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Updated guidance for the drought code overwintering adjustment

by Chelene Hanes and Mike Wotton

Drought triggers and sustains overnight fires in North America

by Kaiwei Luo, Xianli Wang, Mark de Jong, and Mike Flannigan

Photo: Two stacked clouds illuminated by the glow of an overnight firestorm around Adams Lake, British Columbia, in August 2023, during a record-breaking fire season in Canada. provided by Amir Paz.

Updated guidance for the Drought Code overwintering adjustment

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2023 was the worst fire season in recorded history in Canada. One of the contributing factors to this epic year was widespread drought throughout the country. In Canada, the primary measure of seasonal and season-to-season drought is the Drought Code (DC). The DC is one of three soil moisture codes within the Fire Weather Index (FWI) System. Within wildfire operations, the DC is primarily used to indicate when extended suppression effort may be needed due to burning in deeper, denser fuels; fuels that, once dry, can sustain deep and prolonged burning and connect parts of the landscape that previously may have provided fuel breaks.

Drought conditions that influenced the 2023 fire season appear to be persisting into 2024 for some regions. What little snow has accumulated is melting rapidly, prompting an early start to the fire season in some provinces. These dry, deep organic layers are also contributing to the number of holdover fires in BC, NWT, and AB. These dry conditions are cause for concern and are warranting many questions regarding start-up values for the FWI System.

The rate of drying in the heavy fuels tracked by the DC is quite slow (its drying timelag is almost two months); therefore, it functions as the long-term memory of the FWI System. Simple procedures were developed in the 1970s to overwinter the DC, allowing the carry-over of drought conditions from one season into the next when conditions warranted. In recent years, the overwinter adjustment has been applied more frequently in western regions of the country. This operational decision is based on the assumption that if regions received more than 200 mm of overwinter precipitation this was enough to fully recharge any fall moisture deficits to saturation in the spring. The 200 mm threshold is based on the original moisture capacity of the Soil Moisture Index, from which the DC was derived (Turner, 1972). The overwintering adjustment has been calculated more often in regions that typically receive less than this threshold.

In contrast, eastern provinces typically follow the assumption noted by Van Wagner (1987) “Experience so far is that an overwinter adjustment is almost never necessary in eastern Canada”. This assumption has led to little organizational knowledge on how to apply the adjustment when needed. Many regions in the east typically receive overwinter precipitation amounts much greater than 200 mm, so the assumption is any deficit will likely be recharged. But as the climate is changing, the experience from the late 1970s and early 1980s may need to be updated. By assuming that one must always overwinter or never overwinter, bias is being introduced into the DC calculations (Hanes, 2022). Agencies or regions that always overwinter may be introducing a dry bias, and those that never overwinter a wet bias. The intent of this research note is to help reduce some of that bias and provide updates on the current state of knowledge regarding overwintering the DC.

The Overwinter Adjustment circa 1978

The overwintering procedures set by Turner and Lawson (1978) are as follows (see adjacent text box for a history of this calculation). In a normal year, assuming sufficient precipitation occurred over the winter and drought conditions did not exist the previous fall, the default spring DC (DC_s) starting value is 15. The starting value of 15 is used because the FWI System calculations start three days after snowmelt. It is assumed some drying occurred over those three days; therefore, the DC starts just below saturation. In contrast, if drought conditions are suspected in the spring, the mathematical procedure to overwinter the DC is applied. This procedure is a rough approximation of the mechanisms affecting winter and spring moisture transfer from evaporation, sublimation, discharge, and percolation (Turner & Lawson, 1978; Van Wagner, 1987). The standard adjustment has four inputs: 1) the DC value of the last day of FWI System calculation from the previous fall (DC_f); 2) the total precipitation (in mm) between that date and the start of FWI System calculations in the spring (P_{ow} (Overwinter Precipitation in mm)); 3) the carry-over fraction of the fall moisture deficit (a: 1.00, 0.75, or 0.50); and, 4) an estimate of the fraction of winter precipitation effective at recharging depleted moisture reserves in spring (b: 0.50, 0.75, or 0.90) (Turner & Lawson 1978). Fire managers estimate the last two inputs, and the adjustment is applied when P_{ow} is less than 200 mm. The adjustment takes the following form:

DC Overwintering History

- The DC was developed from the Soil Moisture Index (SMI) (Turner, 1966, 1972)
- Overwintering the DC was originally discussed in Turner (1972)
- The percentage of overwinter precipitation contributing to spring moisture (i.e. (b) coefficient) was gauged at 0.4 to 0.75 based on adjustments to agricultural estimates for forests and to account for more permeable frost structure in forest stands
- Additional guidance was derived from drought conditions in Ontario in 1976 (Stocks, 1979)
- An official overwinter procedure was laid out in Turner and Lawson (1978)
- The SMI, and originally the DC, had a moisture capacity of 200 mm at saturation
- This is the basis for the 200 mm overwinter precipitation threshold
- Alexander (1982, 1983) provided further details for DC overwintering specific to prairie provinces and NWT
- In 1987, Van Wagner decreases the moisture capacity of the DC to 100 mm
- The overwinter adjustment is still based on a 200 mm storage capacity from the SMI
- Lawson and Armitage (2008) republished the overwinter guidance from Turner and Lawson (1978) with no changes

$$Q_s = a \cdot Q_f + b(3.94 \cdot P_{ow}) \qquad \text{Equation1}$$

Where Q_f = final fall moisture equivalent, and Q_s=starting spring moisture equivalent.

Q_f is calculated by:

$$Q_f = 800 \exp(-DC_f/400) \qquad \text{Equation 2}$$

The overwinter adjustment assumes that any error in the DC starting value will correct itself after substantial rain; otherwise, it can be carried through for much of the fire season (Van Wagner, 1985). Several days of heavy rain or equivalent snowmelt can reduce the DC to zero. If these precipitation events do not occur, the DC can be biased for most, if not all of the fire season (Hanes et al., 2023).

Updates to the Overwinter Adjustment

Fall DC and Station Shut-down

Based on the widescale use of automated weather stations, it is feasible and encouraged to run weather stations until the forest floor in a region has frozen. In areas with snow cover, the date of lasting snow accumulation on the ground is a reasonable surrogate for estimating this date. The arbitrary ending of DC calculations on a convenient calendar date (such as November 1) is no longer valid. If snow data is not available, or the region does not receive snowpack, the station DC calculations continue until the occurrence of three consecutive days of a maximum daily temperature below 5°C (Wotton & Flannigan, 1993). Measuring fire weather until these conditions are met eliminates the need to estimate the carry-over fraction of the fall moisture deficit (a); a is always 1 in this situation, removing a potential source of error on the front end of the overwinter calculation. If, for some reason, the agency weather station network does not calculate DC up to this date, it is recommended instead to calculate the DC until these conditions are met using an alternate weather stream, i.e. a nearby Environment and Climate Change Canada (ECCC) station, or reanalysis data from fine-scale numerical models.

When to apply the overwinter adjustment

While it is perhaps counter-intuitive, the total amount of overwinter precipitation has been found to be less important to spring fire activity than the Drought Code values at the end of the season (i.e. at freeze up) (Hanes et al., 2020). Less snow does not necessarily mean more fire, nor does it mean larger fires or more escape fires. If drought conditions do not exist in the fall, there is no drought to carry over. We assume the soils are frozen over the winter in most regions of Canada; therefore, reduced snowpack will not create drought conditions in saturated soils. Consequently, fall drought conditions should be driving the need to apply the overwinter adjustment, not snowpack. High DC values in the fall should signal potential drought the following spring, and overwinter conditions should be closely monitored, including the timing of snow melt and ground thaw.

Overwinter precipitation totals can be estimated using agency-installed pluvio gauges at fire weather stations, from nearby year-round ECCC weather stations, or from fine-scale gridded precipitation products such as the Canadian Precipitation Analysis (CaPA)[a].

Spring Startup and DC adjustment

Ultimately, DMC and DC calculations should be started after the forest floor has begun to thaw (and is therefore able to receive and lose moisture). In the operational implementation however, given that ground temperature is not routinely monitored, surrogates for this calculation starting point should be used. In snow-dominated regions where snow data is available, stations should start three days after snow melts in the open. This does not change from previous guidance (Turner & Lawson, 1978; Lawson & Armitage, 2008). If snow data is not available, or the region does not receive snowpack, the station should start after three consecutive days of maximum daily temperature above 12°C (Wotton & Flannigan 1993).

If DC values were close to saturation the previous fall (e.g. <50), there is no drought to carry over into the next spring. If fall DC values were elevated, the overwinter adjustment should be calculated using Equations 1 and 2 above, regardless of overwinter precipitation totals.

[a]https://eccc-msc.github.io/open-data/msc-data/nwp_rdpa/readme_rdpa-datamart_en/

Based on soil moisture monitoring datasets being collected as part of ongoing research at numerous locations in Ontario and Alberta (Hanes et al., 2023) and in British Columbia (BC)[b], we have identified that the range in effectiveness of winter precipitation in recharging moisture reserves in spring (*b*) is much more variable than previously thought (Table 1). This value can range from 0 to 1! That is, it is not limited to values 0.5 and above. We have calculated (*b*) using the fall moisture value at the time of snow accumulation or freeze-up and the spring moisture value at the time of soil thaw to estimate (*b*) based on the change in moisture[c].

b = (spring moisture – fall moisture)/ fall moisture   Equation 3

Preliminary analysis of overwinter conditions at various sites across the country suggests a relationship between the length of time between the date of snow melt and the date of soil thaw may influence the value of (b). This relationship appears to be dependent on local conditions. Still, generally-speaking, if soil thaw is close to the date of snowmelt, more meltwater is available to recharge the duff layers (see the example from Red Earth, AB in Figure 1; *note this relationship is regionally dependent and preliminary, therefore, should not be used for other locations*). The timing of snowmelt can be quite variable from year to year and region to region (e.g. ranging from March to May). The timing of soil thaw seems to be more consistent in these snow dominated regions, typically occurring in late April to mid-May. If snow melts weeks before the soil thaws, very little of that meltwater may end up as recharge. More data is needed to fully quantify this relationship, but it does make intuitive sense.

Table 1. Overwinter conditions for seven locations in BC, AB, and ON were set up with automated in-situ soil moisture and soil temperature probes. Data are listed only for years where the overwinter adjustment was calculated based on elevated fall DC values (DC_f). Snow data were from nearby Environment and Climate Change (ECCC) stations or on-site snow measurements, where available. DC values were from nearby fire weather stations (DC_s = calculated spring DC). Overwinter Precipitation (P_{ow}) was calculated from on-site year-round precipitation sensors, nearby ECCC stations, or from the Canadian Precipitation Analysis (CaPA). Soil thaw dates were from in-situ soil temperature sensors and (*b*) values were from in-situ soil moisture sensors.

Site	Data Range	Date of Snow accumulation	DC_f	Number of Days between Spring Snow Melt & Soil Thaw	P_{ow} (mm)	b	DC_s
Revelstoke, BC	2022-2023	2022-11-08	154	28	504	0.91	15
Houston, BC	2021-2022	2021-11-15	469	61	150	0.23	294
Smithers, BC	2021-2022	2021-11-11	182	7	222	0.05	149
Red Earth, AB	2017-2022	2017-11-02	400	23	250	0.75	15
		2018-11-04	298	43	151	0.29	148
		2019-11-25	111	29	132	0.37	15
		2020-11-05	124	38	152	0.11	83
		2021-11-09	496	31	180	0.27	257
		2022-11-02	319	24	117	0.86	24
Edson, AB	2019-2021	2019-09-27	107	10	136	0.00	107
		2020-10-16	322	0	81	0.20	256
		2021-11-01	473	6	83	0.22	369
Dryden, ON	2020-2023	2020-10-20	99	36	25	0.00	98
		2021-11-11	57	0	174	1.00	15
		2022-11-07	223	3	50	1.00	81
Chapleau, ON	2017-2023	2020-10-19	71	7	333	0	71
		2021-11-04	211	0	358	0.37	15

[b] Data for sites near Smithers and Houston locations in BC provided by Vanessa Foord, Research Climatologist, North Area, BC Ministry of Forests

[c] If the spring moisture estimate is less than the previous fall moisture estimate $b = 0$

Additional guidance on measuring (*b*) the recharge effectiveness, was provided in a previous newsletter (Hanes et al., 2022). This can be done with handheld soil moisture probes at the same location in the fall and spring, or by using in-situ automated moisture probes installed at stand-alone soil moisture and soil temperature stations or attached to a fire weather station. If no other information is available, estimating the recharge effectiveness, (*b*), to be 0.5 is a conservative good start. Based on current data, if field observation provides good confidence that surface snowmelt occurred well before ground thaw, then that starting value of (*b*) could be adjusted downward. If the observations from field personnel indicated that a significant amount of the snowpack melt occurred around the same date as ground thaw, then that value of (*b*) could be adjusted upward.

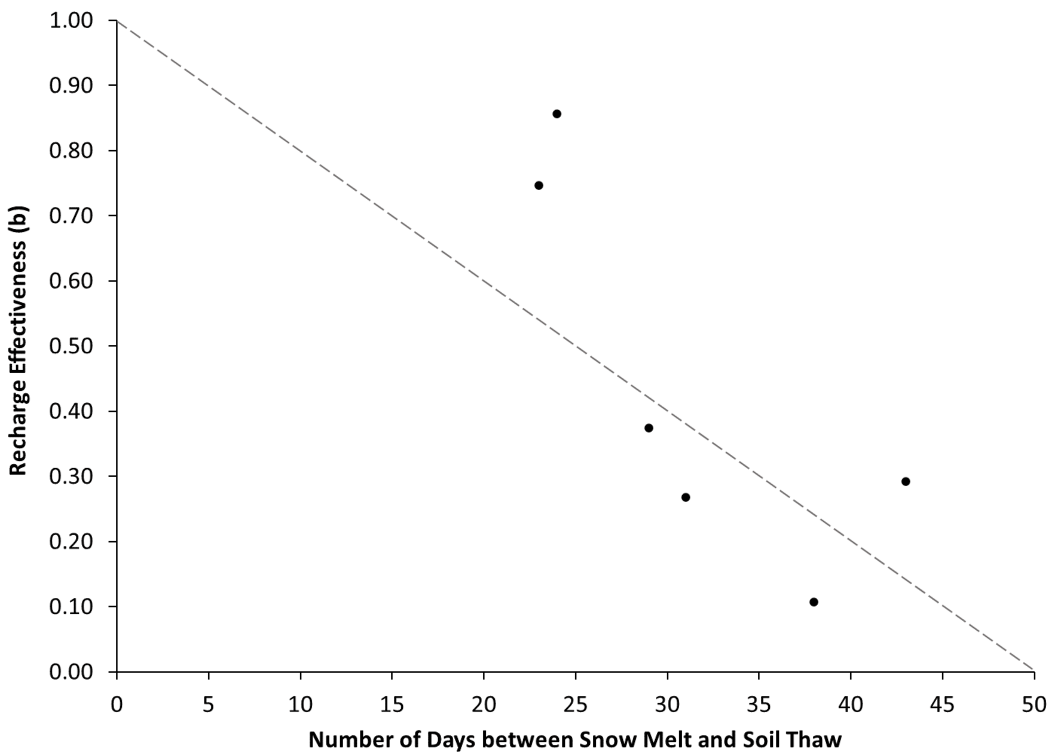

Figure 1. Example of the relationship between the recharge effectiveness (*b*) and number of days between snow melt and soil thaw at Red Earth, AB for overwinter periods 2017 - 2023. Dotted line is the 1:1 line.

Summary

The estimation of the overwinter adjustment to the DC is not a perfect science. When originally developed, it was a process that was thought to be required occasionally. Present conditions suggest it may be required more frequently, requiring a more robust procedure. The relationships between spring moisture, soil thaw, snowpack conditions, and overwinter precipitation are complicated and appear to vary regionally and annually. This makes development of a simple new adjustment difficult and requires significant data.

Remote sensing products of soil moisture are potentially good sources of information that can be used to identify areas that may be wetter or drier than other regions and to therefore compare uncertain overwintering assumptions (i.e. is this region still dry from last fall?). Current research indicates these products are not yet able to substitute for the DC in tracking deep organic layer moisture, or as surrogates to provide start-up values (Hanes et al., 2023). The absolute moisture content or change in moisture content of organic forest soils is different from mineral soils, which these remote sensing products have been validated and calibrated against. Organic soils are typically more porous, have different bulk densities and therefore, store water differently. These products are also still working out the influence of lakes and forest biomass on moisture retrievals.

In the interim, updated guidance is still needed for fire managers to determine how to start their DC values this spring in regions with drought carry-over. This article has aimed to provide the initial findings from our ongoing field-based research and to translate these into updated guidance, particularly to the estimation of the overwinter adjustment coefficients (Table 2).

Table 2. Updates to the estimation of (a) and (b) coefficients needed in the overwinter adjustment Equation 1. These are updates from Table 9 found in Lawson and Armitage (2008).

	Previous Methodology		**Updated Methodology**	
Constant	*Values*	*Criteria*	**Values**	**Updated Criteria**
Carry-over fraction of last fall's moisture (a)	*1.0*	*Daily DC calculated up to 1 November, continuous snow cover, or freeze-up, whichever comes first*	1.0	- calculate DC_f (season ending DC) until continuous snow cover or freeze-up; whichever comes first -if agency weather stations were shut down prior to meeting the above criterion use an alternate weather stream to calculate DC_f until criterion above is met
	0.75	*Daily DC calculations stopped before any of the above conditions met or the area is subject to occasional winter chinook conditions, leaving the ground bare and subject to moisture depletion*		
	0.9	*Forested areas subject to long periods in fall or winter that favor depletion of soil moisture*		
Effectiveness of winter precipitation in recharging moisture reserves in spring (b)	*0.9*	*Poorly drained, boggy sites with deep organic layers*	0 to 1	Highly variable depending on snow conditions, melt timing, local factors (i.e. soil characteristics) and soil temperature at the time of melt -if soil moisture data is available calculate (b) based on the change in moisture from fall to spring -0.5 is a conservative estimate if no other information is available. This number can be higher or lower based on the timing of melt relative to ground thaw, snow conditions and local factors.
	0.75	*Deep ground frost does not occur until late fall, if at all; moderately drained sites that allow infiltration of most of the melting snowpack*		
	0.5	*Chinook-prone areas and areas subject to early and deep ground frost; well-drained soils favoring rapid percolation or topography favoring rapid runoff before melting of ground frost*		

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Congratulations to Ellen Whitman, Trebek Initiative 2024 research awardee!

Forest fire research scientist Ellen Whitman is among nine individuals granted the Trebek Initiative 2024 research award, one of two fire scientists awarded since 2021.

Her project will examine how wildfires and climate change affect plant communities in burned areas within climate-sensitive forests in western Canada. Results will inform land-use planning, fire management, and possible expansion of protected forest areas. Learn more

Drought triggers and sustains overnight fires in North America

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Full article is available here: https://www.nature.com/articles/s41586-024-07028-5

Background

Asymmetric warming, where nights are warming more rapidly than days resulting from anthropogenic climate change, may significantly impact diurnal fire activity. Although changing daytime conditions are known to exacerbate fires, the potential shifts in nighttime burning have received less attention, as nighttime fires are typically hindered by cooler and moister atmospheric conditions and increased moisture in the fine fuels. This conventional understanding of the day-night fire pattern has been widely applied to fire suppression and prescribed, cultural, and agricultural burning. However, recent reports from frontline firefighters and satellite observations have indicated an increase in the frequency and duration of nighttime fire incidents in Canada and the USA and an increase in the number and intensity of nighttime fire "hotspots". These findings raise concerns that increasing nighttime flammability in certain regions may be expanding the diurnal burning period towards a tipping point, where the absence of nighttime conditions acting as a break on fire activity could lead to self-perpetuating overnight burning and thus larger, longer duration fires.

Fire activity has been widely linked to weather conditions captured by fire weather indices and meteorological parameters, such as the Canadian Fire Weather Index System (CFWIS) and vapor pressure deficit (VPD, a widely used metric measuring how rapidly the atmosphere dries fuel). CFWIS components are the most commonly used indices for both operational and research purposes regionally and globally. CFWIS firstly tracks potential fuel moisture conditions in surface fine fuel and moderate and deep organic layers at daily or hourly time-steps, capturing the varying speeds with which these fuels react to ambient weather. Using the resulting fuel moisture codes, CFWIS then derives indices of potential fire behavior: potential rate of spread, available fuel, and fire intensity. The extent to which fires can burn at night is partly governed by diurnal weather fluctuations and corresponding changes in small-diameter-dead surface fuel moisture. The day-night extrema values (daytime maximum and nighttime minimum) and range of these factors can be important for overnight burning as they determine both the initial conditions at the start of the night and nighttime minima, while a smaller day-night range may sustain longer-lasting nighttime burning. Large-diameter-dead surface fuels and sub-surface soil and organic materials that react slowly to meteorological conditions may also play a key role in overnight burning as they provide relatively stable influences on fires despite diurnal meteorological fluctuations.

Here, we systematically explored the emerging overnight burning phenomenon for the first time, including its extent, characteristics, drivers, implications, and prediction, using geostationary satellite images, terrestrial fire records, fire weather indexes calculated from climate data, and machine learning. This study will contribute to the knowledge gaps surrounding diurnal fire activity and its changing nature and has practical implications for nighttime fire management.

Substantial overnight burning

Summary of overnight burning - distribution in space and time

We studied the diurnal cycles of 23,557 fires that occurred in North America during 2017-2020, and a total of 1,095 overnight burning events (OBEs, defined as nights when fires burned through the entire night) were identified in 340 fires (Fig. 1). OBEs were rare in small fires but common in large fires. Out of a total of 21,116 fires smaller than 1,000 ha, only 11 OBEs were identified. Large fires (>1,000ha) accounted for the remaining 99% of OBEs (n=1,084), which constituted 2.2% of the total nights for these large fires. Among these large fires, 20% were OBE fires, with this proportion rising as high as 35% in western mountain areas. OBEs were mostly concentrated in western mountain areas (Temperate mountain system: 45%, and Subtropical mountain system: 31%) and the Boreal region (13%), where large fires were also the most prevalent. OBEs peaked in summer (June-August) and fall (September-November) in western mountain areas, with few occurring in spring (March-May), while around a quarter of OBEs in the Boreal occurred in spring, especially in Alberta (Fig. 1).

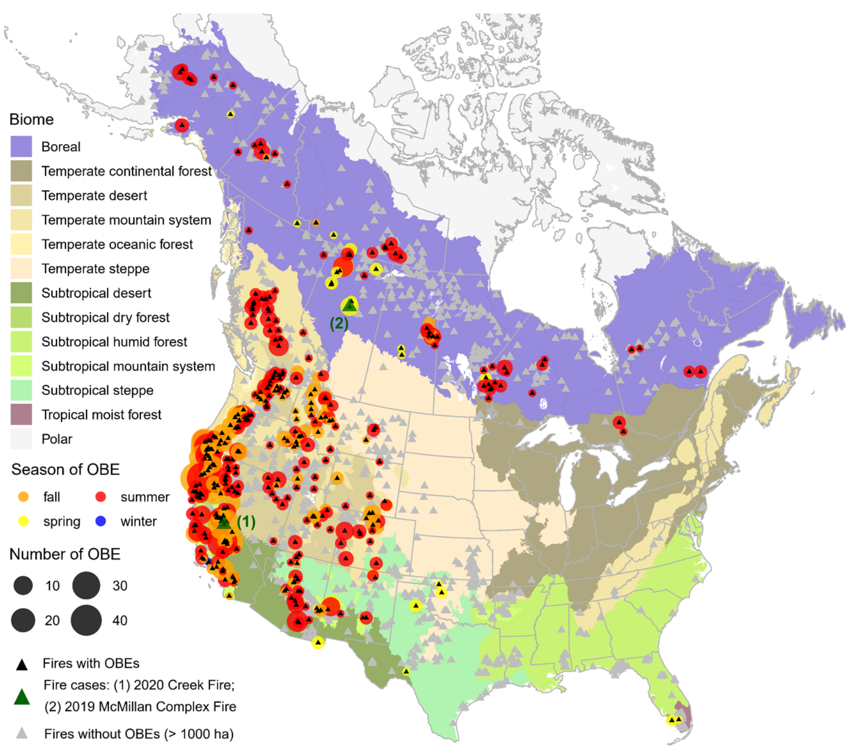

Figure 1. Substantial overnight burning in North America, 2017-2020. The map shows the season (e.g., summer: June-August) and the number of OBEs per OBE fire, which are represented by the color and size of filled circles, respectively. When OBEs within a fire occur in multiple seasons, the geographic position is jittered and plotted multiple times with different colors for clearer visualization. The background is colored by biome classifications. All OBE fires are represented by black triangles. A total of 1,095 OBEs was identified in 340 out of 23,557 fires, and 99% of OBEs were associated with large fires (> 1,000 ha). Among these large fires, 20% were OBE fires. OBEs were mostly concentrated in western mountain areas and the boreal region. Multi-OBE fires were the predominant form of OBE fires and accounted for 85% of all OBEs, with the top 10 multi-OBE fires averaging 27.1 nights of overnight burning. The numbered green triangles represent two large fire cases that are discussed further: (1) the 2020 Creek Fire (California, Subtropical mountain system) and (2) the 2019 McMillan Complex Fire (Alberta, Boreal).

Overnight burning promotes extreme fires

More overnight burning, larger burned area

We found a positive correlation between fire size and the number of OBEs (Fig. 2a). Notably, fires larger than 1,000 ha, while comprising only 10% of all fires, were responsible for 90% of the total area burned in North America during 2017-2020 based on the fire datasets.

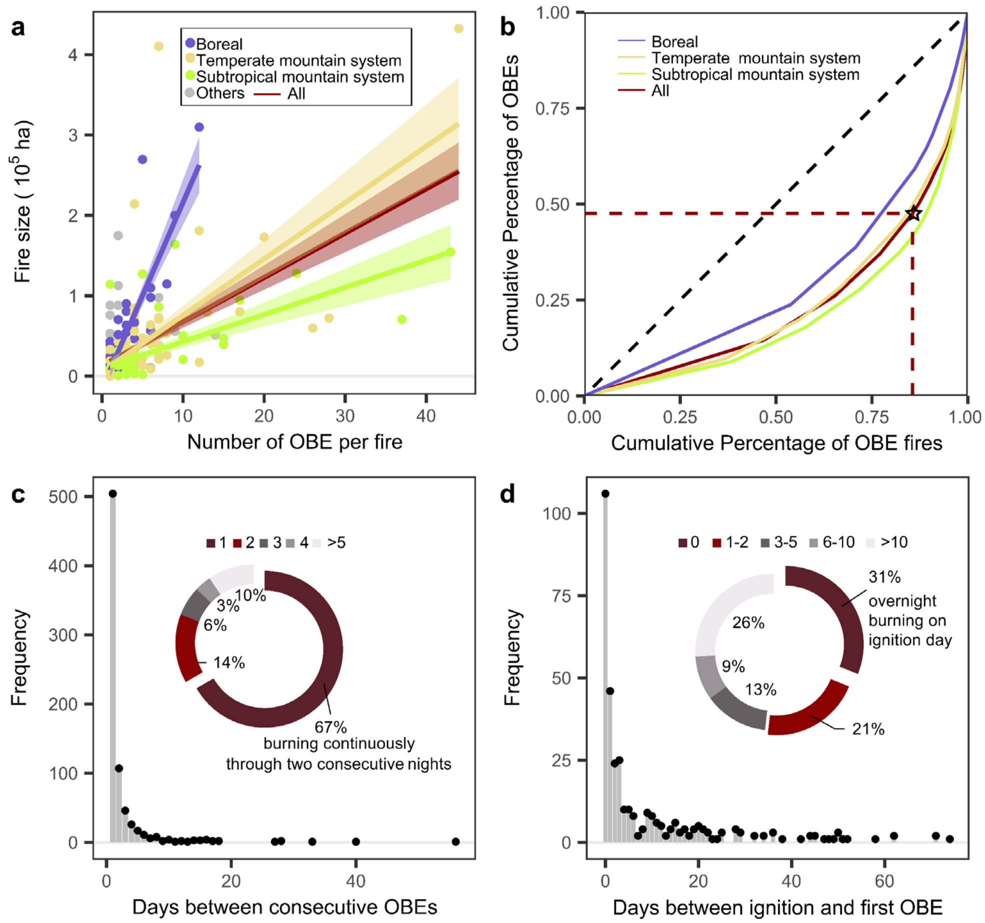

Figure 2. Overnight burning promotes extreme fires. (a) Fire size vs. the number of OBEs per OBE fire by biome and for all biomes combined ("All"). Relationships are fitted using linear regression, and in all cases, $P<0.05$, indicating that fire size is positively correlated to the number of OBEs. The shaded area surrounding the line represents the uncertainty ranges of the 95% confidence interval. (b) Cumulative percentage of OBE fires vs. cumulative percentage of OBEs by biome and for all biomes combined ("All"). The cumulative percentage of OBE fires is ordered by the number of OBEs, with single-OBE fires starting at 0% and fires with the highest number of OBEs at 100%. Red dashed lines indicate that 14% of OBE fires contributed to more than half of all OBEs. (c) The frequency and distribution of the number of days between each OBE and the successive OBE in multi-OBE fires. In 67% of cases, OBEs occurred on two consecutive nights, indicating a frequent consecutive occurrence of OBEs. (d) The frequency and distribution of the number of days between fire ignition and the occurrence of the first OBE for all OBE fires. In 52% of OBE fires, the first OBE occurred within two days of ignition, and in 31% of OBE fires, an OBE occurred on the ignition day. For better visualization, the only OBE fire (1 out of 340 OBE fires) with a time interval after ignition exceeding 100 days was excluded from the bar chart but included in the pie chart.

More overnight burning takes place in fewer extreme fires

Multi-OBE fires (fires with more than one OBE) were the predominant form of OBE fires and accounted for 85% of all OBEs (Fig. 1). More than 50% of OBEs were concentrated in just 14% of OBE fires (Fig. 2b), with the top 10 multi-OBE fires averaging 27.1 nights of overnight burning (Fig. 1). About two-thirds (63% and 62%, respectively) of OBE fires were multi-OBE fires in temperate and subtropical mountain systems, which actively burned through 5.4 and 6.4 nights on average, respectively.

Burning through consecutive nights for days and even weeks

OBEs tend to occur consecutively. Calculating the number of days between two successive OBEs in each multi-OBE fire indicated that most OBEs are temporally clustered, often occurring continuously or within a short time interval during the lifetime of a fire (Fig. 2c). For example, 43 OBEs were identified within 52 days of the Creek Fire in California during the 2020 fire season, resulting in a total area burned exceeding 150,000 ha.

Early onset of overnight burning after ignition

The first OBE of all OBE fires tended to occur in the first few days after ignition; over 50% of the first OBE occurred within two days of ignition, and nearly one-third of the first OBE occurred on the day of ignition (Fig. 2d). This leaves little time for firefighting interventions, which combined with the consecutive occurrence of OBEs, increases the likelihood of OBE fires becoming out of control and reaching large final sizes.

The number and characteristics of overnight burning – still underestimated

We used Earth Observation fire products from the geostationary satellite as it is the only source of regular, high-frequency fire detections (≤ 15-minute temporal resolution) and is, therefore, the only satellite system capable of identifying OBEs. Notably, the number and characteristics of OBEs and OBE fires reported herein are still likely to be conservatively estimated given our stringent requirements for identifying an OBE and the omission errors of Earth observation-based active fire detection algorithms (e.g., cloud/vegetation canopy obscuration, oblique sensor observation angles, and small and/or smoldering fires with limited fire extents and intensities that fall below the minimum detection thresholds).

Drivers of overnight burning

Elevated fire weather - hotter, drier, windier conditions associated with overnight burning

We examined the differences in all fire weather variables (including daily slow-reacting variables and the daytime and nighttime extrema values of hourly fast-reacting variables), as well as the day-night range of fast-reacting variables, between OBEs and non-OBEs within fires larger than 1,000 ha. We focused on this analysis in the five major biome-season groups with 100 or more OBEs, which included Boreal summer, Temperate mountain system summer and fall, and Subtropical mountain system summer and fall. Significantly hotter, drier, and windier conditions were found for OBEs compared to non-OBEs as almost all fire weather variables showed significantly lower (relative humidity) and higher (other variables) values for OBEs (one-sided Mann–Whitney U test, $P < 0.05$; Fig. 3a, 3b).

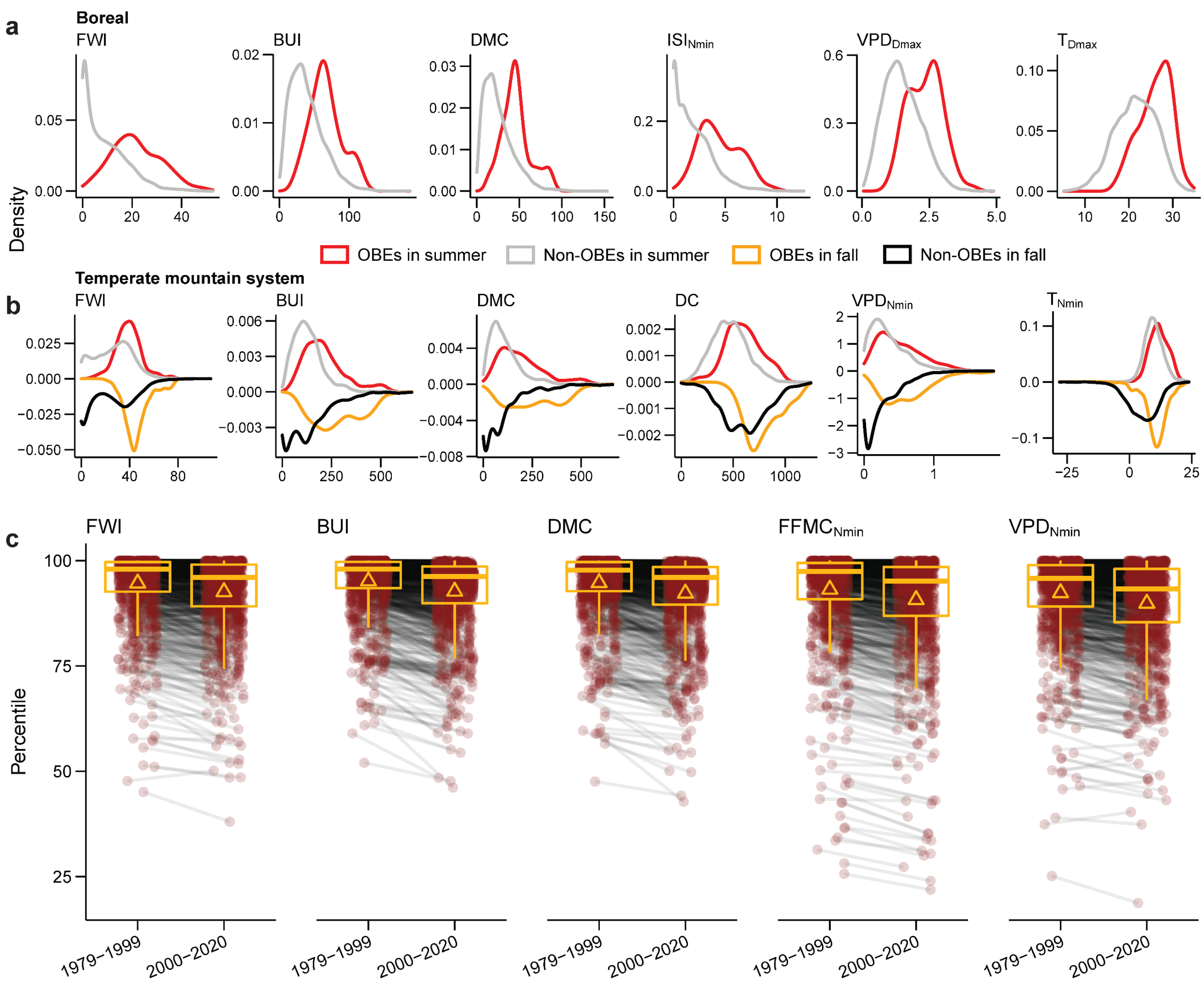

Figure 3. Fire weather is elevated during overnight burning and has become more extreme over time. Significant greater (one-sided Mann-Whitney U test, $P < 0.05$) fire weather conditions for OBEs (red for summer and orange for fall) than those for non-OBEs (gray for summer and black for fall) within fires larger than 1,000 ha in the (a) Boreal and (b) Temperate mountain system. We invert the y-axis of these distributions in fall for clearer visualization. (c) The line-linked paired points respectively represent the percentile of fire weather for each OBE within fires larger than 1,000 ha relative to comparable observations during the 1979-1999 and 2000-2020 periods at the same geographic location. The 1979-1999 percentiles are significantly higher than the 2000-2020 percentiles for each fire weather variable (paired Wilcoxon test, $P < 0.05$), indicating an increasing trend in fire weather conditions conducive to overnight burning in recent decades. Box plots display the distribution of these percentile values, with a median line, mean triangle, and box ends representing first and third quartiles. Whiskers extend to values within 1.5 times the inter-quartile range.

Extreme fire weather - supporting overnight burning and fire spread

Moreover, to assess the fire weather extremes for OBEs, we calculated the percentile value of each OBE's fire weather variable from fires larger than 1,000 ha relative to the distribution of values extracted from records for the years 2000-2020 and 1979-1999 in the corresponding fire perimeter. The value of each fire weather variable for OBEs generally exceeded the 90th percentile of comparable observations during 2000-2020 in the same location (Fig. 3c). Extreme fire weather conditions were indicative of potentially high burning intensity (FWI) and fire spread (ISI). Days and nights associated with OBEs were prone to becoming "fire spread days", characterized by substantial area growth, leading to large fire sizes.

Accelerated disruption of diurnal fire cycle - rise in extreme conditions conducive to OBEs over recent decades

Notably, for OBEs, co-located fire weather percentiles calculated based on the 2000-2020 climatology were significantly lower (paired Wilcoxon test) than those calculated based on the 1979-1999 climatology (Fig. 3c), indicating an increasing trend in fire weather conditions conducive to overnight burning in recent decades.

Drought as the main driver - the cumulative fuel dryness and amount played a crucial role in burning through the night

To further understand the underlying drivers of recent OBEs, we constructed random forest binary classification (i.e., OBEs or non-OBEs) models for nights of fires larger than 1,000 ha in the five major biome-season groups to determine the relative importance of fire weather variables. The results indicated that cumulative fuel dryness and amount (i.e., drought-related variables) played a crucial role in supporting OBEs (Fig. 4). Specifically, either DMC or BUI was found to be the most important factor in all groups. Notably, surface fine fuel moisture (FFMC) and potential fire spread (ISI) also strongly influenced OBEs in Boreal summer and Temperate mountain system summer.

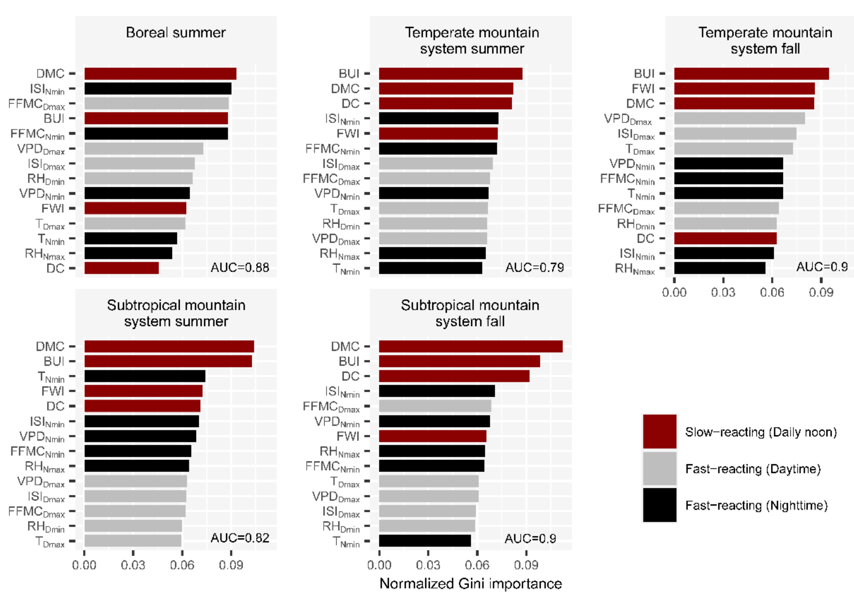

Figure 4. Drought conditions are the major driver of overnight burning. For each major biome-season group, we calculate the normalized mean decreases in the Gini coefficient of fire weather variables using the random forest model to classify OBEs or non-OBEs for nights of fires larger than 1,000 ha. The variables are ranked from the most important to the least important. Slow-reacting variables are represented by dark red horizontal bars, and daytime and nighttime extrema of fast-reacting variables by gray and black bars, respectively. Drought conditions play a crucial role in supporting OBEs as either DMC or BUI (cumulative fuel dryness or amount; drought-related variables) was found to be the most important factor in all groups. The performance of the models is evaluated by the area under the receiver operating characteristic curve (AUC).

Overnight burning is predictable

Daytime conditions largely set the foundation for occurrences of overnight burning

In operational wildfire management, fire danger indices and adjective ratings used for decision-making are typically generated at a daily (i.e., local noon) timestep, rather than an hourly one, especially in remote areas. To explore the potential predictability of OBEs (i.e., whether the coming night is an OBE or not) in such an operational setting and to understand the coupling between daytime conditions and nighttime burning, we constructed logistic regression models for nights of fires larger than 1,000 ha in five major biome-season groups using different combinations of daily-noon slow-reacting variables given the importance of these variables (Fig. 4). The results indicated that OBEs were predictable and that daytime conditions largely set the foundation for their occurrence. For each biome-season group, at least 66% of OBEs were correctly predicted. For example, in the best-performing model for the Temperate mountain system fall, 82.6% of OBEs were correctly predicted (Fig. 5).

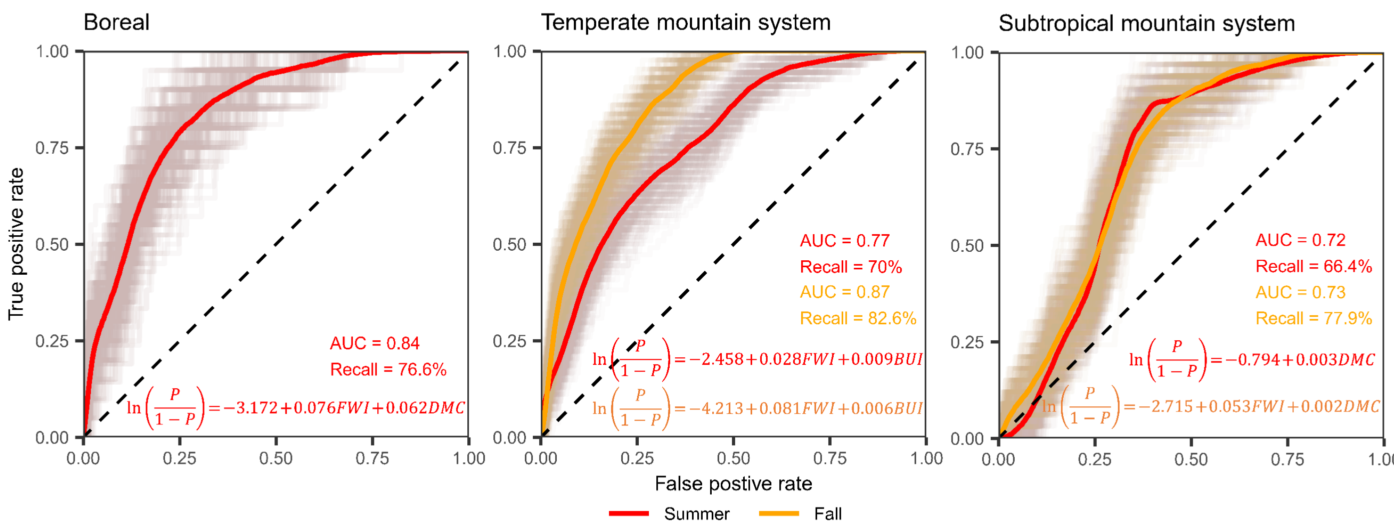

Figure 5. Overnight burning is predictable based on daytime fire weather conditions. Logistic regression models were built to predict whether nights of fires larger than 1,000 ha were OBEs or non-OBEs in each major biome-season group, using daily fire weather variables only. The receiver operator characterization curve (ROC) of each resample (background gray lines) for a 50 times 5-fold cross-validation and the ROC from all resamples (colored lines) are shown in each subplot, with the overall area under ROC (AUC) value presented. The recall represents the percentage of correctly predicted OBEs among observed OBEs. The equations in each subplot show the logistic equations for the model output in different biomes, where P represents the probability of OBE occurrence. At least 66% of OBEs were correctly predicted for each group, indicating that OBEs are predictable and that daytime conditions largely set the foundation for their occurrence. The overall ROC, AUC, recall, and logistic equations are colored by season, i.e., red for summer and orange for fall.

Overnight fires: an emerging but understudied challenge

Overnight burning challenges fire management

Overnight burning presents significant challenges for fire management. Firstly, conditions conducive to OBEs typically occur when fire suppression capacity is already stretched. The extended burning duration, larger burned area and intensity, and extreme fire behavior can exponentially increase containment expenses. Secondly, the early onset of OBEs after ignition leaves little time for firefighters to react, and the consecutive occurrence of OBEs limits containment options. Multi-OBE fires, the dominant form of overnight burning, are therefore harder to extinguish and more likely to become escaped fires. Thirdly, firefighters face limited time for rehydration, sleep, and reduced body temperature, exacerbating physical and mental stress. Reduced visibility and more complicated nighttime situations further escalate this adversity. To cope with these challenges, early fire detection efforts and developing new tools that allow for more effective decision-making may be viable approaches given the increasing budget pressures on fire management. For example, as we show here for the first time, OBEs are predictable based on daytime conditions. Combining these findings with fire weather forecasting and real-time data assimilation of observations in an operational system could enhance strategic and tactical management decisions.

Droughts – why and how?

We identified that the main drivers of OBEs were cumulative fuel dryness and availability, which aligns with previous studies that have suggested that nighttime fires (e.g., higher occurrence and longer persistence) favor drier conditions. These factors not only react slowly to diurnal fluctuations but also exhibit time-lags of days to weeks, which prevent fires from being extinguished during adverse nighttime conditions. This may also explain why OBEs usually occur on consecutive or nearly consecutive nights (Fig. 2c).

Seasonal and regional variations in drivers

Nonetheless, the drivers of OBEs may still vary between regions and seasons. For instance, nearly a quarter of Boreal OBEs were identified in spring when fuel dryness and availability usually cannot accumulate sufficiently. The qualitative analysis of the 2019 McMillan Complex fire, Alberta and previous research on large spring fires in Alberta indicate that wind may play an important role in spring OBEs in the Boreal.

Fast-reacting variables' impact

Sudden changes in nighttime conditions, such as the passage of a dry cold front or the onset of heatwave conditions, can also weaken or even eliminate the nighttime barrier to fires, resulting in OBEs. In addition to their role in promoting OBEs, the importance of fast-reacting variables also lies in the fact that they can inhibit overnight burning. For instance, even when drought indicators have accumulated to high levels, these fast-reacting variables can interrupt the consecutive occurrence of OBEs, as demonstrated in the qualitative analysis of the 2020 Creek Fire. It is also worth noting that cumulative fuel dryness and availability are primarily induced by prolonged periods of insufficient precipitation and high temperatures, further underscoring the significance of fast-reacting variables.

Futures scenarios – the transitions to flash, intensified, and prolonged droughts

We have found a rise in extreme fire weather conditions conducive to OBEs in recent decades, which is consistent with the prolonged drying period (e.g., extreme droughts in the western USA) and increasing trends in fire-conducive weather during the day or night. However, the relationship between diurnal fire activity and climate change remains largely understudied. Firstly, as climate change drives the transition to flash, intensified, and prolonged droughts, it is expected to compress the time frame within which factors leading to OBEs accumulate. This could potentially result in a future scenario where OBEs occur more rapidly and occur more frequently in succession, posing significantly greater challenges for mitigation and management.

Futures scenarios – asymmetric warming

Secondly, warming is eroding the climatological barrier that traditionally restricted nighttime fires. The asymmetric increasing trend in fast-reacting variables, such as temperature and VPD, therefore holds the potential to drive broader shifts in diurnal burning patterns, leading to an increased occurrence of OBEs that may rely less on drought conditions. The non-linear impact of asymmetric warming, where a slight increase in daytime temperatures may disproportionately enhance diurnal flammability, adds an additional layer of complexity to this issue. To gain a deeper understanding of this complex relationship, future research should involve the examination of both fuel and climatological factors evaluated in an integrated day-night manner. Furthermore, insights into how diurnal burning patterns are expected to shift regionally and globally in the future can provide both scientific and practical values for confronting future fire challenges.

Conclusion

Compared to interannual, annual, and seasonal fire activity, diurnal fire activity - especially the nighttime aspect - has long been overlooked. However, the recent widespread occurrence of unexpected and extreme OBEs in conventional large-fire-prone areas in North America has highlighted the urgency of this research. 99% of OBEs were associated with large fires (>1,000ha), and at least one OBE was identified in 20% of these large fires. OBEs were early onset after ignition (>50% of the first OBE of all OBE fires occurred within 2 days of ignition), and OBE frequency was positively correlated with fire size. These findings combined with the frequent consecutive occurrence of OBEs are challenging traditional diurnal fire knowledge and current fire management practices. The occurrences of OBE are associated with extreme fire weather, particularly intensified fuel dryness and availability (i.e., drought conditions). Drought conditions disrupt the usual balance of diurnal flammability and promote overnight burning, which is a key mechanism fostering large active fires. Our study also emphasizes the predictability of OBEs with daily-noon conditions, providing new insights into the diurnal fire cycle with implications for nighttime fire management.

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