as well as post-ignition

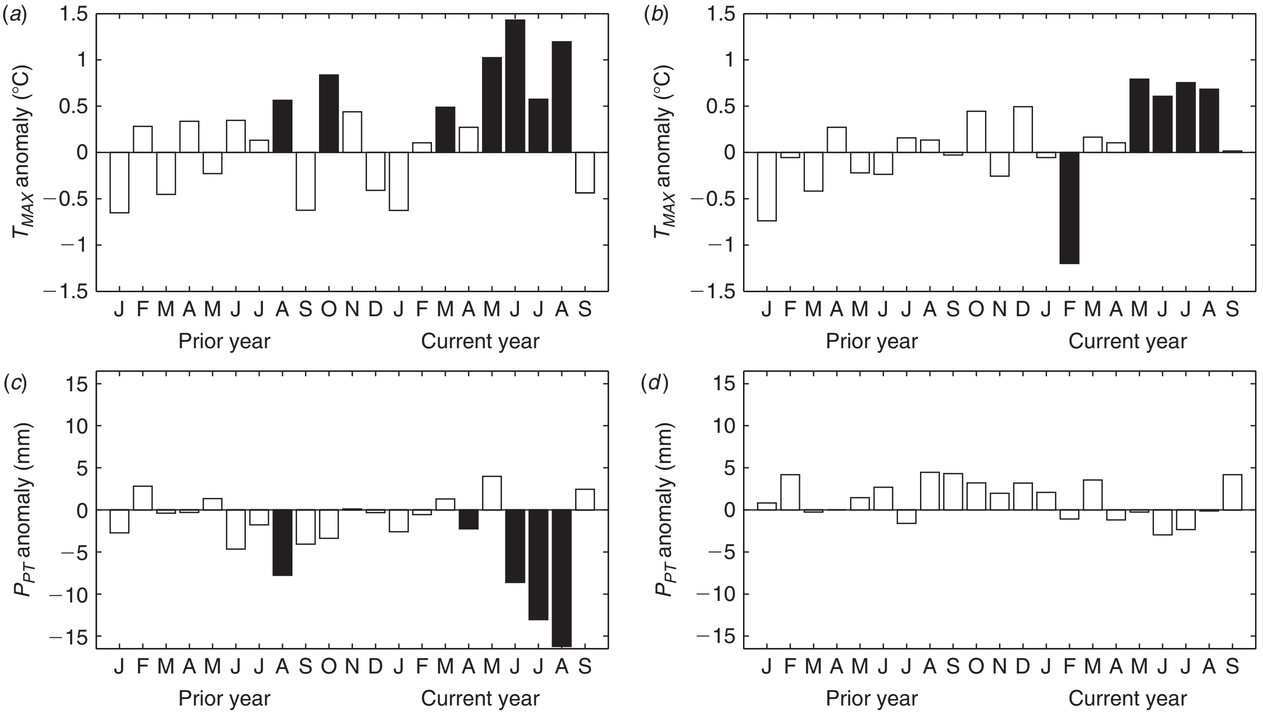

Fig. 2. Composite monthly climate anomalies for large fires >13 000 ha (left) and small fires <1200 ha (right) for temperature (T_{MAX}) (top) and precipitation (P_{PT}) (bottom). Anomalies are taken with respect to the 1980–2007 period. Black bars denote statistical significance at the 99% confidence interval.

meteorological conditions on wildfire growth, we used correlation and regression analyses and composite analysis. Correlation and linear regression were performed between the response variables (area burned and log area burned) and the climate and meteorological predictor variables. A composite analysis was performed to compare differences in low-frequency climate and higher-frequency weather conditions between small wildfires (<1200 ha) and large wildfires (>13 000 ha). Statistical significance was assessed using a *t*-test at the 99% confidence interval. Finally, we examined daily 500-hPa geopotential height fields from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis to elucidate the influence of the large-scale atmospheric circulation regimes (e.g. blocking) on wildfire growth.

Results

Composite analysis suggests that the antecedent influence of climate on wildfire is limited to temperature 1–2 months before the fire season (Fig. 2). Positive temperature anomalies in May and during the fire season from June through August were observed for both large and small wildfire classes. Correlation between the logarithm of area burned and monthly climate shows that June temperature the year of the fire is the strongest predictor of area burned per fire ($r = 0.24$), in agreement with Duffy *et al.* (2005). However, composite June temperature anomalies between small and large fire classes reveal no significant differences, suggesting that although above-average temperatures enable wildfires, they do not appear to sufficiently factor into whether the fire stays small or becomes large.

No discernible antecedent climate signal was observed for precipitation between small and large fire classes. However, large fires were associated with strong negative precipitation anomalies during June, July and August (JJA) the year of the fire, whereas negligible JJA precipitation anomalies were observed for small fires. This indicates that below-average precipitation during the fire season contributes to the potential for large fire growth rather than antecedent moisture anomalies. This contrasts with relationships found in the western United States that suggest antecedent seasonal moisture deficits contribute to the potential for large fires (e.g. Westerling *et al.* 2003). In most of the western USA, however, the primary wet season occurs during the winter and spring seasons before the summer fire season, whereas in the Alaskan interior, winter and spring are typically relatively dry (20–30% of the annual precipitation falls across the interior between the months of December and May) and moisture is generally unavailable to vegetation and duff owing to sub-freezing temperatures until snowmelt occurs in spring, where it may modify early-season fire potential. The July–August overlap between the primary fire season (June–August) and the primary wet season (July–September; Shulski and Wendler 2007) points to the importance of the arrival of in-season precipitation (i.e. shift in the timing and magnitude of the wet season) as a primary determinant of fire size.

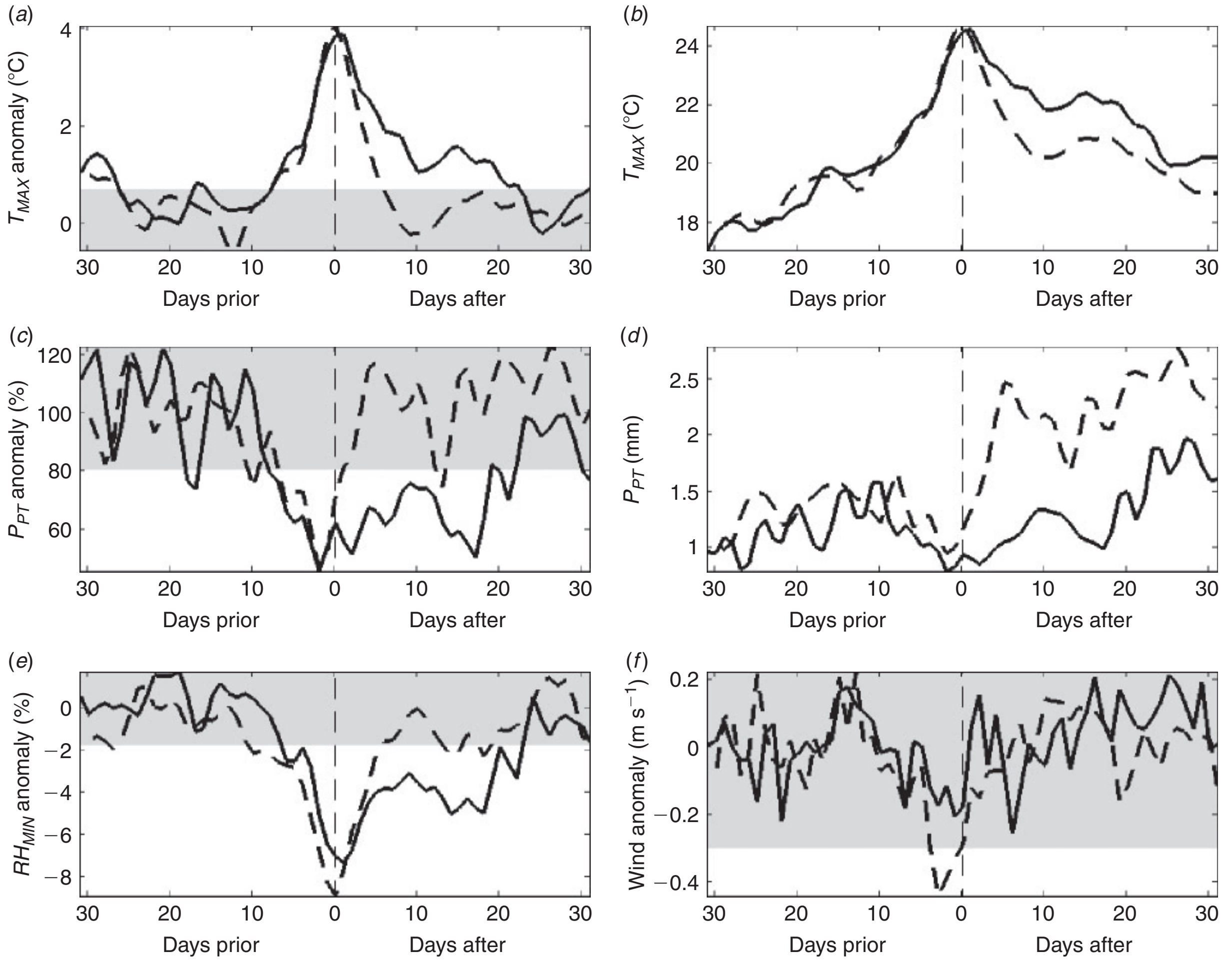

Fig. 3. Composite daily meteorological variables for small fires <1200 ha (dashed) and large fires >13 000 ha (solid) relative to ignition date. Composites of daily maximum temperature anomalies (T_{MAX}) and raw values are shown in (*a*) and (*b*) respectively, whereas composite daily precipitation (P_{PT}) anomalies (expressed as a percentage of normal) and raw values are shown in (*c*) and (*d*) respectively. Daily minimum relative humidity anomalies (RH_{MIN}) and wind speed anomalies are shown in (*e*) and (*f*) respectively. Values plotted outside of the grey shading in anomaly plots are considered to be statistically significant at the 99% confidence level.

Similarly to antecedent climate, results suggest no significant difference between antecedent meteorological conditions for large and small fire classes. Significant anomalies 7–10 days before the ignition date, characterised by above-normal temperatures and below-normal relative humidity and precipitation were seen for both small and large fires (Fig. 3). These findings suggest that short-term sub-monthly moisture deficits are significant enough to cure the duff layer for ignition potential, in agreement with other studies in boreal ecosystems (e.g. Nash and Johnson 1996; Wotton 2009), and highlight the importance of atmospheric processes at sub-monthly timescales on wildfire ignition in Alaska.

In contrast to the similarity between antecedent conditions associated with large and small fires, significant differences were observed between post-ignition conditions. For small fires, the warm and dry conditions favourable for fire ignition and growth present before the ignition date typically dissipated within a week following ignition as mean daily precipitation totals surpassed 1.5 mm, resulting in increased duff moisture (Fig. 3). For large fires, antecedent conditions that enabled ignition potential continued, on average, nearly 3 weeks following the ignition date. The lack of daily mean precipitation totals exceeding 1.5 mm following ignition for large fires reduces or maintains the duff moisture. Collectively, the multiweek moisture deficit associated with large fires allows DMC values to increase post ignition, thereby sustaining extreme fire danger and enabling fire growth, whereas DMC values for small fires rapidly decline with the return to climatological normals within a week following ignition (Fig. 4).

These results suggest that the DMC and timing of precipitation post ignition play a strong role in determining fire size. Average antecedent curing times (number of days before ignition date without crossing a precipitation threshold) for both the 2-mm and the fire-slowing event thresholds were not significantly different between large and small fires. However, additional curing periods post ignition clearly delineated the two fire classes. On average, a daily precipitation total of greater than 2 mm occurred only 5 days after ignition for small fires, whereas the dry spell extended nearly 10 days after ignition for large fires (Fig. 5*a*). Likewise, a fire-slowing event was typically observed within 10 days after ignition for small fires, compared with nearly 25 days for large fires (Fig. 5*b*). These results illustrate that prolonged dry spells and periods without significant widespread precipitation strongly favour fire growth and large wildfire potential.

To investigate the connection between prolonged dry spells and large-scale atmospheric circulation, we examined 500-hPa geopotential height fields. We constrained our focus to occurrences of widespread fire ignitions, identified by multiple ignitions within the study area over a 5-day period under the condition that fires were either all small fires or all large fires. Composite 500-hPa geopotential height fields for the 10 multiple large-fire starts and 10 multiple small-fire starts show a blocking pattern over interior Alaska the week before the onset of ignition (Fig. 6*a*, *b*). Blocking and large-scale subsidence act in concert to promote warm, dry conditions, inhibit convective precipitation and result in a rapid depletion of fuel moisture that allows for conditions conducive to large wildfire potential (e.g. Johnson and Wowchuk 1993; Skinner *et al*. 1999). Composite 500-hPa geopotential height 8 to 14 days following ignitions of small fires shows a breakdown in the ridge (Fig. 6*d*), whereas the blocking pattern persists up to 2 weeks following ignition for large fires (Fig. 6*c*). The inability of synoptic systems to penetrate the blocking ridge inhibits the onset of widespread precipitation that typically provides sufficient precipitation (>2 mm) to wet fuels enough to retard or inhibit fire ignition potential and growth. We reinforced these findings by estimating the blocking frequency (Tibaldi and Molteni 1990) over interior Alaska using the entire set of small and large fire classes. For small fires, blocking frequency rapidly decreased to climatology (5%) a week following ignition, whereas for large fires, blocking frequency remained close to 25% up to 2 weeks following ignition (not shown).

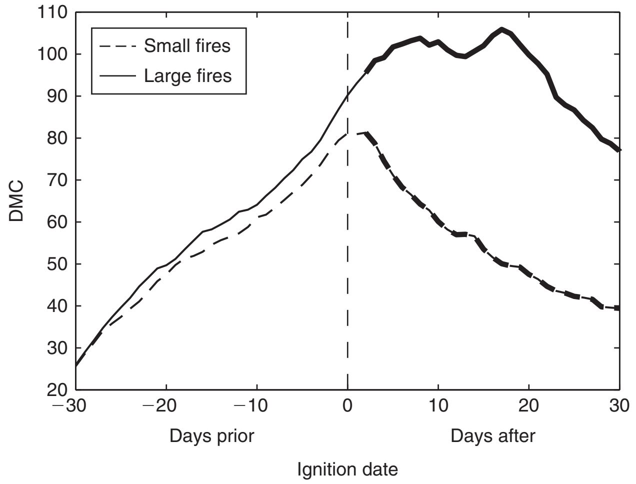

Fig. 4. Composite daily Drought Moisture Code (DMC) for small fires <1200 ha (dashed) and large fires >13 000 ha (solid) relative to ignition date. Bold lines show statistically significant differences at the 99% confidence level.

Discussion and conclusions

Previous studies (e.g. Duffy *et al*. 2005) have shown a strong relationship between antecedent and in-season temperature and area burned in Alaska. Results from the present study support these findings to the effect that wildfires in the ALFD occur preferentially during years with anomalously warm May–August temperatures. However, our results suggest that antecedent conditions have negligible influence in determining the growth and eventual area burned by individual wildfires (e.g. Figs 2, 3), and thus our findings can be considered complementary to the findings of Duffy *et al*. (2005). Although antecedent conditions were not found to be an important factor for fire growth, they may be important in other processes behind seasonal fire activity. We hypothesise that anomalously warm conditions in May–June act either to exacerbate snowmelt and the seasonal drying of fine fuels (e.g. grasses) and the duff layer, thus increasing ignition efficiency (e.g. Jandt *et al*. 2005), or to decrease atmospheric stability and provide conditions conducive to increased lightning ignitions.

Although the influence of antecedent conditions on fire size was shown to be negligible, post-ignition weather conditions were shown to differentiate between large and small fires. Large

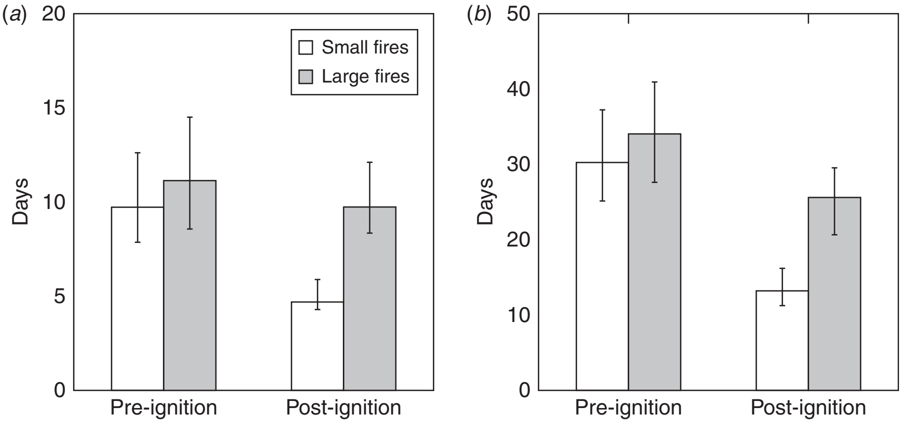

Fig. 5. Mean curing time for (*a*) a day with at least 2 mm of precipitation, and (*b*) a fire-slowing event, before and following fire ignition for small and large fires. Error bars denote the 99% confidence interval.

fires were enabled by prolonged warm and dry periods that endured several weeks following ignition as a consequence of persistent large-scale blocking, whereas sufficient precipitation to reduce fire growth typically occurred within a week after ignition in the case of small fires. These results suggest that the frequency and timing of significant precipitation events, rather than monthly temperature or monthly precipitation amount, are critical determinants of large wildfires in Alaska. For example, the third largest wildfire season on record occurred in 2005 (1.8 million ha burned) in Alaska and was marked by an anomalously wet period in July across the interior. Extended dry periods in June and again from late July into August allowed for two windows of large wildfire growth (with 32 fires in the large-fire class). By contrast, an anomalously warm April–August in 2007 (the second warmest on record behind 2004) only produced a single fire in the large fire class owing to frequent widespread precipitation throughout the fire season.

From an operational perspective, our results suggest that in-season weather, particularly prolonged dry spells, is critically important in determining the fire growth in Alaska. These findings support the active monitoring of fire danger indices in conjunction with short-range, deterministic weather forecasts and ensemble medium-range forecasts by operational fire management. Recent efforts have focussed on using antecedent climate information for long-range forecasting of fire season. Although processes may link antecedent conditions to other factors involved with fire activity, predictive linkages between the memory in the climate system (i.e. sea-surface temperatures, sea ice, land surface conditions) and conditions favourable to fire growth (e.g. blocking) remain elusive. Additional processed-based understanding of the timing and susceptibility of the fuel matrix to ignition, and mechanisms responsible for widespread lightning are needed to fully understand the combination of factors that contribute to seasonal fire activity in Alaska.

Likewise, much effort has been made to project future area burned using global climate model (GCM) projections. Although an increase in the frequency of large-fire seasons has been observed over the last couple decades concurrent with increases in temperature over Alaska, our results suggest that extrapolation on the basis of projected warming might fail to account for the processes involved in fire ignition and growth. A comprehensive approach to predicting future wildfire potential in Alaska should attempt to account for factors that contribute to ignition potential (e.g. critical DMC indices), ignitions (lightning- and human-caused) and fire growth in addition to the dynamic vegetation response to climate change and a host of climate-change-assisted disturbance mechanisms (e.g. fire, insects). The prior three factors suggest the need to incorporate high-frequency meteorological conditions into modelling considerations that might be otherwise muted in approaches that only use monthly data. Furthermore, models based on historic relationships relative to fixed calendar days also build in an assumed stationarity of the timing of fire season. To illustrate this point, an ensemble of GCMs forced by a moderate emissions scenario suggest a slight (10%) reduction in the longest dry spell (daily total precipitation <2 mm) over the Alaska interior by the mid-21st century for present-day fire season (June–August), thereby limiting large fire growth potential. However, an earlier snowmelt and increase in early season moisture deficit due to warming may partially offset the effect of increased precipitation on DMC and increase the availability of fuels to ignition earlier in the year. Such conditions may promote an advancement of primary fire season into a climatologically drier time of the year that might result in longer dry spells and windows conducive to large fire growth.

The complex influence of weather and climate on wildfire provides considerable challenges to projecting current and future wildfire regimes not only in Alaska, but globally. Our

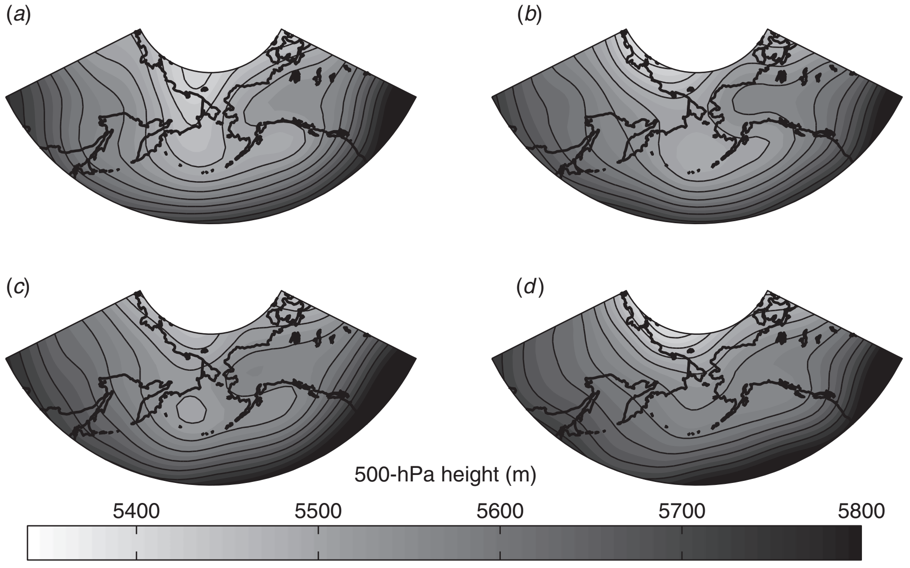

Fig. 6. Composite 500-hPa geopotential height averaged over the 7 days prior to ignition dates for (*a*) multiple large fires and (*b*) multiple small fires, and averaged 7–14 days following ignition dates for (*c*) large fires, and (*d*) small fires. Solid isoheights are plotted every 40 m starting at 5360 m.

findings, however, indicate that incorporating this complexity is necessary to produce the most accurate projections of fire activity, both for operational fire management and for the global research community in developing models of carbon emissions.

Acknowledgements

The authors thank the two anonymous reviewers and the associate editor for their valuable constructive feedback. This research was supported by the National Science Foundation Idaho Experimental Program to Stimulate Competitive Research (EPSCoR) and by the National Science Foundation under award number EPS-0814387.

References

Abatzoglou JT, Redmond KT, Edwards LM (2009) Classification of regional climate variability in the state of California. *Journal of Applied Meteorology and Climatology* **48**(8), 1527–1541. doi:10.1175/2009JAMC2062.1

Balshi MS, McGuire AD, Duffy PA, Flannigan MD, Walsh J, Melillo J (2009*a*) Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. *Global Change Biology* **15**(3), 578–600. doi:10.1111/J.1365-2486.2008.01679.X

Balshi MS, McGuire AD, Duffy PA, Flannigan MD, Kicklighter DW, Melillo J (2009*b*) Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. *Global Change Biology* **15**, 1491–1510. doi:10.1111/J.1365-2486.2009.01877.X

Bessie WC, Johnson EA (1995) The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* **76**, 747–762. doi:10.2307/1939341

Chapin FS, Oswod MW, Van Cleve K, Viereck LA, Verbyla DL (Eds) (2006) 'Alaska's Changing Boreal Forest.' (Oxford University Press: New York)

Chapin FS, III, Trainor S, Huntington O, Lovecraft A, Zavaleta E, Natcher D, McGuire AD, Nelson J, Ray L, Calef M, Fresco N, Huntington H, Rupp TS, DeWilde L, Naylor R (2008) Increasing wildfire in Alaska's boreal forest: pathways to potential solutions of a wicked problem. *BioScience* **58**(6), 531–540. doi:10.1641/B580609

Daly C, Neilson RP, Phillips DL (1994) A statistical–topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology* **33**, 140–158. doi:10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2

DeWilde L, Chapin FS, III (2006) Human impacts on the fire regime of interior Alaska: interactions among fuels, ignition sources, and fire suppression. *Ecosystems* **9**, 1342–1353. doi:10.1007/S10021-006-0095-0

Duffy PA, Walsh JE, Graham JM, Mann DH, Rupp TS (2005) Impacts of large-scale atmospheric–ocean variability on Alaskan fire season severity. *Ecological Applications* **15**, 1317–1330. doi:10.1890/04-0739

Flannigan MD, Harrington JB (1988) A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80). *Journal of Applied Meteorology* **27**, 441–452. doi:10.1175/1520-0450(1988)027<0441:ASOTRO>2.0.CO;2

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2005) Future area burned in Canada. *Climatic Change* **72**, 1–16. doi:10.1007/S10584-005-5935-Y

IPCC (2007) 'Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.' (Eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller) (Cambridge University Press: Cambridge, UK, and New York)

Jandt RR, Allen JA, Horschel EA (2005) Forest floor moisture content and fire danger indices in Alaska. Bureau of Land Management, Technical Report 54. (Fairbanks, AK)

Johnson EA, Wowchuk DR (1993) Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Canadian Journal of Forest Research* **23**, 1213–1222. doi:10.1139/X93-153

Kasischke ES, Turetsky MR (2006) Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters* **33**, L09703. doi:10.1029/2006GL025677

Kasischke ES, Williams D, Barry D (2002) Analysis of the patterns of large fires in the boreal forest region of Alaska. *International Journal of Wildland Fire* **11**(2), 131–144. doi:10.1071/WF02023

Mesinger F, DiMego G, Kalnay E, Mitchell K, Shafran PC, Ebisuzaki W, Jovic D, Woollen J, Rogers E, Berbery EH, Ek MB, Fan Y, Grumbine R, Higgins W, Li H, Lin Y, Manikin G, Parrish D, Shi W (2006) North American regional reanalysis. *Bulletin of the American Meteorological Society* **87**, 343–360. doi:10.1175/BAMS-87-3-343

Nash CH, Johnson EA (1996) Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. *Canadian Journal of Forest Research* **26**, 1859–1874. doi:10.1139/X26-211

Nowacki G, Spencer P, Brock T, Fleming M, Jorgenson T (2001) Ecoregions of Alaska and neighboring territory. (US Geological Survey Data Publication: Reston, VA) Available at http://agdc.usgs.gov/data/projects/fhm/ [Verified 25 August 2010]

Peterson TC, Vose RS (1997) An overview of the Global Historical Climatology Network temperature database. *Bulletin of the American Meteorological Society* **78**, 2837–2849. doi:10.1175/1520-0477(1997)078<2837:AOOTGH>2.0.CO;2

Shulski M, Wendler G (2007) 'The Climate of Alaska.' (University of Alaska Press: Fairbanks, AK)

Shulski M, Wendler G, Alden S, Larkin N (2005) Alaska's exceptional 2004 fire season. In 'Proceedings: Sixth Fire and Forest Meteorology Symposium', October 2005, Canmore, Canada. Available at http://ams.confex.com/ams/pdfpapers/97633.pdf [Verified 26 April 2011]

Skinner WR, Stocks BJ, Martell DL, Bonsal B, Shabbar A (1999) The association between circulation anomalies in the midtroposphere and area burned by wildland fire in Canada. *Theoretical and Applied Climatology* **63**, 89–105. doi:10.1007/S007040050095

Tibaldi S, Molteni F (1990) On the operational predictability of blocking. *Tellus* **42A**, 343–365.

Turner MG, Baker WL, Peterson CJ, Peet RK (1998) Factors influencing succession: lessons learned from large, infrequent natural disturbances. *Ecosystems* **1**, 511–523. doi:10.1007/S100219900047

Van Wagner CE (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technical Report 35. (Ottawa, ON)

Westerling AL, Brown TJ, Gershunov A, Cayan DR, Dettinger MD (2003) Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society* **84**(5), 595–604. doi:10.1175/BAMS-84-5-595

Wotton BM (2009) Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environmental and Ecological Statistics* **16**(2), 107. doi:10.1007/S10651-007-0084-2

Manuscript received 27 April 2010, accepted 29 September 2010