Overwintering fires rising in eastern Siberia

Wenxuan Xu, Rebecca C Scholten, Thomas D Hessilt, Yongxue Liu and Sander Veraverbeke

Abstract

Overwintering fires are a historically rare phenomenon but may become more prevalent in the warming boreal region. Overwintering fires have been studied to a limited extent in boreal North America; however, their role and contribution to fire regimes in Siberia are still largely unknown. Here, for the first time, we quantified the proportion of overwintering fires and their burned areas in Yakutia, eastern Siberia, using fire, lightning, and infrastructure data. Our results demonstrate that overwintering fires contributed to $3.2 \pm 0.6\%$ of the total burned area during 2012–2020 over Yakutia, compared to $31.4 \pm 6.8\%$ from lightning ignitions and $51.0 \pm 6.9\%$ from anthropogenic ignitions (14.4\% of the burned area had unknown cause), but they accounted for $7.5 \pm 0.7\%$ of the burned area in the extreme fire season of 2020. In addition, overwintering fires have different spatiotemporal characteristics than lightning and anthropogenic fires, suggesting that overwintering fires need to be incorporated into fire models as a separate fire category when modelling future boreal fire regimes.

1. Introduction

Arctic-boreal ecosystems have been a long-term carbon sink [1], storing approximately double the amount of carbon as currently in the atmosphere [2]. Fire is the primary disturbance in boreal regions where the climate is warming faster than in other parts of the world [3]. Recent increases in boreal fires threaten the large boreal soil carbon reservoirs by direct carbon emissions from combustion [4] and indirect carbon emissions that may result from fire-induced permafrost thaw [5, 6]. The burned area within a fire season usually stems from a combination of anthropogenic and lightning ignitions in the southern boreal forest, shifting towards a lightning-dominated fire regime in the remote northern boreal forest [7]. Recently, researchers discovered another unexpected source of burned area, overwintering (‘zombie’) fires, which, in part, may be responsible for the early start of recent boreal fire seasons [8]. Overwintering fires are seemingly extinguished on the surface at the end of the boreal fire season; however, they locally smoulder belowground in carbon-rich organic soils throughout the winter. In the subsequent fire season, smouldering fires re-emerge as flaming forest fires when weather conditions favourable for fire spread arrive in spring after snowmelt (figure 1) [8–10]. Smouldering overwintering fires burn deep into the organic soils and may as such emit soil carbon that had been preserved over several fire cycles [9, 11]. The first evidence of the widespread occurrence of overwintering fires came from Scholten et al [9] who combined records from fire managers with satellite imagery and other geospatial data over Alaska, USA, and the Northwest Territories, Canada. They found that between 2002 and 2018, overwintering fires were responsible for less than 1\% of the burned area in these regions. However, after large fire years, overwintering fires accounted for more than 5\% of the annual burned area in some years and more than 30\% of the annual burned area in one individual year. The majority of burned area in the circumpolar boreal forest is located in Eurasia [12]. The prevalent re-emergence of overwintering fires after hot and dry summers with extreme fire activity suggests that overwintering fires may be more widespread, including in...
Siberia, with the ongoing intensification of boreal fire regimes [11, 13].

Eastern Siberia experienced anomalously high fire activities in 2019 and 2020 [14], and the 2020 fire season spurred the first scientific discussion on the proliferation of overwintering fires in eastern Siberian fire regimes [8, 10]. Still, the role of overwintering fires and their contribution to the fire regimes in eastern Siberia has remained unexplored. We here created daily burned area maps by merging the 500 m Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 burned area product and the 375 m Visible Infrared Imaging Radiometer Suite (VIIRS) 1-band active fire product between 2012 and 2020. Subsequently, we adapted and optimized an overwintering fire detection algorithm [9] to operate over Yakutia, jointly using fire, lightning, and infrastructure data (figure S1 available online at stacks.iop.org/ERL/17/045005/mmedia). For the first time, we assessed the contribution of overwintering fires to the annual burned area in Yakutia, eastern Siberia, between 2012 and 2020. In addition, we compared the spatio-temporal characteristics of overwintering fires with those from anthropogenic and lightning fires.

2. Materials and methods

2.1. Study area

Yakutia, also known as Sakha, is a republic of Russia, located in eastern Siberia, and occupies most of the Northeastern part of the Eurasian continent, covering over 3 million km$^2$. The whole territory of Yakutia lies in the zone of perennially frozen soils and over 40% of its territory lies within the Arctic Circle. Yakutia consists of Arctic and boreal vegetation communities. Arctic tundra vegetation covers the ecosystems near the northern coastline and in higher elevation subarctic regions. Forests dominate the central and southern parts of Yakutia: boreal forests cover the majority of Sakha and these forests are dominated by larch tree species [15]. Cold continental climate prevails in

![Figure 1. Two overwintering fire examples in Yakutia, Russia, illustrated by Sentinel-2 false-colour image (band 12-band 8A-band 2) time series. Burn scars from the fire season in 2019 (a) seemingly extinguished on the surface but smoulder belowground throughout the winter (b), and re-emerge in spring when the snow has melted (c), thereby generating additional burned area (d). Fire perimeters were mapped manually for these examples.](image-url)
Figure 2. Illustration of the daily burned area mapping and fire start retrieval. (a) The MCD64A1 burned area product in 2020 overlaid over a Sentinel-2 image from 12 September 2020. (b) The VNP14IMG active fires product in complement of the MCD64A1 product. (c) The retrieved fire perimeters. (d) The daily burned area maps and fire start retrieval.

Yakutia with most of the area covered with snow for between 225 and 250 days yr\(^{-1}\) [15]. Yakutsk, the capital of Yakutia, has an average January temperature of \(-40.9^\circ\text{C}\) and is considered one of the coldest cities in the world [16]. Climate change has resulted in higher temperatures over much of Yakutia in recent decades [17, 18]. For example, a new record temperature of 38 \(^\circ\text{C}\) within the Arctic Circle was recorded in Verkhoyansk, Yakutia, in June 2020 during a prolonged heatwave that increased droughts and stimulated wildfires [14]. Forest fires in Yakutia include low-intensity surface fires as well as high-intensity canopy fires [19, 20]. The majority of carbon emissions from these fires stem from burning in organic soils [12], which may facilitate the survival of overwintering fires [9].

2.2. Daily burned area maps
We derived daily burned area maps for Yakutia between 2012 and 2020 at 500 m spatial resolution by combining the MODIS Collection burned area product (MCD64A1) [21] and the VIIRS daily active fire product (VNP14IMG) [22]. The MCD64A1 burned area product has relatively large omission errors due to its coarse resolution [23, 24], which affected the characterization of burned areas in Yakutia (figure 2(a)). Therefore, we complemented the burned area estimates from the MCD64A1 product with the VIIRS active fire product as it proved to fill some of the omission errors from the MCD64A1 products thanks to its high detection rate (figure 2(b)) [25]. The VIIRS active fire data also has omission errors when used to indicate burned area due to cloud and smoke cover, or when fires are spreading fastly between subsequent acquisitions [25]. As such, the MCD64A1 and VNP14IMG were used in a complementary fashion in order to minimize omission errors. We classified 500 m by 500 m pixels that included the centre of a VIIRS active fire detection but were not classified as burned in the MCD64A1 product as burned pixels, complementing the burned area pixels from the MCD64A1 product. Given the inclusion of other thermal anomalies than fire in the VNP14IMG product, we only complemented the MCD64A1 burned area with burned area from the VNP14IMG product within a 5 km buffer of MCD64A1 product. The resulting burned area in Yakutia between 2012 and 2020 was 44% larger than the burned area from the MCD64A1 burned area product alone (table S1). To separate burned area in individual
fire perimeters, we created a 500 m buffer around all burned area pixels, and we attributed fragmentary burned pixels that were not attached to the core burned area but within the buffer to the fire perimeter of the core burned area (figure 2(c)). These fragmentary burned pixels at the edges of large fire scars result from omission errors in the remotely sensed burned area product. When not accounted for, these fragmentary burned pixels can erroneously be seen as separate ignitions, and this results in overestimations of the number of fire ignitions in boreal regions in existing global fire segmentation products [26]. Due to the uncertainties in the temporal reporting accuracy of the MCD64A1 product [27], all burned pixels of our combined burned area product were assigned a day of burning from the nearest VIIRS active fire observation (figure 2(d)). When no VIIRS pixels were present within 1 km of burned pixels from the MCD64A1 product, we retained the day of burning from the MCD64A1 product. As a result, we created annual burned area progression (day of burning) maps. Large boreal fires often coalesce from multiple fire starts. We thus retrieved fire starts by searching for local minima within the day of burning maps within each fire perimeter by using a search radius of 10 km. This approach allows retrieval of multiple fire starts for larger burn complexes that originated from multiple fire starts (figure 2(d)). When the local minimum contained multiple pixels with the same day of burning, we estimated the locations of the first day of burning (hereafter referred to as fire start locations) as the centroid of these neighbouring pixels.

2.3. Ignition attributions

We derived fire start locations based on the daily burned area maps and annual fire perimeters. We used spatial and temporal constraints based on a snow cover product (MCD10A1), the Global Lightning Detection Network (GLD360) lightning data, and OpenStreetMap (OSM) infrastructure data, to attribute fire starts to lightning, anthropogenic, and overwintering fires (figure 3). We buffered all lightning strike locations in Yakutia using a 3 km buffer based on the positional accuracy of the lightning detection network [28]. Lightning fires often smoulder for several days after the strike in boreal organic soils before being detected by satellites [9]. We accounted for this holdover time when attributing fire starts to lightning by allowing a time lag of up to six days between a buffered lightning strike and a fire start [9]. We used vector data on roads and powerlines to attribute fire starts to anthropogenic fires. We classified fire starts that occurred within 5 km of roads and powerlines as anthropogenically ignited as suggested from prior work on relationships between distance from roads and anthropogenic fire starts in parts of Siberia [29, 30]. Overwintering fires re-emerge early after spring snowmelt and in close proximity of the burn scar of the year before [9]. We computed maps of the annual first snow-free day (when fractional snow cover drops below 15%) in spring from the MCD10A1 snow cover product, and we calculated the local snowmelt onset day within 10 km buffers of each fire start location. Fire starts within 1 km of the burned area from the year before that occurred within 60 days after the local snowmelt onset were attributed to overwintering fires [9]. Fire starts that could not be attributed to lightning, anthropogenic and overwintering fires, remained unclassified in the unknown class.

2.4. Burned area attribution

Spatially adjacent burned areas from large boreal fires may stem from multiple different fire starts that grew together. For these fires, we estimated the contribution of each fire cause category, lightning, anthropogenic, overwintering, and unknown causes, to the total burned area by proportionally dividing the burned area in each fire perimeter among its constituting fire starts from different causes. In our initial attribution of fire causes, some fire starts were assigned to multiple fire causes. To account for the attribution uncertainty for these fire starts with multiple possible fire causes, we developed six scenarios that included all possible attribution priorities between the different fire causes (figure 3). These scenarios are only applicable to fire starts that have at least two possible fire causes. The burned area from lightning, anthropogenic, and overwintering fires was also estimated using the same scenarios. We calculated the mean burned area in each fire category from the six different fire cause attribution scenarios.

2.5. Fire size distributions

Overwintering fires are known to often remain small [9], yet fire sizes from overwintering fires have not yet been compared with fire sizes from lightning and anthropogenic fires. To do so, we calculated frequency-fire size probability distributions. Frequency-fire size probability distributions follow a power-law (heavy-tailed) relationship [31, 32]. The power-law takes the form of:

$$f(\text{fire size}) = \alpha \cdot \text{fire size}^{-\beta}$$  \hspace{1cm} (1)

where the number of fires per fire size bins of 1 km$^2$ was estimated, with $\beta$ and $\alpha$ as regression coefficients. We estimated the distributions of small versus large fires for lightning, anthropogenic, and overwintering fires separately using fire size probability distributions. Because cumulative frequencies may obscure underlying trends in finite data sets, we followed Malamud et al [33] using the frequency densities defined as

$$f(\text{fire size}) = \frac{\delta N}{\delta \text{fire size}}$$  \hspace{1cm} (2)
Figure 3. Schematic diagram example of uncertainties that may occur in the attribution of fire starts when fire starts could be attributed to multiple fire causes. (a) Assessment of individual fire starts attributions between anthropogenic (A) lightning (L) and overwintering (O) fires based on different spatiotemporal constraints. (b) Six scenarios developed to assign attribution priorities for fire starts with multiple possible causes. For instance, in scenario 1, the fire starts with multiple possible fire causes are classified in the attribution order of overwintering first, lightning second, and anthropogenic third. The six different scenarios included all possible combinations of priority assignments.

3. Results

Yakutian landscapes include extensive larch forests and carbon-rich peatlands in the continuous permafrost zone, which feature frequent fires with a burned fraction of more than 5% yr$^{-1}$ of the total area between 2012 and 2020 (figure 4(a)). The estimated burned area in Yakutia of 7.2 Mha in 2020 far exceeded the annual burned area estimates between 2012 and 2019, and was, in part, driven by an unprecedented heatwave resulting in early snowmelt and rapid drying of fuels (figure S2) [14, 19, 34]. In 2020, the mean snowmelt at locations of overwintering fires was earlier (mean day of the year = 134.0, standard deviation = 6.5 days) than between 2012 and 2019 (mean day of the year = 137.6, standard deviation = 11.3 days). Overwintering fires re-emerged earlier in 2020, too, (mean day of the year = 165.9, standard deviation = 20.0 days) compared to the period between 2012 and 2019 (mean day of the year = 170.6, standard deviation = 17.9 days).
of the year = 177.5, standard deviation = 22.2 days) (figure S3).

We assessed all fire start attributions based on the spatiotemporal constraints and quantified the burned areas accordingly using the six different fire cause attribution scenarios (figure S4, tables S2 and S3). Overwintering fires in Yakutia accounted for 3.2 ± 0.6% of the total burned area between 2012 and 2020, compared to 31.4 ± 6.8% from lightning ignitions, 51.0 ± 6.9% from anthropogenic ignitions, and 14.4% of the burned area had unknown cause (figure 4(b)). Overwintering fires contributed remarkably to the fire activity in 2020 and accounted for 7.5 ± 0.7% of the annual burned area, which was about seven times as much as the burned area from overwintering fires between 2012 and 2019. Lightning, anthropogenic, and overwintering fires occupy different parts of the landscape. Much of the burned area is concentrated between 60° N and the Arctic Circle, where a human-dominated fire regime prevails because of human accessibility. Farther North, within the Arctic Circle, lightning fires dominated most of the landscape (figure 4(c)). Overwintering fires were widespread and scattered along the latitudinal gradient in Yakutia. Notably, overwintering fires contributed to 9.2 ± 0.9% of the burned area within the Arctic Circle in Yakutia in 2020 (figure 5).

Re-emerging overwintering fires demonstrated different spatiotemporal characteristics than anthropogenic and lightning fires. The overwintering fires started in early spring, around the same time as anthropogenic fires, but well before the occurrence of lightning ignitions (figure 6). They, however, have a shorter temporal niche than anthropogenic fires, which occur almost throughout the year, but a longer temporal niche than lightning fires, which are
Figure 5. Latitudinal differences in cause of burned area in Yakutia, Russia, between 2012 and 2020. The mean burned area estimates from anthropogenic, lightning, and overwintering fires, and fires with unknown cause, in each latitudinal interval was derived from the six fire cause attribution scenarios.

Figure 6. Temporal characteristics of overwintering fires compared to anthropogenic and lightning fires. Daily cumulative burned area per fire cause in Yakutia in (a) 2012–2018, (b) 2019, and (c) 2020. The dotted lines represent the first and last day of burning of each fire cause. The uncertainty ranges (standard error of the mean estimates) are indicated by the shaded areas.

Concentrated in summer in co-occurrence with a seasonal nadir in fuel moisture. The fire size distribution of overwintering fires was also markedly different from lightning and anthropogenic fires as denoted by the power-law exponent $\beta$, which quantifies the ratio of large to small fires [30]. A larger $\beta$ coefficient denotes a larger proportion of small fires in the fire size distribution. The majority of overwintering
Figure 7. Fire size distributions for anthropogenic, lightning, and overwintering fires between 2012 and 2020. The fire size follows a power-law distribution of the form of \( f(\text{fire size}) = \alpha \cdot \text{fire size}^{-\beta} \), with the coefficient of determination \( r^2 \). Circles are frequency densities (the number of ignitions per ‘unit bin’ of 1 km\(^2\)) plotted as a function of burned area. The coefficients \( \alpha \) and \( \beta \) were calculated from the linear regression in log–log space.

Table 1. Overwintering fire size (km\(^2\)) distribution characteristics for 2012–2018, 2019, and 2020.

|                | 2012–2018 | 2019 | 2020 |
|----------------|-----------|------|------|
| 25th percentile| 0.5       | 0.6  | 2.4  |
| Median         | 1.5       | 1.5  | 13.5 |
| 75th percentile| 5.9       | 4.5  | 63.4 |

fires remained small (\( \beta = 1.67 \)), while proportionally more large fires were ignited by humans (\( \beta = 1.22 \)) and lightning (\( \beta = 0.89 \)) (figure 7). For example, 59.2% of overwintering fires remained smaller than 2500 ha, compared to 36.4% for anthropogenic fires, and 16.1% for lightning fires. Overwintering fires remain comparatively small, possibly because of fuel limitations that constrained fire growth in the areas burned the year before. We found that 28.6% of overwintering fires started detected by the VIIRS active fire data were unrecorded in the MODIS burned area data. Notably, overwintering fires in 2020 were clearly larger than in other years with a median fire size of 13.5 km\(^2\), compared to median sizes of overwintering fires of 1.5 km\(^2\) between 2012 and 2019 (table 1).

4. Discussion

Boreal fires are increasing in frequency, extent, and severity as fire regimes are changing with climate warming [4]. Our work provides additional evidence that overwintering fires are an emerging property of an intensifying boreal fire regime in Siberia. Overwintering fires are mainly driven by summer temperature extremes, deep burning, and large annual fire extent influenced directly by climate warming [9]. While the contribution from overwintering fires to the total burned area is less than that of lightning and anthropogenic fires, overwintering fires extend the legacy of a large fire season into the subsequent fire season. Given their re-emergence in early spring, they can contribute to increasingly earlier starts of boreal fire seasons. This may pose additional challenges for fire management agencies that need to be operational in early spring to suppress these fires.

Overwintering fires are generally smaller than lightning and anthropogenic fires. The increased sensitivity of the VIIRS active fire algorithm to small fires allowed detection of some of these small overwintering fires that are omitted by burned area products that are primarily derived from fire-induced reflectance changes at moderate resolution (e.g. 500 m) [9]. The inclusion of VIIRS active fire data thus allowed improvements in characterizing spatiotemporal characteristics of overwintering fires, and a combined virtual constellation of higher resolution polar-orbiting satellites (e.g. Sentinel-2 and Landsat 8/9) may help detect more overwintering fires with fainter thermal anomalies [35, 36], and possibly earlier in the season, in future work.

McCarty et al [8] and Irannezhad et al [10] suggested that overwintering fires may have contributed to an early and unprecedented fire season in the Arctic.
in 2020. We found evidence that overwintering fires in 2020 notably deviated from overwintering fires between 2012 and 2019 because of their earlier re-emergence, larger size and as a consequence larger burned area. This suggests that the extended spring heatwave and drought over Yakutia (figure S2) with consequent early snow melt (figure S3) may have facilitated the early re-emergence of overwintering fires. The large fire sizes of overwintering fires in 2020 compared to overwintering fires between 2012 and 2019 also suggests that the drought conditions in early 2020 may have enabled these overwintering fires to grow larger, despite being partly surrounded by areas that had burned in 2019. Future work could focus on how the growth of these overwintering fires has developed in relation to the availability and moisture conditions of fuels, and fire weather conditions such as vapour pressure deficit, and wind speed and direction. Such an analysis will necessitate a combination of high-resolution datasets on topography, fuels, and fire weather.

Overwintering fires result from deep-burning and smouldering in organic soils, and may thereby influence soil functioning and post-fire recovery trajectories [37]. In addition, overwintering fires may emit significant amounts of carbon [9], but the extended smouldering phase also increases the likelihood of these fires emitting relatively more methane compared to flaming fires [38], further exacerbating climate feedbacks. So far, the phenomenon of overwintering fires has mainly been observed and investigated from satellite imagery. A better understanding of the occurrence and carbon cycle impacts of overwintering fires will need to include detailed in situ measurements at locations where overwintering fires hibernated and re-emerged. Such measurements could include assessing local topographic drainage conditions, soil bulk density, carbon content, and emission measurements when overwintering fires are in a smouldering phase. Given the remote occurrence of overwintering fires, these measurements can be constrained by logistical challenges, which may overcome by close collaborations with local communities near areas where overwintering fires have re-emerged.

5. Conclusions

Although overwintering fires were responsible for a smaller proportion of burned area compared to anthropogenic and lightning fires in Yakutia, eastern Siberia between 2012 and 2020, our work highlighted the importance of overwintering fires and their contribution to the elevated burned area in eastern Siberia in 2020. Given the differences in timing, location of affected landscapes, and fire size distributions of overwintering fires compared to anthropogenic and lightning fires, we call to include overwintering fires as a separate fire cause category in fire models. This study provides the first quantification of the role of overwintering fires in eastern Siberia. Such information is important to further optimize predictions of the fate of overwintering fires in the rapidly changing boreal biome.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.pangaea.de/10.1594/PANGAEA.938118.

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ORCID iDs

Wenxuan Xu https://orcid.org/0000-0001-9883-1520
Rebecca C Scholten https://orcid.org/0000-0002-0144-0572
Thomas D Hessilt https://orcid.org/0000-0003-0315-1675
Sander Veraverbeke https://orcid.org/0000-0003-1362-5125
References

[1] Scharlemann J P W, Tanner E V J, Hiedder R and Kapos V 2014 Global soil carbon: understanding and managing the largest terrestrial carbon pool Carbon Manager 8 81–91
[2] Miner K R, Turetsky M R, Malina E, Bartsch A, Tamminen J, McGuire A D, Fix A, Sweeney C, Elder C D and Miller C E 2022 Permafrost carbon emissions in a changing Arctic Nat. Rev. Earth Environ. 3 55–67
[3] Overland J E, Wang M, Walsh J E and Stroeve J C 2014 Future Arctic climate changes: adaptation and mitigation time scales Earth's Future 2 68–74
[4] Veraverbeke S, Rogers B M, Goulden M L, Jandt R R, Miller C E, Wiggins E B and Randerson J T 2017 Lightning as a major driver of recent large fire years in North American boreal forests Nat. Clim. Change 7 529–34
[5] Gibson C M, Chasmer L E, Thompson D J, Quinton W L, Flannigan M D and Olefeldt D 2018 Wildfire as a major driver of recent permafrost thaw in boreal peatlands Nat. Commun. 9 1–9
[6] Natali S M, Holdren J P, Rogers B M, Treharne R, Duffy P B, Pomerance R and MacDonald 2021 Permafrost carbon feedbacks threaten global climate goals Proc. Natl Acad. Sci. 118 e2100163118
[7] Stocks B J et al 2002 Large forest fires in Canada, 1959–1997 J. Geophys. Res. Atmos. 107 8149
[8] McCarthy J L, Smith T E L and Turetsky M R 2020 Arctic fires re-emerging Nat. Geosci. 13 658–60
[9] Scholten R C, Jandt R, Miller F A, Rogers B M and Veraverbeke S 2021 Overwintering fires in boreal forests Nature 593 399–404
[10] Irannejad M, Liu J, Ahmadi B and Chen D 2020 The dangers of Arctic zombie wildfires Science 369 1171
[11] Walker X J et al 2019 Increasing wildfires threaten historic carbon sink of boreal forest soils Nature 572 520–3
[12] Veraverbeke S, Delcourt C J F, Kuzyakov E, Mack M, Walker X, Hesselt T, Rogers B and Scholten R C 2021 Direct and longer-term carbon emissions from arctic-boreal fires: a short review of recent advances Curr. Opin. Environ. Sci. Health 23 100277
[13] Kim J-S, Kug J-S, Jeong S-J, Park H and Schaeppman-Strub G 2020 Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation Sci. Adv. 6 eaaq3308
[14] Talucci A G, Loranty M M and Alexander H D 2022 Siberian taiga and tundra fire regimes from 2001–2020 Environ. Res. Lett. 17 025001
[15] Troeva E I, Isaev A P, Cherosov M M and Karpov N S 2010 The Far North: Plant Biodiversity and Ecology of Yakutia vol 3 (Dordrecht: Springer Science & Business Media)
[16] Revich B and Shaposhnikov D 2010 Extreme temperature episodes and mortality in Yakutsk, East Siberia Rural Remote Health 10 138–48
[17] Bondur V G, Molchov I I, Voronova O S and Sitnov S A 2020 Satellite monitoring of Siberian wildfires and their effects: features of 2019 anomalies and trends of 20-year changes Dokl. Earth Sci. 492 370–5
[18] Ponomarev E I, Shvetsov E G and Kharuk V I 2018 The intensity of wildfires in fire emissions estimates Russ. J. Ecol. 49 692–9
[19] Kharuk V I, Ponomarev E I, Ivanova G A, Dvinckaya M L, Coogan S C P and Flannigan M D 2021 Wildfires in the Siberian taiga Ambio 50 1953–74
[20] Rogers B M, Soja A J, Goulden M L and Randerson J T 2015 Influence of tree species on continental differences in boreal fires and climate feedbacks Nat. Geosci. 8 228–34
[21] Giglio L, Boschetto L, Roy D P, Humber M L and Justice C O 2018 The Collection 6 MODIS burned area mapping algorithm and product Remote Sens. Environ. 217 72–85
[22] Schroeder W, Oliva P, Giglio L and Caiszar I A 2014 The New VIIRS 375m active fire detection data product: algorithm description and initial assessment Remote Sens. Environ. 143 85–96
[23] Boschetto L, Roy D P, Giglio L, Huang H, Zubkova M and Humber M L 2019 Global validation of the collection 6 MODIS burned area product Remote Sens. Environ. 235 111490
[24] Chen D, Shnev V, Baer A E and Loboda T V 2021 Missing burns in the high northern latitudes: the case for regionally focused burned area products Remote Sens. 13 4145
[25] Oliva P and Schroeder W 2015 Assessment of VIIRS 375 m active fire detection product for direct burned area mapping Remote Sens. Environ. 160 144–55
[26] Andela N, Morton D C, Giglio L, Paugam R, Chen Y, Hantson S, van der Wel G R and Randerson J T 2019 The Global Fire Atlas of individual fire size, duration, speed and direction Earth Syst. Sci. Data 11 529–52
[27] Veraverbeke S, Sedano F, Hook S J, Randerson J T, Jin Y and Rogers B M 2014 Mapping the daily progression of large wildfire fires using MODIS active fire data Int. J. Wildland Fire 23 655–67
[28] Pohjoja H and Mäkelä A 2013 The comparison of GLD360 and EUCLID lightning location systems in Europe Atmos. Res. 123 117–28
[29] Shvetsov E G, Kuzyakov E A, Shestakova T A, Laflamme J and Rogers B M 2021 Increasing fire and logging disturbances in Siberian boreal forests: a case study of the Angara region Environ. Res. Lett. 16 115007
[30] Moskalchenko S A 2009 Fire danger and regeneration in disturbed forest territories of the lower Angara region PhD Thesis Siberian State Technological University Publishing Krasnoyarsk in Russian p 21
[31] Malamud B D, Morein G and Turcotte D L 1998 Forest fires: an example of self-organized critical behavior Science 281 1840–2
[32] Hantson S, Puyo S and Chuvieco E 2016 Global fire size distribution: from power law to log-normal Int. J. Wildland Fire 25 403–12
[33] Malamud B D, Millington J D A and Perry G L W 2005 Characterizing wildfire regimes in the United States Proc. Natl Acad. Sci. 102 4694–9
[34] Overland J E and Wang M 2021 The 2020 Siberian heat wave Int. J. Climatol. 41 12341–6
[35] Liu Y, Zhi W, Xu B, Xu W and Wu L 2021 Detecting high-temperature anomalies from Sentinel-2 MSI images ISPRS J. Photogramm. Remote Sens. 177 174–93
[36] Xu W, Liu Y, Veraverbeke S, Wu W, Dong Y and Lu W 2021 Active fire dynamics in the Amazon: new perspectives from high-resolution satellite observations Geophys. Res. Lett. 48 e2021GL093789
[37] Ceretti G 2003 Effects of fire on properties of forest soils: a review Oecologia 143 1–10
[38] Andrea M O and Merlet P 2001 Emission of trace gases and aerosols from biomass burning Glob. Biogeochem. Cycles 15 955–66