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Future increases in lightning ignition efficiency and wildfire occurrence expected from drier fuels in boreal forest ecosystems of western North America

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E-mail: t.d.hessilt@vu.nl**Keywords:** lightning ignition efficiency, lightning ignition, climate feedback, boreal forest fires, climate warmingSupplementary material for this article is available [online](#)

Abstract

Lightning-induced fire is the primary disturbance agent in boreal forests. Recent large fire years have been linked to anomalously high numbers of lightning-caused fire starts, yet the mechanisms regulating the probability of lightning ignition remain uncertain and limit our ability to project future changes. Here, we investigated the influence of lightning properties, landscape characteristics, and fire weather on lightning ignition efficiency—the likelihood that a lightning strike starts a fire—in Alaska, United States of America, and Northwest Territories, Canada, between 2001 and 2018. We found that short-term fuel drying associated with fire weather was the main driver of lightning ignition efficiency. Lightning was also more likely to ignite a wildfire in denser, evergreen forest areas. Under a high greenhouse gas emissions scenario, we predicted that changes in vegetation and fire weather increase lightning ignition efficiency by $14 \pm 9\%$ in Alaska and $31 \pm 28\%$ in the Northwest Territories per 1°C warming by end-of-century. The increases in lightning ignition efficiency, together with a projected doubling of lightning strikes, result in a 39%–65% increase in lightning-caused fire occurrence per 1°C warming. This implies that years with many fires will occur more frequently in the future, thereby accelerating carbon losses from boreal forest ecosystems.

1. Introduction

The structure of the North American boreal forest is regulated by wildfire occurrence (Bond-Lamberty *et al* 2017). While small human-ignited fires are abundant around population centers in the boreal region (Calef *et al* 2008), the majority of the burned area, about 90%, originates from lightning strikes (Shulski and Wendler 2007, Wendler *et al* 2011). Recent studies project a 33% and 114% increase in lightning density by end-of-century in northwest boreal America (Bieniek *et al* 2020, Chen *et al* 2021) as a consequence of more convection and increases in atmospheric moisture content (Chen *et al* 2021). Fires play an important role in regulating carbon and

energy fluxes in boreal forests (Randerson *et al* 2006, Rogers *et al* 2015) and increases in burned area may further contribute to a positive climate-carbon feedback. This positive feedback stems from both direct fire emissions and longer-term biogeochemical changes associated with fire-induced permafrost thaw (Walker *et al* 2019, Chen *et al* 2021).

In Alaska, USA, and the Canadian Northwest Territories, lightning explained 50% and 41% of the interannual variability in burned area from 1975 to 2015 (Veraverbeke *et al* 2017). Part of the unexplained interannual variability in burned area may stem from surface conditions that influence lightning ignition efficiency, i.e. the likelihood that an individual lightning strike starts a fire. Lightning ignition

efficiency is controlled by lightning, landscape and fire weather characteristics (Anderson 2002, Dissing and Verbyla 2003, Magnussen and Taylor 2012). Lightning characteristics of cloud-to-ground strikes influencing ignition efficiency include polarity, amplitude, and strike multiplicity. Yet the direction and strength of the influence of these lightning characteristics are not well understood, with different studies leading to diverging conclusions regarding the important controls of lightning characteristic on lightning ignition efficiency (Latham and Williams 2001, Larjavaara *et al* 2005, Schultz *et al* 2019). Landscape characteristics also govern lightning ignition efficiency, as variations in topography influence forest cover and fuel moisture status (Dissing and Verbyla 2003, Krawchuk *et al* 2006). Forest plant functional types in boreal North America are dominated by fire embracers such as black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*), which are highly flammable and receptive to ignition (Rogers *et al* 2015). Deep and severe burning in organic soils may alter forest composition from conifer-dominated to deciduous-dominated forests thereby potentially changing lightning ignition efficiency over the North American boreal forest (Walker *et al* 2018, Mekonnen *et al* 2019, Mack *et al* 2021). Fire weather conditions also influence lightning ignition efficiency, as they directly influence fuel moisture content, which is inversely related to lightning ignition efficiency (Wotton and Martell 2005, Sedano and Randerson 2014, Abatzoglou *et al* 2016). Peterson *et al* (2010) estimated the probability of ignition from dry lightning strikes to be 30%–50% higher than that from lightning strikes accompanied by precipitation. Previous studies have mainly focused on a single predictor when attempting to explain variability in lightning ignition efficiency, and have often ignored the interactions between the different driver variables.

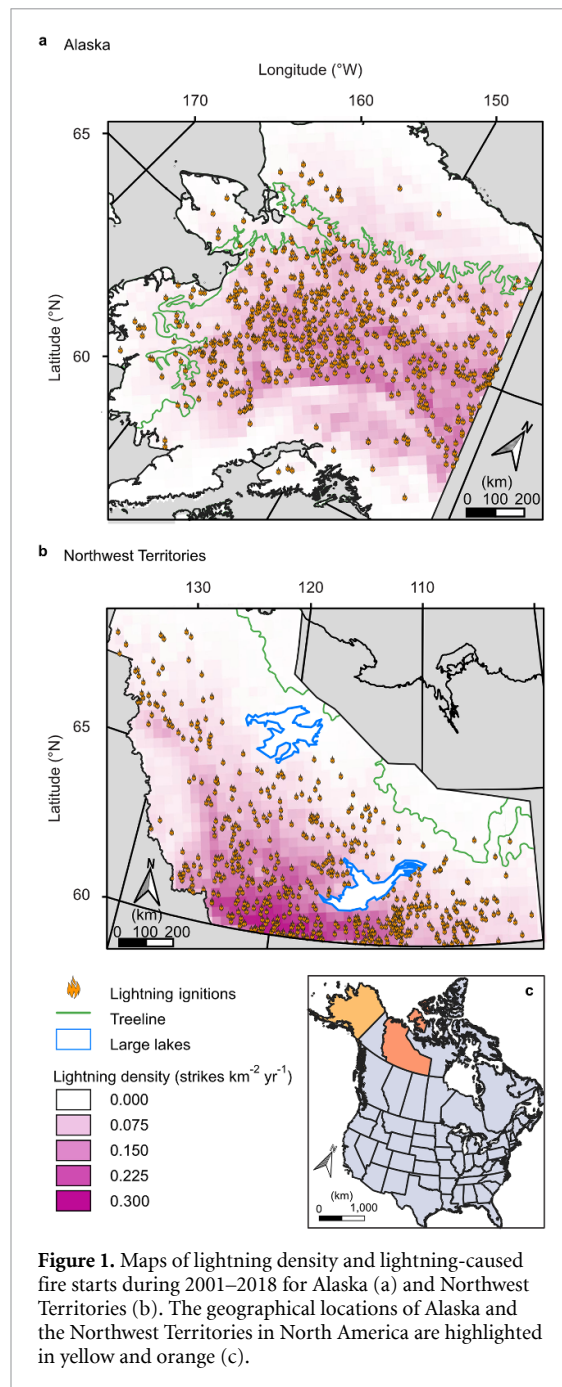
Alaska and the Northwest Territories provide ideal testbeds to investigate the drivers of lightning ignition efficiency as both regions recently experienced high lightning fire years and high spatial resolution time series of both lightning and wildfire occurrence are publicly available (Veraverbeke *et al* 2017). In this study, we assessed the influence of lightning, landscape, and fire weather characteristics on lightning ignition efficiency for these regions between 2001 and 2018 using penalized ridge logistic regression. We used the statistical relationship derived from the contemporary observations together with future predictions of vegetation and fire weather to project changes in lightning ignition efficiency by the end of the 21st century. Finally, we combined our estimates of changes in lightning ignition efficiency with previously published estimates of changes in lightning flash rate to predict changes in future fire occurrence in western boreal North America.

2. Methods

2.1. Data

We constrained our analysis to Alaska (1723 337 km²) and the Northwest Territories (1346 106 km²), which collectively included over 2.5 million recorded lightning strikes and almost 13 million ha of burned area from 2001 to 2018 (figure 1). Lightning data was obtained from the Alaska Lightning Detection Network (Farukh and Hayasaka 2012) and Canadian Lightning Detection Network (CLDN) (Burrows and Kochtubajda 2010). The lightning datasets include information about the location, timing, amplitude and polarity of cloud-to-ground lightning strikes. In 2012, the prior Alaskan Impact system was replaced with a time of arrival system that increased lightning detection efficiency by 1.5-fold (Bieniek *et al* 2020). We focused on the time period from 2001 to 2018, but separated the Alaskan dataset between the old (2001–2012) and new (2012–2018) detection networks. Between 2001 and 2018, the positional accuracies differ in time and space. For assigning a wildfire start to an individual lightning cloud-to-ground flash occurrence, we imposed a 2.5 km buffer around the cloud-to-ground strikes from the old dataset and a 500 m buffer for the cloud-to-ground strikes from the new dataset. The accuracy of the CLDN decreases northwards but since the majority of lightning and fire starts occurred in southern areas of the Northwest Territories, we imposed a conservative buffer of 2.5 km around the cloud-to-ground lightning strikes for the entire territory (figure 1(b)).

The location and timing of fire start in Alaska and the Northwest Territories were derived from the Alaskan Fire Emission Database (AKFED) version 2 (Scholten *et al* 2021a). AKFED version 2 combined fire perimeter data from the Alaskan and Canadian Large Fire Databases (Kasischke *et al* 2002, Stocks *et al* 2002) with surface reflectance changes (at 500 m resolution) and active fire detections (at 1000 m resolution) from the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 (Veraverbeke *et al* 2017). AKFED version 2 detects individual fires as small as a single 500 m pixel of 25 ha. The ignition detection algorithm extracted the timing and location of fire starts inside fire perimeters. The fire start timing accuracy is within a day (Veraverbeke *et al* 2014). When the exact fire start location was confounded because multiple active fire detections occurred at the same time, the start location was defined as the centroid of these pixels. In these cases, a spatial uncertainty equaling the standard deviation of the pixels' *x* and *y* coordinates was calculated. The location accuracy of the fire start location derived from a single burn pixel was estimated as the nominal nadir 1000 m resolution from the MODIS active fire product. For fire starts derived from multiple burned pixels the ignition location accuracy was determined by adding



1000 m to the spatial uncertainty of the ignition location.

For the set of landscape drivers, we acquired annual tree cover data from Terra MODIS vegetation continuous fields Collection 6 product at a 250 m resolution (Hansen *et al* 2003). Elevation, slope and aspect were derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model version 2 at 30 m resolution (Abrams *et al* 2020). We retrieved land cover over Alaska from LANDFIRE's Fuel Characteristics Classification System at a 30 m resolution (Ottmar *et al* 2007). For the land cover of the Northwest Territories, we used the MODIS Global Land Cover Time Series V5.1 with 17 land cover classes

defined by the International Geosphere Biosphere Programme product, which has a 250 m spatial resolution (Pouliot *et al* 2009). We adapted future land cover classes for Alaska and the Northwest Territories from Mekonnen *et al* (2019) and Holsinger *et al* (2019) (tables S1 and S2 available online at stacks.iop.org/ERL/17/054008/mmedia). The land cover classes were aggregated to a 1 km resolution, and the fractional covers of each class per 1 km² pixels were calculated.

Fire weather was derived from meteorological data from the North America Regional Reanalysis (NARR) (Veraverbeke *et al* 2017) and the fifth generation of the European Centre for Medium-Range Weather Forecast (ECMWF) reanalysis (ERA5). NARR provides three-hourly meteorological conditions at 32 km resolution while ERA5 has hourly meteorological conditions and daily fire weather indices at approximately 28 km resolution. We extracted precipitation, air temperature at 2 m height, relative humidity and wind speed over Alaska and Northwest Territories. For the NARR dataset, we used these to calculate the fine fuel moisture code (FFMC, representing the daily drying of the top 1–2 cm of the organic soil), duff moisture code (DMC, representing the drying of the 5–10 cm of the sub organic soil over 12 d) and drought code (DC, representing the drying of the 10–20 cm of the organic layer over 52 days) from the Canadian fire weather index system (Van Wagner 1987). For ERA5, we retrieved these fire weather indices from the ERA5 fire weather dataset (Vitolo *et al* 2020). We extracted the gridded meteorological data from each NARR and ERA5 grid cell corresponding to a lightning strike or fire start location within our study domain.

2.2. Identifying lightning-caused fire starts

We explicitly matched cloud-to-ground lightning strikes with the location and timing of fire starts. The holdover time can be several days to months (Scholten *et al* 2021b) since boreal fires often undergo a smoldering phase before emerging as a flaming fire that can be detected by satellite sensors (Giglio *et al* 2003, Rein *et al* 2008, Schroeder *et al* 2014). To account for this, we estimated the lag time through a simulation of fire starts (supplementary information). We compared the number of lightning ignition matches between observed lightning strikes and random ignitions with the number of matches between observed lightning strikes and ignitions. We found the number of random matches to exceed the observed matches for five and more days after the strike for the most accurate Alaskan network (figure S1). Aiming at balancing between commission and omission errors, we therefore set the temporal constraint in the analysis to 120 h after each lightning strike (figure S1). We also accounted for a temporal uncertainty of one day in the timing of fire start. When multiple lightning strikes were matched with a

single fire start, we calculated a spatiotemporal proximity index A (Larjavaara *et al* 2005) to assign the most likely cloud-to-ground lightning strike to the fire start:

$$A = \left(1 - \frac{T}{120}\right) \cdot \left(1 - \frac{S}{S_{\text{con}}}\right) \quad (1)$$

in which T is the lag time between lightning and fire detection (in hours), S is the distance between lightning and ignition (in km), and S_{con} is the spatial constraint (in km). The spatial constraint results from spatial uncertainties in lightning strike and fire start locations, and was calculated as the sum of the largest spatial uncertainties in the lightning strikes and ignition locations per lightning network dataset. Using this attribution approach, we found 689 and 550 unique lightning-caused fire starts in Alaska and the Northwest Territories, respectively (figure 1).

2.3. Drivers of lightning ignition efficiency

The cloud-to-ground strikes and their spatially and temporally matched lightning, landscape and fire weather variables consisted of a large number of explanatory variables among which mutual correlations occurred. We therefore used penalized ridge logistic regression to estimate influences on the ignition outcomes of the cloud-to-ground strikes (ignition or no ignition) and estimate the importance of the drivers on lightning ignition efficiency (Hastie *et al* 2009). The logistic equation for the probability of $Y = 1$ is:

$$P(Y = 1) = \frac{1}{1 + e^{-(\beta_0 + \sum(\beta_i X_i))}} \quad (2)$$

where β_0 is the intercept, β_i are the regression coefficients, and X_i represents the predictor variables. All lightning, landscape and fire weather predictor variables are represented in table S3. Conversely to the traditional logistic regression (equation (2)), we introduce bias in the regression through the penalty term L2 (λ). The term λ is multiplied with all β_i to shrink the coefficients for a better prediction. By this, potential overfitting of our models is minimized, and the technique is suitable for large datasets with mutually correlated variables (Zou and Hastie 2005). The λ is determined by the loss function for logistic regressions (equation (3)) through a five-fold cross-validation optimization of the maximum likelihood estimation, $L(y, \hat{y})$

$$L(y, \hat{y}) = -\sum [y_i \log(\hat{y}_i) + (1 - y_i) \log(1 - \hat{y}_i)] \quad (3)$$

where y is the observed lightning ignition outcome and $\hat{y}$ is the predicted probability value. Through the five-fold cross-validation, we found a λ that resulted in cross-validation errors within one standard deviation. The ridge logistic regression models were calibrated on a training data set (80% of

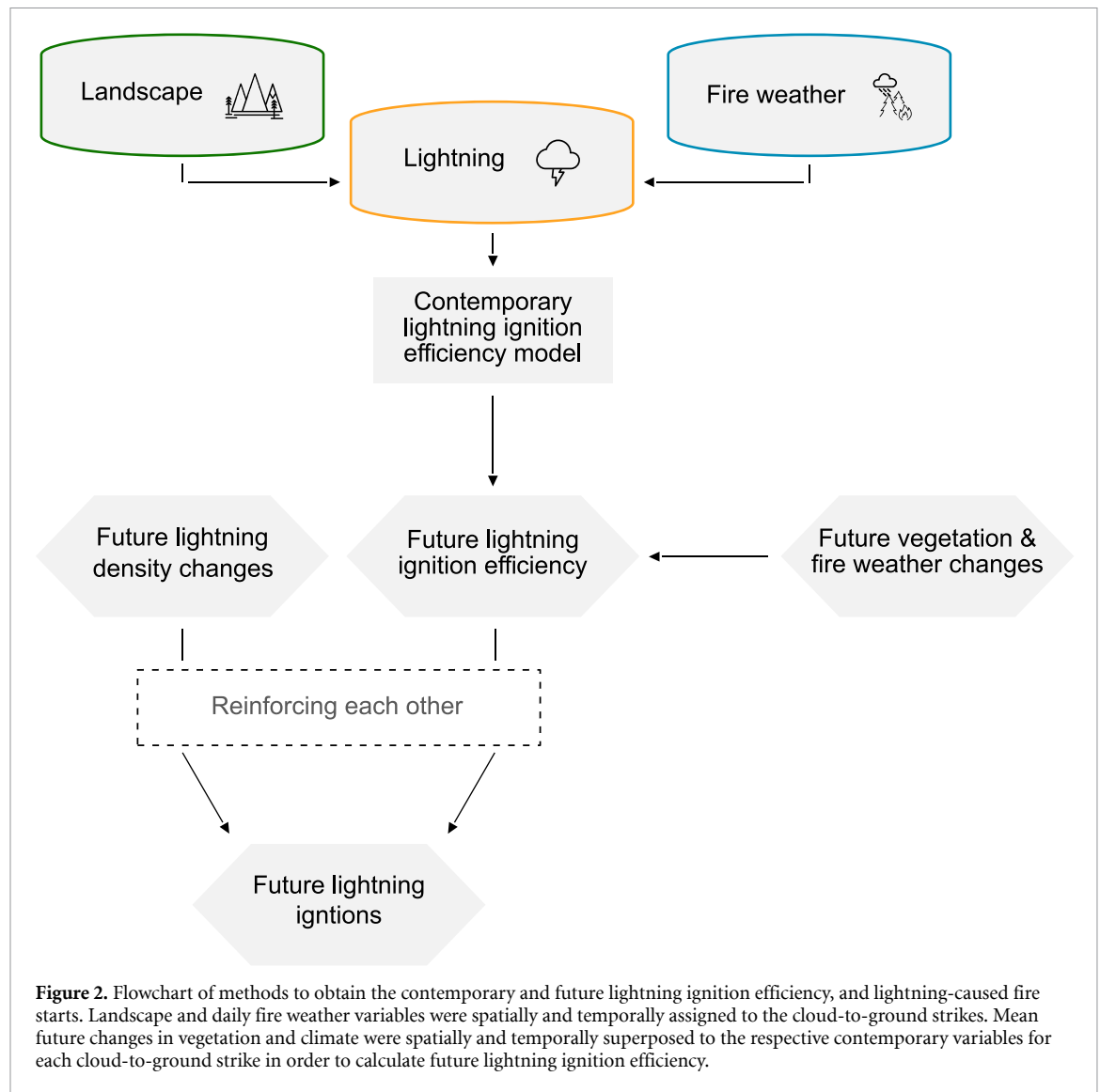
the total dataset) and its performance was assessed on an out-of-sample evaluation dataset (20% of the total dataset). We evaluated model performance using receiver operating characteristic (ROC) curve. The two-dimensional area under the ROC curve (AUC) quantified the performance metric of the regression model for the out-of-sample part of the dataset. The AUC is a measure of model discrimination power for a binary variable, in our case cloud-to-ground lightning strikes igniting a fire vs. strikes that did not ignite a fire (Hosmer *et al* 2013).

We explored the drivers of lightning-caused ignition by separation of cloud-to-ground strikes into two classes: those causing fire starts and those that did not. We evaluated differences in the driver variables between these two populations for statistical significance using a Wilcoxon-Mann-Whitney rank sum test.

2.4. Future lightning ignition efficiency and number of fires

We used our logistic regression model for all drivers to estimate future lightning ignition efficiency by applying the predicted net changes in vegetation and fire weather in accordance spatially and temporally to each cloud-to-ground lightning strike (figure 2 and table S3). The lightning characteristics polarity, amplitude, and multiplicity were kept static since they revealed no explanatory power as drivers for contemporary lightning ignition efficiency (figures 3 and S2). First, we changed the vegetation cover by implementing previously defined vegetation change trajectories for our study areas (Holsinger *et al* 2019, Mekonnen *et al* 2019) (tables S1, S2 and supplementary information), and fire weather conditions based on the calculated mean change relative to 2001–2018 from 16 climate models (table S4) (Taylor *et al* 2012). For future vegetation shifts, we used the mean relative change in each vegetation cover class for Alaska (Mekonnen *et al* 2019) and the Northwest Territories (Holsinger *et al* 2019). The relative changes were added to the contemporary vegetation cover for mid- and end-of-century scenarios (tables S1 and S2). The two separate lightning datasets from Alaska only covered relatively short time periods. We evaluated the performance of the Alaska 2012–2018 logistic regression model based on the Alaska 2001–2012 dataset. It performed satisfactory, and thus we utilized this model for the Alaskan region (figure S2). The model for the Northwest Territories was evaluated on the full 2001–2018 period and used to assess future changes in climate and vegetation (figure S2).

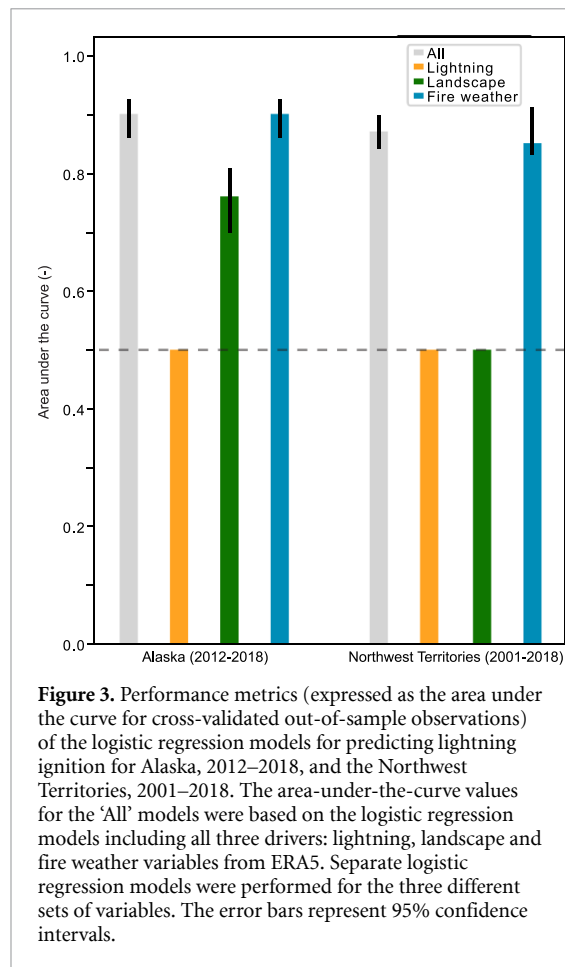
We defined the fire season for each region as the interannual mean day of fire starts $\pm$ two standard deviations which captured 95% of the lightning fire starts across the entire region. Using this definition, the Alaskan fire season started on day of the year (DOY) 145 and ended on DOY 210, whereas for the Northwest Territories the fire season started on DOY



190 and ended on DOY 230. For each of the 16 models, we calculated the gridded daily average of meteorological variables (precipitation, relative humidity, temperature, and wind speed) and fire weather indices (FFMC, DMC, and DC) over the fire season for 2001–2018, 2050–2067 and 2082–2099. For the latter two periods, this was done by retrieving the model delta changes in meteorological variables and fire weather indices between contemporary time and the two future scenarios. These model daily means were superimposed to the respective NARR and ERA5 grid cells to estimate and match future meteorological and fire weather conditions with lightning strikes, spatially and temporally. This approach assumes no changes in synoptic variability, but rather superimposes mean changes from CMIP5 models to the observed 2001–2018 meteorological and fire weather fields. Since we only considered days in which cloud-to-ground strikes occurred, we estimated the probability of fire occurrences for each cloud-to-ground strike for contemporary time and for the two future scenarios with the dynamic changes in vegetation and

fire weather. We then averaged the ignition success of all lightning strikes per grid cell to calculate the lightning ignition efficiency. We compared regionally averaged lightning ignition efficiency of the 16 models for the future scenarios with contemporary lightning ignition efficiency. Uncertainty in future lightning ignition efficiency was estimated from the multi-model standard deviation of the 16 models.

The number of future lightning-caused fire starts—the number of lightning strikes multiplied with the lightning ignition efficiency—was estimated by multiplying regionally averaged lightning ignition efficiency with previously published estimates of increases in lightning under a high greenhouse gas emission representative concentration pathway 8.5 emission scenario for our study areas (Veraverbeke *et al* 2017, Bieniek *et al* 2020, Chen *et al* 2021) (supplementary information) (table S5). To estimate the future lightning-caused fire occurrences for both time periods, we linearly extrapolated the mean and standard deviation of the projected lightning densities for the missing time period. We performed a Taylor series



approximation in which we propagated the error from the multiplication of future lightning densities with the lightning ignition efficiency. There are differences in the reference periods and models used in these studies and in our lightning efficiency model. Nevertheless, we used these best-available estimates of future lightning in combination with our lightning efficiency model to estimate future changes in lightning ignition.

3. Results

3.1. Drivers of lightning ignition efficiency

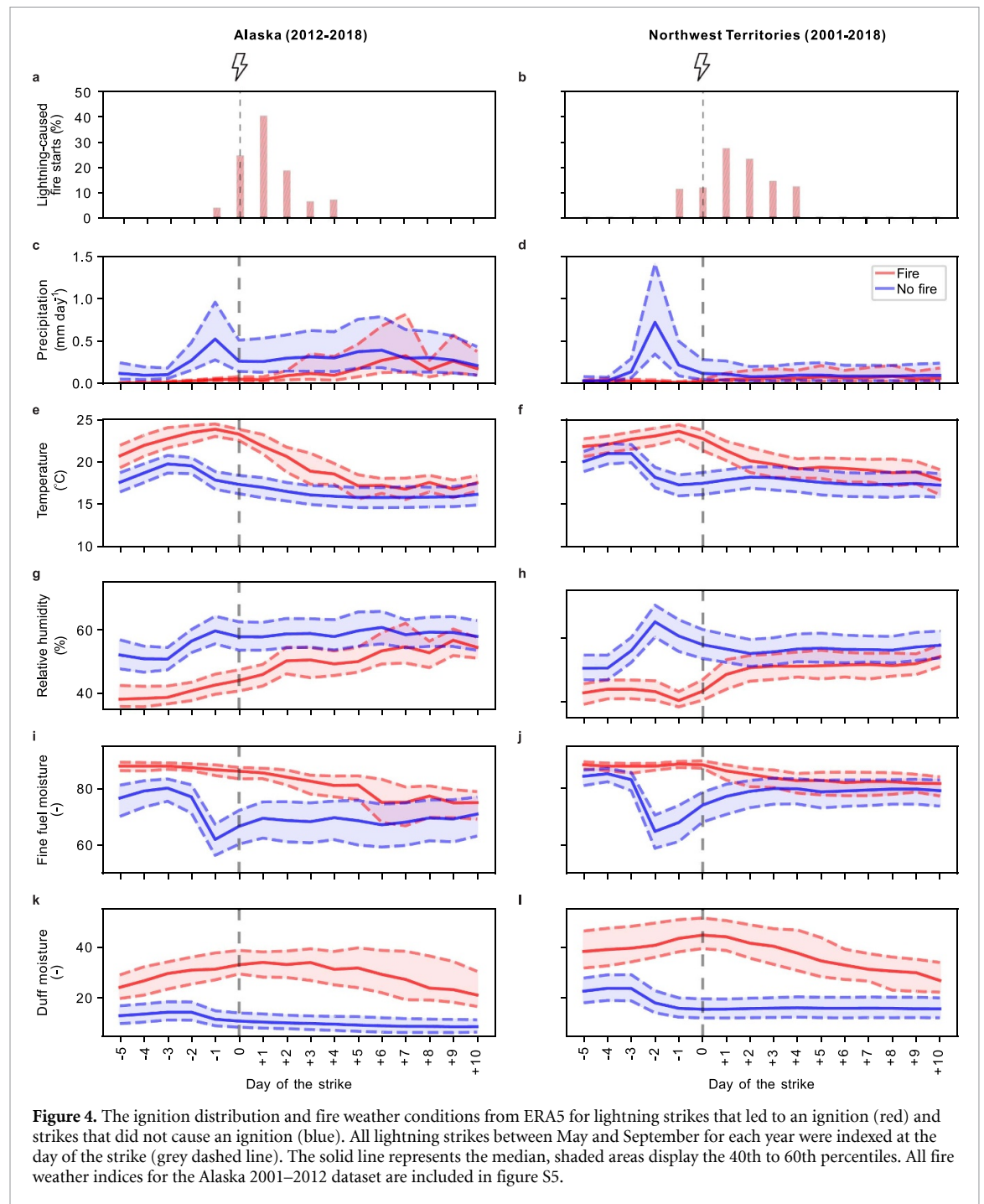
Analyses of logistic regressions (tables S3 and S6) indicated that fire weather is the major driver controlling the lightning ignition efficiency regardless of study region and dataset, and that landscape drivers exerted some control when using the higher resolution lightning dataset of Alaska 2012–2018 (figures 3, S2 and S3). The performance of models using fire weather as the single set of predictors was slightly lower than the model that included all three sets of drivers, regardless of which weather dataset was used (figures S2 and S3). The lightning and landscape characteristics had no influence on the lightning ignition efficiency using the lower resolution

lightning datasets (Alaska 2001–2012 and the Northwest Territories) (figures 3, S2 and S3). Similarly, if we artificially degraded the spatial accuracy of the newest lightning dataset of Alaska 2012–2018 from a 500 m buffer to a 2.5 km buffer, the landscape control on lightning ignition efficiency was no longer apparent (figure S4). The logistic regression models performed slightly better when ERA5 data was used as fire weather data compared to the models that used NARR as fire weather input (figures S2, S3 and table S6).

Characteristics for lightning strikes that caused an ignition and those that did not were inconsistent between regions (table S7). We found a higher likelihood of lightning-caused fire occurrences at lower elevation, likely because these areas are more densely forested (table S7). Lightning-caused fire starts were also more likely to occur with higher tree cover and higher cover of evergreen conifers and generally less herbaceous and deciduous cover ($p < 0.01$; table S7).

Exploration of underlying individual fire weather variables revealed that lightning-caused fire starts were more likely to occur on days with higher surface air temperatures and lower levels of precipitation and relative humidity (figure 4 and table S7). Days with fire starts recorded an average of approximately 1 mm less precipitation, 5 °C higher air temperature, and 16% lower relative humidity than the days with lightning strikes but no ignition (table S7). Lightning-caused fire starts were also associated with drier fuels in the days prior to the strike than lightning strikes that did not yield an ignition (figure 4). We observed higher fuel moisture codes, and thus drier conditions, for lightning-caused fire starts. In Alaska, the FFMC for lightning with ignition was 83.1 ± 9.3 compared to a FFMC of 63.1 ± 19.6 for lightning strikes without ignition. Similarly for the Northwest Territories, the FFMC for lightning with ignition was 84.7 ± 10.3 compared to 67.6 ± 16.9 for lightning without ignition. Other fire weather variables and fuel moisture codes also demonstrated statistically significant separation between the two classes (figure 4 and table S7).

Both surface temperature and relative humidity correlated significantly with a larger probability of a lightning-caused fire. With a warmer surface temperature, the lightning ignition efficiency also increased substantially (Spearman $r = 0.83$, $p < 0.001$ for Alaska and Spearman $r = 0.75$, $p < 0.001$ for the Northwest Territories) (figure S5). We observed an inversed relationship between relative humidity and lightning ignition efficiency (Spearman $r = -0.75$, $p < 0.001$ for Alaska and Spearman $r = -0.68$, $p < 0.001$ for the Northwest Territories) (figure S5). Warm and dry conditions in early summer led to a climatological apex of FFMC and DMC in late June corresponding with the seasonal peak of lightning-caused fire starts for all regions (figure S6). The faster responding FFMC and DMC were more influential than the

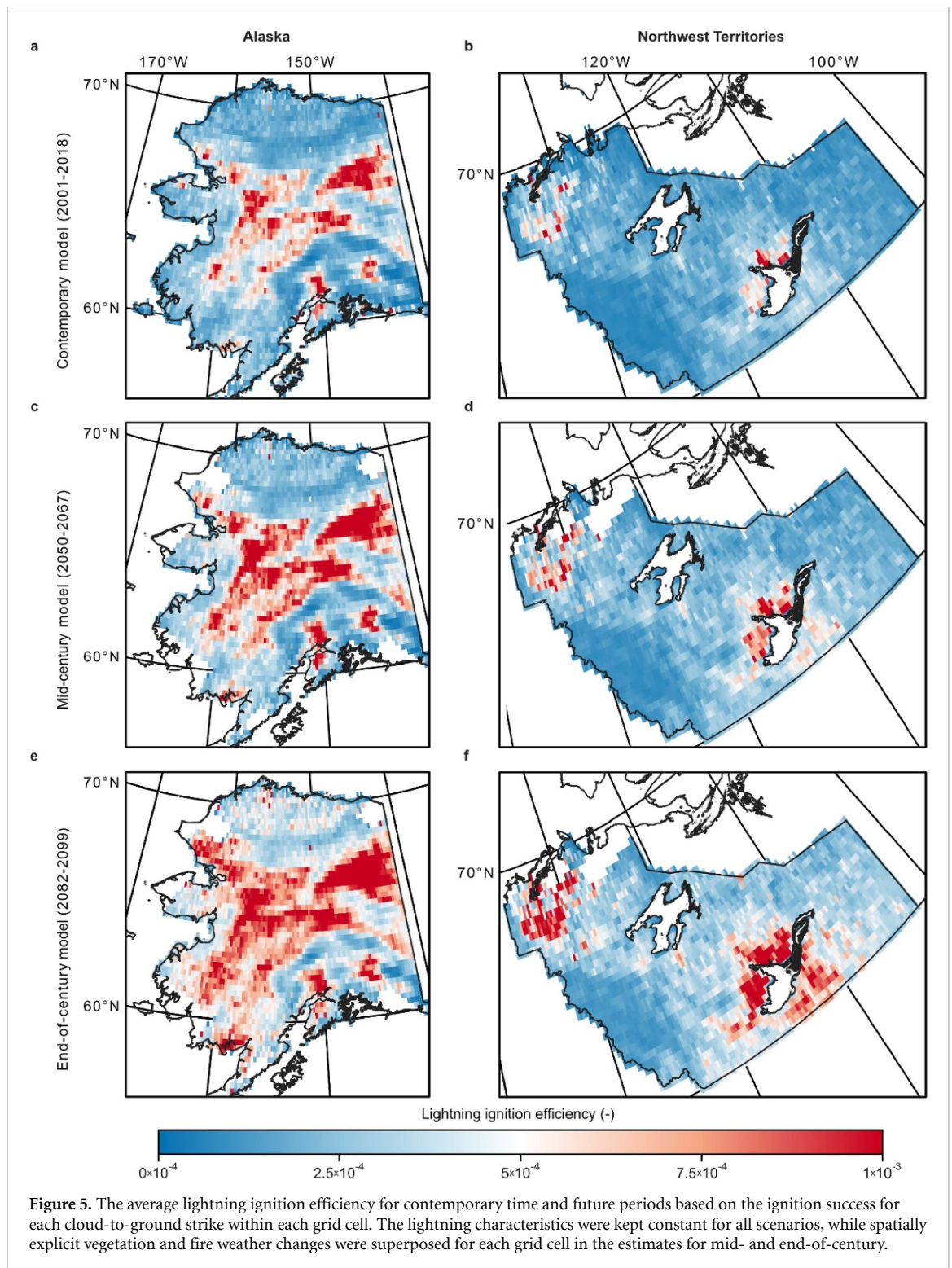


longer-term drying of the thick organic soil layer represented by the DC. Both FFM and DMC correlated with the ignition probabilities retrieved from the logistic models (Spearman $r = 0.78$, $p < 0.001$ for FFM and Spearman $r = 0.66$, $p < 0.001$ for DMC for Alaska, and Spearman $r = 0.76$, $p < 0.001$ for FFM and Spearman $r = 0.77$, $p < 0.001$ for DMC for Northwest Territories).

3.2. Future lightning ignition efficiency and fire occurrences

Between two and five of every 10 000 cloud-to-ground lightning strikes led to a fire start that was detected using MODIS satellite imagery. Specifically,

we estimated that for Alaska the mean contemporary lightning ignition efficiency was about 4.3×10^{-4} and for the Northwest Territories the lightning ignition efficiency was 2.0×10^{-4} during the fire season (figures 5(a) and (b)). We estimated future changes in lightning ignition efficiency using our logistic model that ingested vegetation and fire weather changes. Future climate with shifts in vegetation and drier fuels will result in an estimated $16 \pm 9\%$ relative increase for every 1°C of global warming in lightning ignition efficiency for Alaska, and $23 \pm 16\%$ for Northwest Territories by 2050–2067 (table 1). By the end of the century, estimates of the relative increases for every 1°C of global warming in lightning ignition efficiency



were $14 \pm 9\%$ for Alaska and $31 \pm 28\%$ for Northwest Territories (table 1). Our future estimates of lightning ignition efficiency demonstrated large scale patterns of increased ignition efficiency in Interior Alaska, the lightning prone northwestern tundra region of Alaska, and the southern parts of the Northwest Territories (figure 5). Using our models, we found that our estimates of future changes in lightning ignition efficiency were dominantly driven by future changes in fire weather, with small to negligible effects of

future vegetation changes on lightning ignition efficiency (table S8).

Prior studies have reported increases in lightning between 9 and 37% per 1°C of global warming by mid- and end-of-century (table 1) (Veraverbeke *et al* 2017, Bieniek *et al* 2020, Chen *et al* 2021). These increases in lightning strikes and lightning ignition efficiency will lead to compound effects for lightning-ignited fires. Compared to the contemporary period, we estimate increases in lightning-caused fire starts

Table 1. Future increases per 1 °C global warming increase in lightning ignition efficiency (this study), lightning (previous studies) and combined lightning ignition for mid- and end-of-century relative to the contemporary period. The global mean surface temperature increases of 2.0 °C and 3.7 °C from the high emission RCP8.5 scenario were used for the mid-century and end-of-century scenarios (IPCC 2014). Uncertainty in lightning ignition efficiency was derived from the multi-model standard deviation. The uncertainties in lightning ignition efficiency and lightning were propagated to calculate the uncertainty in future lightning ignition.

Time	Lightning ignition efficiency		Lightning			Lightning ignition	
	Alaska	Northwest Territories	Alaska	Northwest Territories	References	Alaska	Northwest Territories
2050–2067	16 ± 9%	23 ± 16%	30 ± 21%	12 ± 13%	Veraverbeke <i>et al</i> (2017)	51 ± 23%	38 ± 21%
			37 ± 4%		Bieniek <i>et al</i> (2020)	59 ± 10%	
			27 ± 7%	33 ± 5%	Chen <i>et al</i> (2021)	47 ± 11%	64 ± 17%
2082–2099	14 ± 9%	31 ± 28%	23 ± 16%	9 ± 10%	Veraverbeke <i>et al</i> (2017)	40 ± 18%	43 ± 30%
			31 ± 3%		Bieniek <i>et al</i> (2020)	49 ± 9%	
			22 ± 5%	26 ± 5%	Chen <i>et al</i> (2021)	39 ± 10%	65 ± 28%

between 47 ± 11% and 59 ± 10% in Alaska, and between 38 ± 21% and 64 ± 17% in the Northwest Territories per 1 °C of global warming for mid-century. Our estimated relative increases per 1 °C of global warming for end-of-century are between 39 ± 10% to 49 ± 9% more lightning-caused fire occurrences in Alaska, and between 34 ± 30% to 65 ± 28% more lightning-caused fire starts in the Northwest Territories (table 1).

4. Discussion

The dominant driver of contemporary lightning ignition efficiency and future changes in lightning ignition efficiency was fire weather, regardless of region or reanalysis dataset used in our analysis. Our projected increases in lightning ignition may be conservative as the lengthening of the fire season by several weeks (Flannigan *et al* 2013) may further expand the temporal window during which dry fuels and lightning strikes coincide. Recent warming in northwest boreal America has advanced snowmelt in spring (Stone *et al* 2002, Ali *et al* 2012), and early snowmelt has been linked to large fire years in several ecosystems (Westerling *et al* 2006, Semmens and Ramage 2012). The compound effects of earlier drier fuels as consequence of earlier snowmelt (Jandt *et al* 2005) and lightning have the potential to start fire seasons earlier (Westerling *et al* 2006). In the boreal, early season fires can grow larger than late season fires because the probability of fire spreading through larger areas under severe fire weather during the middle of the fire season increases for early season fires (Sedano and Randerson 2014, Veraverbeke *et al* 2017). Additionally, other studies have reported an extension of the growing season and fire season in the fall (Flannigan *et al* 2013, Jolly *et al* 2015), which would further increase the likelihood of large fires. Earlier and warmer springs over boreal North America may trigger a cascade of processes which could increase the

frequency of thunderstorms and lightning. Warming and more frequent heatwaves may result in increased evapotranspiration from vegetation, soils and surface water. The additional water vapor in the atmosphere may feed convection and ice graupel formation in thunderstorms which in turn may lead to more abundant lightning strikes. The co-occurrence of convective precipitation and lightning strikes seems to contradict our finding of dry fuel availability as the main driver of lightning ignition efficiency. Projected increases in vapor pressure deficit over western boreal North America are expected to counterbalance increases in summer precipitation, thereby contributing to surface drying (Chen *et al* 2021). Our findings reinforce the importance of short-term drying of surface fuels for lightning-caused fire occurrences (Wotton *et al* 2010, Abatzoglou *et al* 2016) but also underline the importance of dry lightning as ignition source (precipitation < 2.5 mm d⁻¹ (Dowdy 2020)). Future increases in air temperature may exceed increased in dewpoint temperature which leads to higher cloud base heights and drier lower troposphere (Chepfer *et al* 2014). This can further drive the likelihood of the occurrence of dry thunderstorms and lightning ignitions. Moreover, there is considerable small-scale spatial variability in precipitation associated within single thunderstorm cells. During the same thunderstorm event some locations may experience heavy rainfall, which may constrain ignition, while a few kilometers away, precipitation may evaporate before it reaches the ground thereby making the landscape vulnerable to dry lightning (Rorig *et al* 2007). Fire weather can vary dramatically over short distances in topographically diverse areas such as Alaska. With fire weather being the most important driver, and yet at the coarsest resolution in our analysis, a dynamic downscaling of contemporary and future fire weather and lightning may lead to a better understanding of the interactions between dry fuel availability and lightning. This knowledge is required

to further advance our predictive modeling capabilities of future boreal fires, and their effects on the carbon balance.

We found no major influences on lightning ignition efficiency by lightning and landscape in the Northwest Territories, and the landscape driver only showed some influence on lightning ignition efficiency when using the high-resolution lightning dataset of Alaska (2012–2018). The lightning datasets did not include information on the long-continuing current, which may influence lightning ignition efficiency (Fuquay *et al* 1967, Anderson 2002, Larjavaara *et al* 2005). However, positively charged cloud-to-ground lightning strikes are more likely to sustain long-continuing currents (Saba *et al* 2010). In our analysis, we found that approximately 85% of the lightning-caused fires in the western North America were started by negatively charged cloud-to-ground strikes, resembling the overall distribution of negatively and positively charged cloud-to-ground strike (table S7). This result may imply that the earlier found relationships between long-continuing current and lightning ignitions cannot be generalized and requires further investigation. The most accurate lightning dataset of Alaska 2012–2018 identified a more important role for several individual drivers, and captured smaller-scale influences of vegetation on lightning ignition efficiency that were not apparent when using the other lightning datasets with lower spatial accuracy. This suggests that local topography and vegetation cover influence lightning ignition efficiency. Dense conifer forests exhibited a higher lightning ignition efficiency (table S7), however, this bottom-up control on lightning ignition efficiency is highly localized within the immediate vicinity of the lightning strike. This finding reinforces the need for lightning and land cover datasets with high spatial accuracy and resolution. Currently, the lightning network is dense in the southern boreal forest, yet its detection efficiency and spatial accuracy drop when approaching the ecotone between the boreal forest and tundra (Burrows and Kochtubajda 2010, Farukh and Hayasaka 2012). Chen *et al* (2021) demonstrated that the forest-to-tundra ecotone will be especially prone to increases in lightning with more than a doubling of the amount of lightning by end-of-century. Compounding lightning and dry fuels are already driving tundra fire occurrences in Alaska (He *et al* 2022, Vachula *et al* 2022). Our results reinforce these findings and from our future projections, we expect more frequent tundra fires in the future (figure 5). Carbon emissions from lightning-caused tundra fires may impose a strong positive feedback to climate warming (Mack *et al* 2011). We therefore call for a further northwards expansion and accuracy upgrade of the lightning detection networks for the purpose of better quantifying bottom-up controls and long-term trends in the lightning ignition efficiency.

When projecting the impact of increased deciduousness in future Alaskan forests (Rogers *et al* 2015, Mack *et al* 2021), we found that the landscape control slightly mitigated projected increases in lightning ignition efficiency that are driven by changes in fire weather (table S8). Similar large-scale vegetation conversions (Baltzer *et al* 2021) may also influence lightning ignition efficiency in the Northwest Territories. However, these dynamics were not apparent from our model that was constructed using a lightning dataset with a lower spatial accuracy (table S8). In these modeling efforts, we used existing spatially explicit projections of future vegetation cover over our study regions (Holsinger *et al* 2019, Mekonnen *et al* 2019). Recent efforts have modeled future forest composition and flammability at the level of individual trees for western boreal North America (Foster *et al* 2022), however, such efforts are yet to be conducted in a spatially continuous manner. This type of highly detailed information about vegetation type and flammability could be very valuable to re-evaluate the landscape control on contemporary and future lightning ignition efficiency.

Our work shows the important effects of pre-existing dry fuel availability on the ignition efficiency of lightning and boreal forest fire occurrences. The findings are based on combining three separate modules that estimate changes in vegetation, lightning and ignition efficiency. Our analysis has therefore leveraged the best available datasets on lightning, fire starts, and contemporary and future vegetation and fire weather. Nevertheless, our work urges for a better understanding of the interactions between drought, convection, lightning, vegetation, fuel and fire starts at landscape scale.

5. Conclusion

Our study is the first to assess the interactive effects of lightning, landscape and fire weather characteristics on lightning ignition efficiency in boreal forest ecosystems of Alaska, USA, and the Canadian Northwest Territories. Our findings show lightning ignition efficiency is largely controlled by top-down weather conditions, with a weaker control from plant functional type composition evident when using higher spatial resolution lightning data from Alaska, USA. Lightning ignition efficiency was strongly influenced by short-term (within a day) drying of organic soils. The occurrence of dry versus wet lightning varies at landscape scale and thus exerts an important control over lightning ignition in boreal forests. Combining our estimates of future changes in dry fuel availability, forest cover and lightning resulted in increases in lightning-caused fire starts that are larger than previously estimates from increases in lightning alone. Our work suggests that compound effects of dry fuels and lightning may accelerate the transition of the boreal

biome through increases in fire occurrence and associated burned area and carbon emissions.

Data availability statement

The lightning strike for Alaska are freely available from the Alaska Interagency Coordination Center—Alaska Fire Service (<https://fire.ak.blm.gov/predsvecs/maps.php>). Lightning strike data for the Northwest Territories is available upon request from Environment and Climate Change Canada. Fire ignition data are available from the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics ([10.3334/ORNLDAAC/1812](https://doi.org/10.3334/ORNLDAAC/1812)). Elevation data are available from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 3 (<https://e4ftl01.cr.usgs.gov/ASTT/>). Tree cover data are available from the Terra Moderate Resolution Imaging Spectroradiometer vegetation continuous field product version 6 (<https://e4ftl01.cr.usgs.gov/MOLT/>). The Fuel Characteristics Classification System Fuelbeds for Alaska can be downloaded from LANDFIRE (https://landfire.gov/version_download.php). The MODIS annual land cover of Canada (25 classes) are available from Government of Canada (<https://open.canada.ca/data/en/dataset/39518dfa-bb8d-8a04-b36b-50b4310527a2>). The contemporary fire weather variables were derived from North America Regional Reanalysis (www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr), and from the fifth generation of the European Centre for Medium-Range Weather Forecast; meteorological variables (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview>), and fire weather indices (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-fire-historical?tab=overview>) reanalysis of the global climate Future fire weather was derived from simulations from 16 CMIP5 models. The archived climate model output can be accessed online (<https://esgf-node.llnl.gov/projects/cmip5/>).

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no competing interests.

Code availability

The code used in the analyses is available from the corresponding author upon request.

Additional information

Supplementary information is available in the online version of the paper.

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