

RESEARCH ARTICLE

Evaluating the Alaska Blocking Index as an indicator of wildfire potential in Alaska's central eastern interior

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Abstract

Increased Arctic air temperatures and evaporative fluxes have coincided with more frequent and destructive high-latitude wildfires. Arctic fires impact ecosystems and people, especially at the community-level by degrading air quality, destroying agriculture, and threatening life and property. Central Eastern Interior (CEI) Alaska is one such region that has recently experienced the effects of wildfire activity related to warming air temperatures. To improve our ability to identify fire weather events and assess their potential for extreme outbreaks at actionable lead times relevant to fire weather forecasters and managers, new metrics and approaches need to be established and applied toward understanding the physical mechanisms underlying such wildland fire characteristics. Our study uses a new, regional atmospheric circulation metric, the Alaska Blocking Index (ABI), to describe midtropospheric air pressure around Alaska, which is subsequently related to CEI fire weather conditions at the Predictive Service Area (PSA) scale in climatological and extreme events frameworks. Of note, during years of high fire activity, Build-Up Index (BUI) values tend to be anomalously high during the duff and drought phases across the CEI PSAs, though comparatively lower BUI values are still associated with high fire activity in the Tanana Zone-South (AK03S) PSA. Likewise, extreme BUI values are strongly tied to high ABI values and well-defined upper-air ridging circulation patterns in the duff and drought periods. The statistical skill of mean daily ABI values in the 6–10 day period preceding extreme duff period BUI values is modest ($\tau^2 > 14\%$) in the Upper Yukon Valley (AK02) PSA, a hotbed of

Robert Ziel: Retired.

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wildland fire activity. Extremes in ABI and CEI BUI often occur in tandem, yielding regional predictability of upper-air weather patterns and extremes and underlying surface weather conditions, by statistical and/or dynamical forecast models, imperative for local community and governmental organizations to effectively manage and allocate Alaska's fire weather resources.

KEYWORDS

Alaska, blocking, fire weather

1 | INTRODUCTION

Surface air temperature warming and an invigorated hydrologic cycle are hallmarks of recent Arctic change (Box et al., 2019). While high-latitude air temperature and moisture patterns and trends are inhomogeneous in space and time, prolonged localized warming, sometimes concurrent with extreme heat events, coupled with drought conditions can create an environment ripe for wildland fire outbreaks. The frequency of these extreme events in the Arctic, like the atmospheric conditions that support them, are spatiotemporally variable (Justino et al., 2023). However, satellite observations have shown an increase in burned area suggestive of prevalent fire activity through time across Alaska's mainland (York et al., 2020), a region noted for widespread warming and an uptick in extreme temperature events during the summer fire season (Ballinger et al., 2023; Bieniek & Walsh, 2017). Anomalously high fire activity, defined as >1 million acres burned, occurred in Alaska during six fire seasons between 1980 and 2020, including during 2019, causing destruction of housing and businesses, widespread power losses, and yielding negative impacts on the region's tourist-driven economy (York et al., 2020).

Summertime heat events conducive to enhanced surface evaporative fluxes and drying across the North American high latitudes are often associated with overlying midtropospheric ridging, or "blocking," circulation patterns (Jeong et al., 2022). These atmospheric patterns may not only precondition the landscape for fire outbreaks through snow-albedo and/or thermodynamic (melt) feedbacks, but may also exacerbate existing fire activity originating from anthropogenic or natural (i.e., lightning) origins (Hayasaka, 2022). The midtropospheric air pressure over Alaska has increased, perhaps as a response to regional warming, in all months and seasons from 1991 to 2020 (Ballinger et al., 2022). These increases in air pressure aloft may be representative of more frequent and/or intense blocking events through time. However, the physical rationale linking domain-averaged air pressure changes in modern global

atmospheric reanalyses to the development of atmospheric blocking signatures in reality can be obscured by the choice of blocking metric(s) analysed (Henderson et al., 2021). Therefore, metric selection is imperative toward identifying and potentially understanding physical connections between blocking patterns and attendant Alaska wildland fire incidence and extremes.

To the latter point, our study will use a relatively new, regional atmospheric circulation metric, the Alaska Blocking Index (ABI; Ballinger et al., 2022), to examine Alaska's surface fire weather as a function of localized weather pattern forcing. The advantage of using this new index is that it has been sensitivity tested, both to geographic shifts in the domain over which the index is calculated as well as in a relative sense to changes in the circum-Arctic midtropospheric pressure field that may arise due to Arctic warming (see Ballinger et al., 2022, sect. 2.2). Thus, for being a relatively simple atmospheric circulation index, the ABI is a robust indicator of regional circulation variability through time (see section 2 for further description). Additionally, to understand how the ABI relates to Alaska fire activity, we use the well-established Build-Up Index (BUI), which is a key component of the Canadian Forest Fire Weather Index (FWI) System and indicator of potential wildfire behaviour (Van Wagner, 1987). The BUI describes the total amount of fuel available in the duff layers for fire consumption and is considered a representative index for landscape flammability based on near-term weather conditions and cumulative drying through the fire season. As an integrated proxy of surface meteorological conditions, the BUI tends to scale (increasing from 0) in conjunction with higher probability of Alaska fire impact (Ziel et al., 2020), rendering it a useful parameter for evaluating potential surface fire weather responses to overlying changes in atmospheric circulation.

Our goal in this study is to evaluate the efficacy of the ABI as an indicator and short-term predictor of Alaska fire weather conditions. To this end, our study has the following objectives: (1) chronicle climatological ABI and fire weather conditions across the fire season, (2) investigate physical settings and temporal relationships between

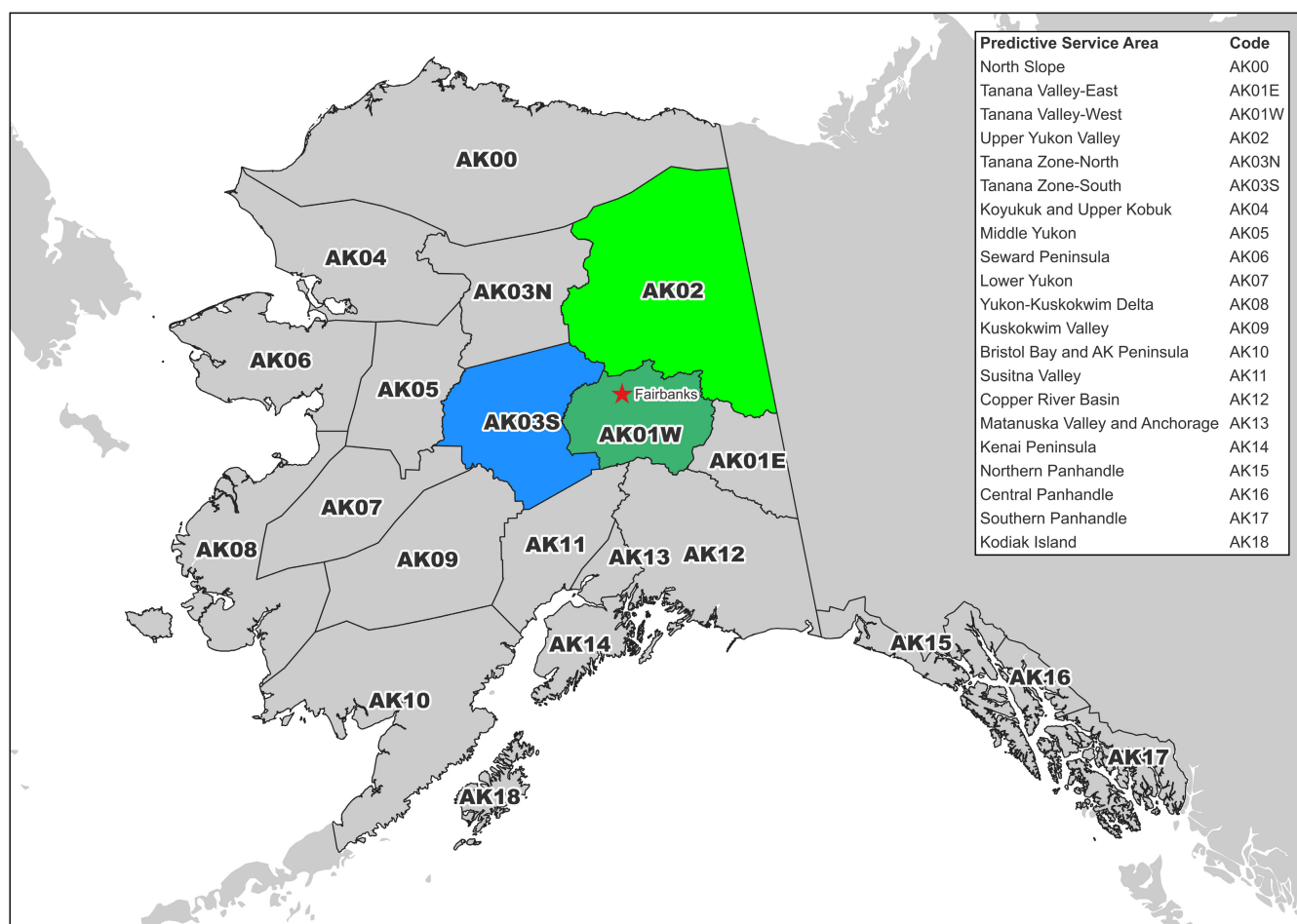


FIGURE 1 Map of Alaska Predictive Service Areas (PSAs) with central eastern interior (CEI) Alaska PSAs of focus, AK01W, AK02 and AK03S, shown in non-grey shading. A star is placed at Fairbanks where the Fairbanks NWS and Munson Ridge SNOTEL sites are approximately located.

the ABI and fire weather conditions and (3) explore the incidence of extreme ABI and BUI values and assess the short-term statistical hindcast predictability, at meteorological-scale lead times (out to 20 days), of the ABI toward capturing intraseasonal *peaks* in fire weather conditions (i.e., BUI extremes). This final step in our analysis highlights a key subseasonal forecasting time window (out to 3 weeks), which, if improved, would benefit Alaska's local communities and wildland fire resource managers and their mobilization efforts.

2 | DATA AND METHODS

2.1 | The temporal limits of the fire season

The AK fire season consists of four phases or periods that occur in succession and are defined based on associated physical drivers of fire activity. We use the Interior

Alaska climatological date ranges determined by Dollard (2020) that have been used in other Alaskan fire analyses (e.g., Sampath et al., 2021), beginning with the wind-driven (i.e., wind; 1 April–10 June), followed by the duff-driven (i.e., duff; 11 June–9 July), drought-driven (i.e., drought; 10 July–15 August), and concluding with the diurnal period (i.e., diurnal; 16 August–30 September). Statistics of these four phases of the fire season are calculated at the Predictive Service Area (PSA) spatial scale, which was established in 2001 based on climatic, ecological and fire history and management considerations (Ziel et al., 2020). For nearly two decades, the Alaska Interagency Coordination Center has used these PSAs for operational forecasting purposes, including for weather-scale fire outlooks. We focus on Alaska's Central Eastern Interior (hereafter CEI for short) PSAs (Figure 1), which include Tanana Valley-West (code: AK01W; 770 m asl maximum weather station elevation), Tanana Valley-East (AK01E; 735 m asl), Upper Yukon Valley (AK02; 885 m asl), Tanana Zone-North (AK03N;

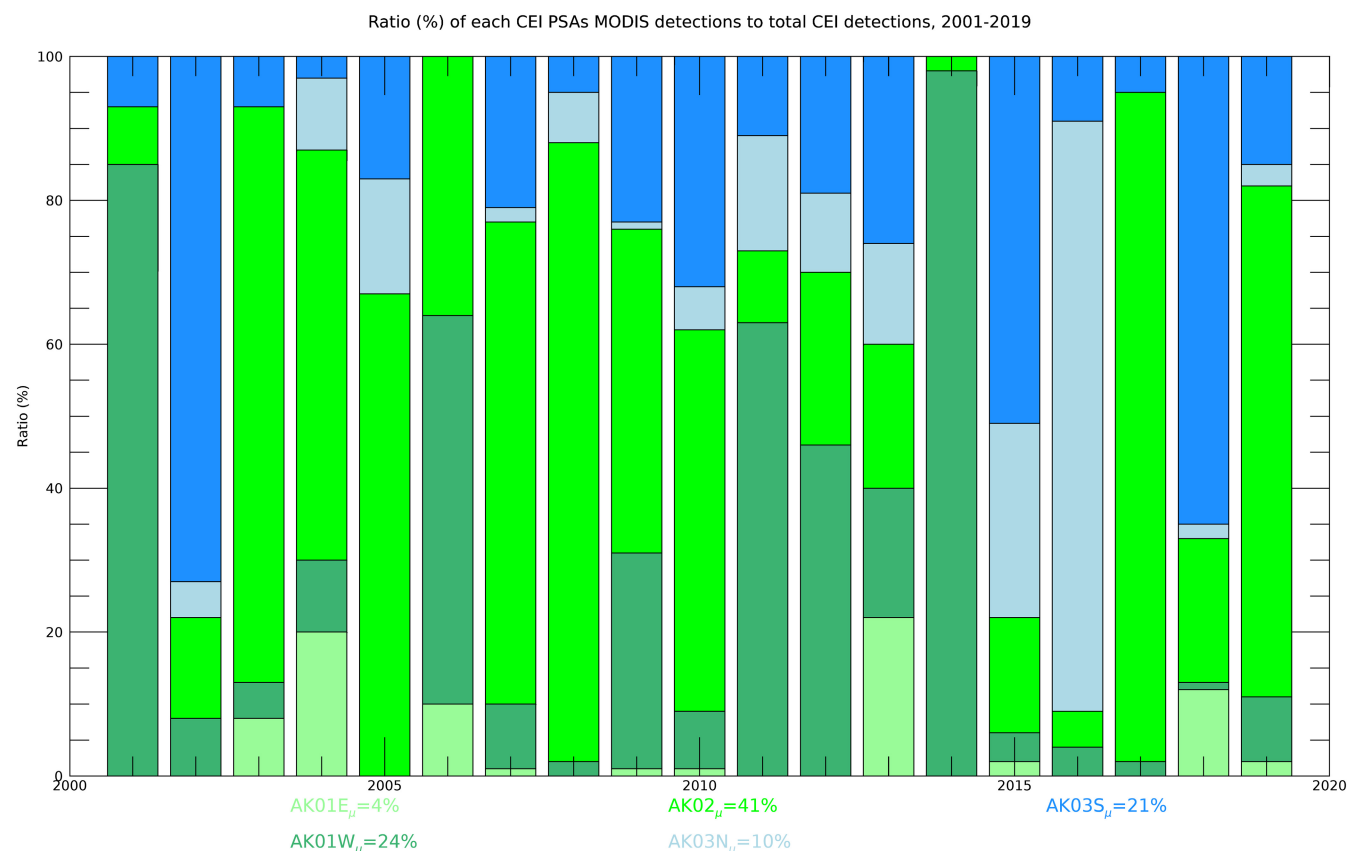


FIGURE 2 Ratio (%) of each CEI PSA's MODIS fire detections to the total CEI detections across sites from 2001 to 2019. The average (μ) percentage of fire detections at each PSA from 2001 to 2019 is shown below the time series with AK01W, AK02 and AK03S averaging 86% of detections within the CEI subregion.

255 m asl) and Tanana Zone-South (AK03S; 630 m asl). Fires detected within these five CEI PSAs account for $\sim 70\%$ of statewide fire detections captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) Active Fire Product since 2001 (Figure S1, Supporting Information). Upon closer inspection of interior PSAs' fire detections from 2001 to 2019, fires observed in AK01W, AK02 and AK03S represent $\sim 86\%$ of the total CEI fires detected (Figure 2). The high relative frequency of fires within these three PSAs compared to the other CEI PSAs motivates our focus on them in analyses that follow.

Snow-off is a key determinate of fire season onset and the initiation of interannual fire index calculations (e.g., BUI, etc.). We briefly look at the start of the wind-driven period by examining the first MODIS fire detections for the Alaska CEI PSAs against observed snow-off, defined here as the last day when $\geq 1''$ snow depth is measured, at the Fairbanks National Weather Service (NWS) offices and Munson Ridge Snow Telemetry (SNOTEL) sites. Snow-off dates from 2001 to 2019 from the Fairbanks NWS offices—located at the Fairbanks International Airport 2001–

2018 (~ 137 m msl) and since 2018 at the Syun-Ichi Akasofu Building on the University of Alaska Fairbanks campus (~ 183 m msl)—and the Munson Ridge (~ 945 m msl) site, are overlaid as a proxy for end-of-season snowmelt timing in Figure S2. The fire weather indices (i.e., BUI) are operationally calculated when the surrounding area is essentially snow-free (Lawson & Armitage, 2008), which here we interpret as the snow-off date. The mean 2001–2019 snow-off for Fairbanks is DOY 112 (22 April in non-leap years). For a common 30-year baseline (1981–2010), this date of snowmelt is similar at DOY 113 (23 April). Of note, the earliest snow-off, 3 April, occurred in 2019. Using MODIS data, Lindsay et al. (2015) showed that the average last date of snow cover from 2001 to 2013 was relatively consistent across the Alaskan interior except in areas of complex terrain, which are partially masked out during construction of our surface fire weather index (i.e., BUI; see Section 2.2) Considering all this information, we elect to use 1 April as the consistent beginning date of the wind-driven phase marking the approximate start of the annual CEI fire season (i.e., wind period).

2.2 | Surface and upper-air datasets

Satellite-derived active fire detections, binned within the Alaska PSAs, are derived from the MODIS Terra and Aqua satellites as described in Ziel et al. (2020). Binary fire presence versus absence has been recorded by Terra since 2001, and this fire detections data product has been extensively quality controlled with a ~97% detection rate (Ziel et al., 2015). Our study includes the MODIS detections spanning 2001–2019 (when this analysis was initiated) as part of comparisons of fire activity captured by the MODIS retrievals against fire weather and fuel conditions described by the BUI.

Aridity is a key characteristic in fire-prone environments. As such, we use an integrated surface weather metric commonly used operationally by Alaska's fire managers and forecasters as well as by academic researchers, the BUI (Stocks et al., 1989), to evaluate flammability and fuel availability at the PSA scale. Fire season severity scales have evolved out of the Canadian Forest Fire Danger Rating System. The BUI specifically has been shaped by the Canadian Forest FWI System, whereby surface air temperature, relative humidity, and precipitation at the daily scale are used to categorize fuel moisture through two codes, the Duff Moisture Code and the Drought Code. These two codes collectively lie at the core of the BUI. This unitless index adheres to five approximate classes: low (BUI = 0–39.9), moderate (40–59.9), high (60–89.9), very high (90–109.9) and extreme (110+).

The BUI version analysed here is from McElhinny et al. (2020). It is derived using meteorological data from ERA5 reanalysis (Hersbach et al., 2020), which are masked following the maximum surface weather station altitude within each PSA (≤ 885 m across all five PSAs surveyed; see individual PSA's maximum station elevation listed in section 2.1). Atmospheric reanalyses offer coherent spatial and temporal coverage in high-latitude environments where observations, including those from surface weather stations, are sparse. Due to differences in underlying model physics, data assimilation systems, and model parameterizations, intercomparisons of reanalysis products often yield different results, and thus biases against observations can vary by reanalysis product. That said, ERA5 surface air temperature and precipitation, two key parameters that comprise the BUI, have been shown to compare favourably against observational products including with regard to trends in Arctic terrestrial weather extremes (Avila-Diaz et al., 2021) thus supporting use of this reanalysis in our study.

Alaska's surface weather and climate is strongly governed by large-scale diabatic processes and atmospheric advection of air masses (Ballinger et al., 2022; McLeod

et al., 2018). As such, we utilize the ABI herein to diagnose circulation pattern intensity and extremes. ABI, version 2 (Ballinger et al., 2022) describes the daily, domain-averaged 500 hPa geopotential height field (in meters) atop Alaska from 55°–75°N, 125°–180°W. A positive (negative) ABI is associated with high (low) mid-tropospheric pressure and a ridge (trough) atop Alaska and tends to favour warming (cooling) over the Alaskan interior through the fire season months (Ballinger et al., 2022). Simply put, the larger the absolute ABI departure from the day-of-year ABI climatological mean tends to signify the magnitude of respective circulation pattern extremes (e.g., anomalous upper-level cyclones or anticyclones).

2.3 | Methodological approaches

To construct time series, daily BUI values by PSA and the daily ABI values are averaged over the duration of each fire season's phase (i.e., climatological date ranges for the wind, duff, drought, diurnal periods outlined in section 2.1) and for each year. We elect to sum MODIS fire counts over the respective climatological phases as these phases tend to contain examples of either low interannual counts and/or fires missed by MODIS tracking that could impact averaged values. In the absence of fire detections, "0" fires are recorded, while only days that register BUI > 0 are used to calculate BUI means by fire phase per year.

We examined the data distributions quantitatively prior to conducting statistical analyses of fire weather and atmospheric circulation relationships. Given the short overlap period between the MODIS fire retrievals that originate in 2001 and the reanalysis-derived BUI and ABI, we selected and applied two robust tests of small dataset normality (i.e., $n \leq 20$ years) to all the fire season-binned time series, the standardized skewness metric (S) and the Shapiro–Wilk (W) test (Mahmoudi et al., 2020; Royston, 1992). Both tests indicate that MODIS fire detection counts across all three CEI PSAs and in all four fire seasons *are not* normally distributed (Table S1). Likewise, the BUI and ABI values exhibit some non-normal statistical characteristics, but not across all seasons and PSAs. For example, AK01W, AK02 and AK03S BUI values are skewed/non-normal (where the W test null hypothesis of data sample normality is rejected) in the duff, drought and diurnal phases, but not in the wind period. The ABI is skewed in the duff and diurnal phases, but does not meet the W test criteria in any of the phases to be considered non-normal. These results inform selection of forthcoming statistical tests.

MODIS, BUI and ABI temporal variability and their relationships are evaluated through multiple approaches. We examine these indices through a climatological lens, that is by comparing day of year mean values during the study period (2001–2019). We subsequently composite ABI and BUI values, averaged over the fire season, by <25th (i.e., low) and >75th (i.e., high) fire count occurrences each year since 2001. By constraining the composites to quartiles, we isolate the five most and least active fire years by phase across CEI PSAs. BUI and ABI daily values are then averaged for all days within that phase where BUI > 0 to obtain the 25th/75th percentile composites. For comparison against average ABI and BUI, average values are defined as all days within each phase that do not fall within the high or low categories where BUI > 0 across 2001–2019. In the event of >5 cases where seasonal fire activity is suppressed (e.g., AK03S during wind period and all CEI PSAs during the diurnal period when several years showed no fire activity), we select composite ABI and BUI values based on low/no fire occurrence in adjacent CEI PSAs during the same phase. We use a non-parametric Mann–Whitney U test to determine statistically significant differences ($p \leq 0.05$) in BUI and ABI mean values between these categories. ERA5 500 hPa geopotential height fields are also mapped following the composite criteria.

To further examine bivariate relationships between MODIS counts, and BUI and ABI values for different fire season phases, we use a Kendall's tau (τ) correlation approach (Kendall, 1938). It is a nonparametric technique that is not constrained by underlying statistical distribution assumptions, similar to its Spearman's rho counterpart, but is comparatively more robust when small sample sizes are analysed.

We build upon the climatological analyses and look deeper into extreme atmospheric conditions associated with fire weather by identifying extreme BUI and ABI days (e.g., where ≥ 95 th percentile index values are found within each of the respective wind, duff, drought and diurnal phases). As an example, 19 July 2019 observed an ABI = 75.37, which fell in the 96th percentile of all duff-season (i.e., 11 June–9 July) days ($n = 2466$) that occurred from 1979 to 2020. This identification process is iterated for all ABI and BUI values over the reanalysis-derived BUI record (back to 1979), and we correlate these extreme value counts, by phase, as a function of time.

Lastly, we apply a simple, nonparametric hindcast statistical model to evaluate the ABI's ability to explain the BUI extreme's variance. To do this, we use a squared Kendall's tau (τ^2) correlation approach to assess mean ABI values' hindcast ability at meteorological scales (e.g., 1–5 days, 6–10 days, 11–15 days

and 16–20 days) to predict ensuing BUI extremes within each fire season phase. Correlation analyses are presented with raw data and with trends removed; the latter is done to decrease the likelihood of a false or amplified bivariate associations that could arise in error from temporally coherent changes in the respective time series.

3 | RESULTS

3.1 | Climatological fire incidence and corresponding surface and upper-air conditions

A comparison of fire counts and mean surface (i.e., BUI) conditions by PSA alongside the large-scale, upper-air pattern magnitude (i.e., mean ABI) from 2001 to 2019 provides insight on the climatological evolution of these surface-atmosphere conditions during the CEI fire season. At AK01W, cumulative fire activity ramps up within the middle of the duff period in late June/early July, then again in early August amidst the middle of the drought period (Figure 3a). The duff period fire maximum is generally preceded by two moderate BUI peaks. One peak is found in the late wind period, and the other BUI peak tends to occur in the days leading up to and overlapping the fire count maximum. The latter BUI peak also precedes the drought fire count peak by roughly 1 month (Figure 3b). As the fire season progresses through boreal summer (JJA), the ABI exhibits a non-monotonic increase due to the proportional relationship between air pressure and temperature against background weather pattern variability (i.e., the passage of transient storm systems; Figure 3c). The ABI day-of-year climatologies are similarly overlaid in Figures 4c and 5c for consistency and comparison with PSA-specific MODIS fire detections and BUI values.

The strongest correlative relationships across the three CEI PSA's MODIS fire counts, BUI values, and the ABI tend to occur in the wind and diurnal phases (τ correlation coefficients are shown to the right of the time series in Figures 3–5). These relationships are robust ($\tau \geq 0.46$) and reflect both the trends with increasing (decreasing) fire incidence and drying (wetting) of surface layers reflected in rising (falling) BUI and ABI values as the season commences (concludes). With trends removed to isolate phase-specific variability, the strongest, statistically significant variability at AK01W is shown between MODIS and BUI ($\tau = 0.29$) and between BUI and ABI during the diurnal period ($\tau = 0.41$). Fewer significant correlations with

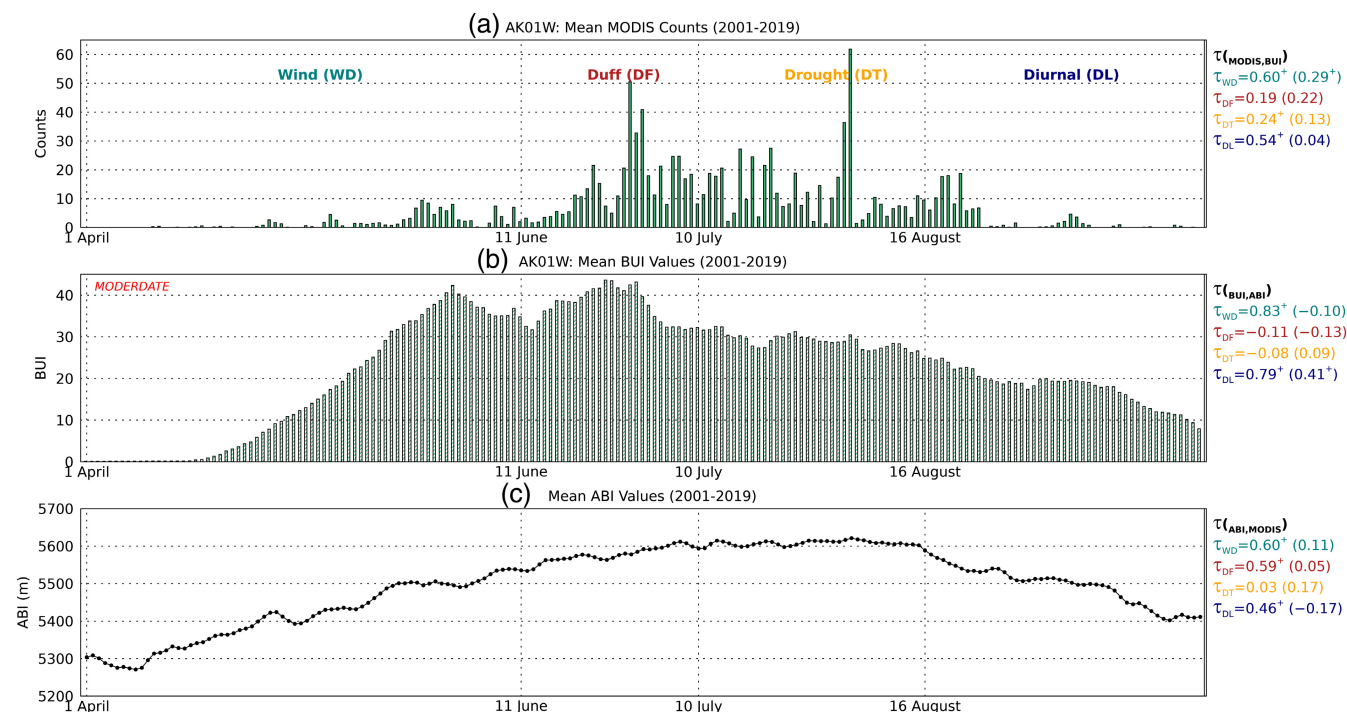


FIGURE 3 AK01W day of year climatologies (2001–2019) across the fire season for (a) MODIS counts, (b) BUI and (c) ABI. The wind (WD), duff (DF), drought (DT) and diurnal (DL) phases are colour coded. Kendall's tau (τ) correlations are given to the right of the panels with detrended correlations are provided in parentheses. As an example, the MODIS correlation with BUI during the wind phase is calculated across all daily averaged MODIS fire counts and BUI values from 1 April–10 June ($n = 71$ days). Statistically significant correlations ($p \leq 0.05$) are marked with a plus (+) superscript symbol.

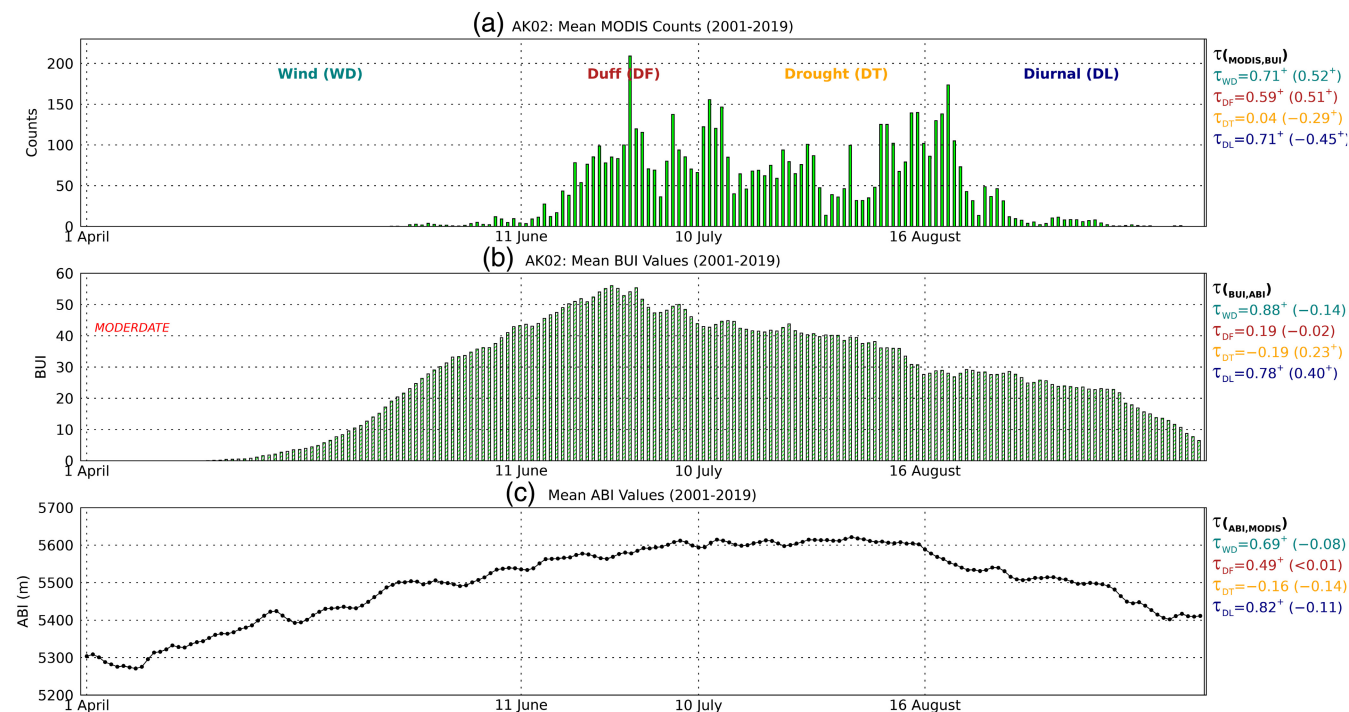


FIGURE 4 AK02 day of year climatologies (2001–2019) across the fire season for (a) MODIS counts, (b) BUI and (c) ABI. The wind (WD), duff (DF), drought (DT) and diurnal (DL) phases are colour coded. Kendall's tau (τ) correlations are given to the right of the panels with detrended correlations are provided in parentheses. Statistically significant correlations ($p \leq 0.05$) are marked with a plus (+) superscript symbol.

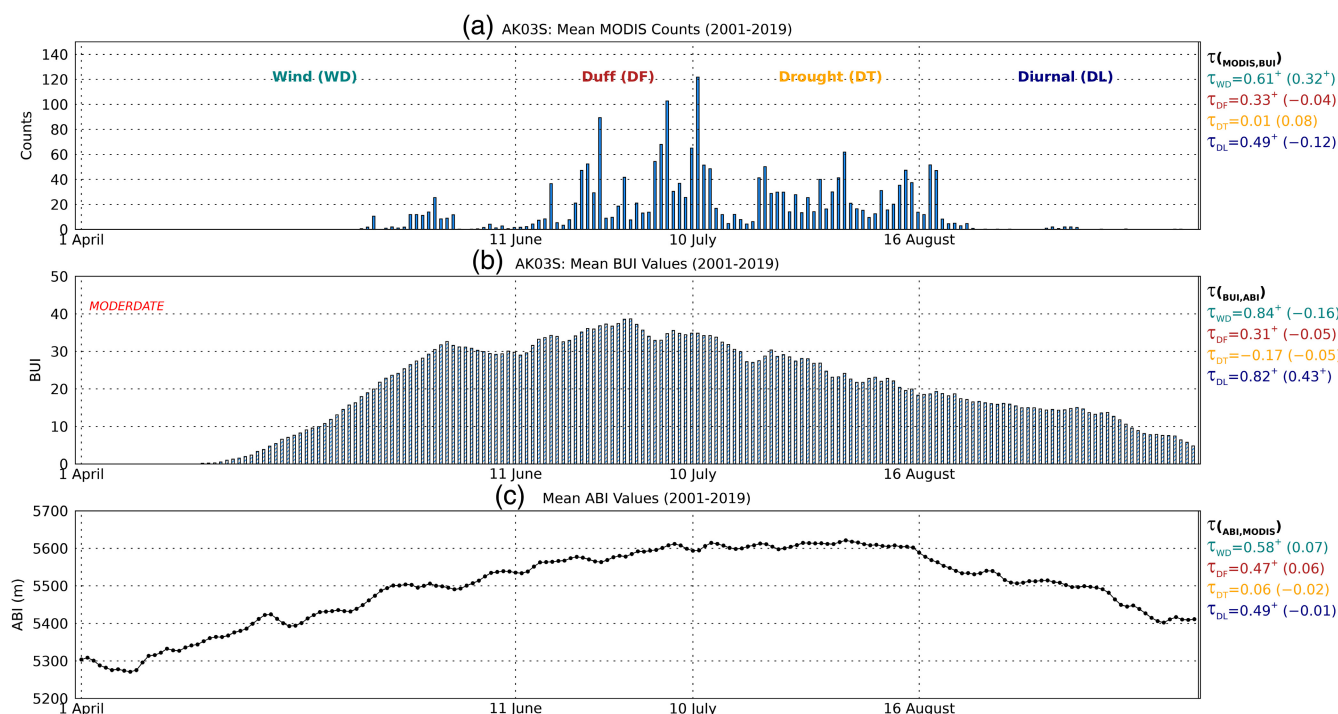


FIGURE 5 AK03S day of year climatologies (2001–2019) across the fire season for (a) MODIS counts, (b) BUI and (c) ABI. The wind (WD), duff (DF), drought (DT) and diurnal (DL) phases are colour coded. Kendall's tau (τ) correlations are given to the right of the panels with detrended correlations are provided in parentheses. Statistically significant correlations ($p \leq 0.05$) are marked with a plus (+) superscript symbol.

detrended data may reflect intraseasonal and interannual variations not well captured by analysing the climatological period.

At AK02, two distinct climatological fire peaks are shown with one in late June in the core of the duff period and the other in mid-to-late August within the diurnal period (Figure 4a). It is important to note that the diurnal peak for this PSA is mainly a function of exceptional late-season fire activity in 2004 (not shown). Similar to AK01W, in tandem with a rise in satellite-detected fires, the duff period maximum is preceded by a steady rise in BUI values. Over the 2 weeks leading up to peak fire activity, the daily-averaged BUI exceeds the moderate category (Figure 4b). However, in the weeks prior to the diurnal period peak in fire detections the BUI values decline, then stagnate at ~ 30 (i.e., within the low class) in the 4–5 days leading up to, overlapping, and following this peak. We again recommend cautious interpretation of AK02 MODIS-BUI diurnal relationships in this case given the role that the anomalously late 2004 fire activity plays in shaping the 20-year MODIS climatology.

The most significant correlations across the four fire season phases are found at AK02. Similar to AK01W,

AK02 fire detections, BUI values, and the ABI correlations are highest, where the trends are included, in the wind and diurnal phases of the fire season across variables ($\tau \geq 0.71$; Figure 4). With trends removed, MODIS and BUI relationships are statistically significant in the wind ($\tau = 0.52$) and diurnal phase ($\tau = -0.45$), respectively (Figure 4a), while the BUI and ABI correlation in the latter phase is also significant ($\tau = 0.40$; Figure 4b). Detrended correlations are also significant between MODIS and BUI in the duff phase ($\tau = 0.51$) and drought phase for BUI versus MODIS ($\tau = -0.29$) and ABI ($\tau = 0.23$), respectively.

There are three peaks in climatological fire detections at AK03S, one in late June and two close together in the first half of July (Figure 5a). As with the aforementioned CEI PSAs, BUI values rise in the weeks preceding the fire onset, but unlike AK01W and AK02 the mean BUI does not exceed 40, the moderate threshold (Figure 5b). BUI values at AK03S show a multimodal distribution with local maxima that occur roughly 7–10 days before the late June and initial July peak in detected fire activity.

As with AK01W and AK02, MODIS fire counts, BUI, and ABI are most strongly related, with trends included, during the wind and diurnal phases ($\tau \geq 0.49$; Figure 5). Similarities are also found across PSAs with statistical

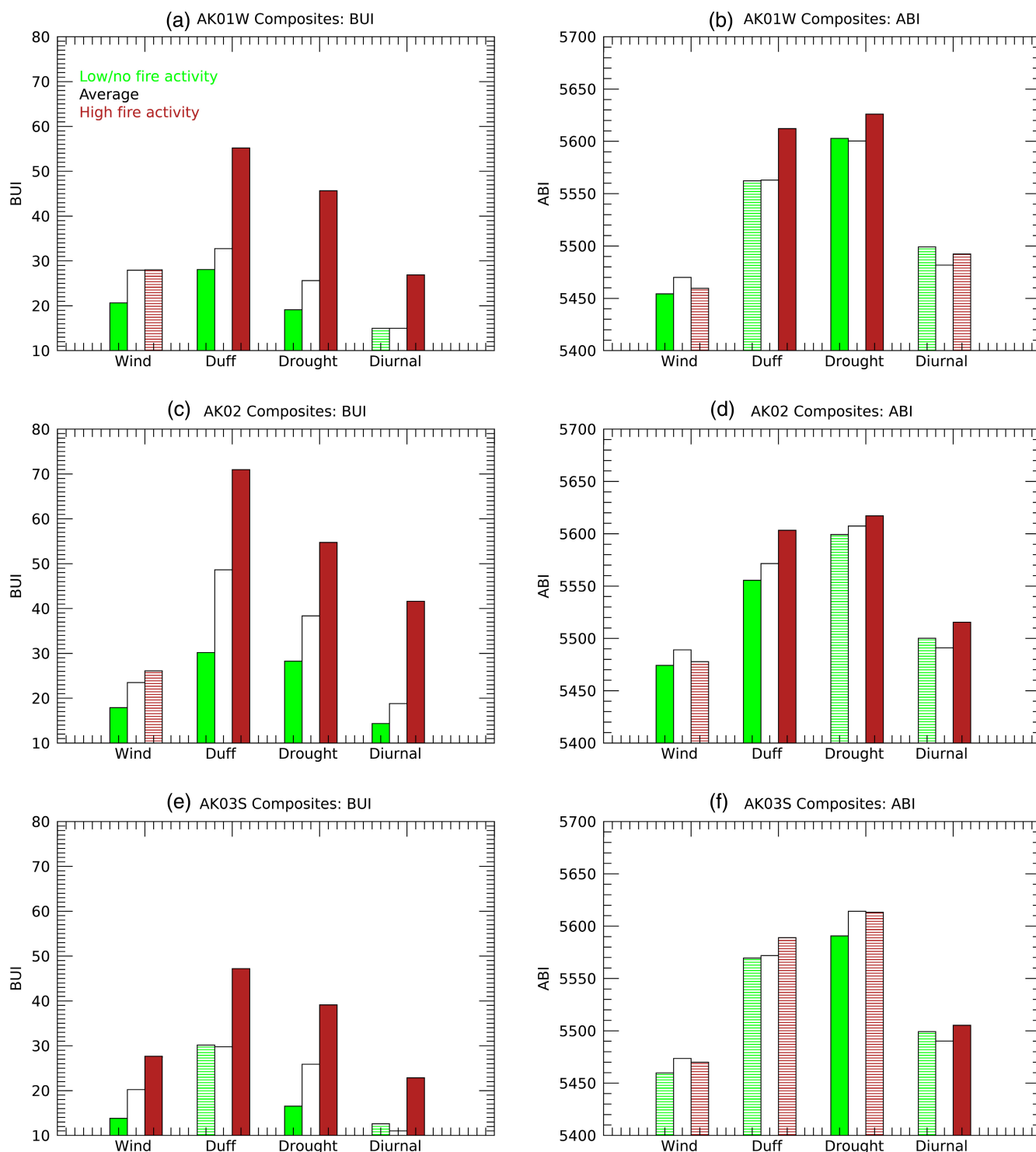


FIGURE 6 BUI (left column) and ABI (right column) mean conditions during anomalous CEI MODIS fire detections (during 2001–2019) for: (a, b) AK01W, (c, d) AK02 and (e, f) AK03S for each fire phase. Anomalous cases are defined as <25th (low fire activity; lime bars) and >75th percentile (high fire activity; dark red bars) total MODIS counts within each phase at each PSA. Average values represent all days within each phase that are not categorized into high or low fire years where BUI > 0 (white bars). Statistically significant high or low differences from average BUI or ABI ($p \leq 0.05$) are indicated by bars with solid fill. Differences between high and low BUI or ABI values are shown in Figure S3.

significance noted between diurnal phase BUI and ABI in the raw correlations ($\tau \geq 0.78$), while detrended correlations are relatively weaker ($\tau \geq 0.40$), yet remain

statistically significant. At AK03S, fire counts, BUI, and ABI associations are also significant with trends included.

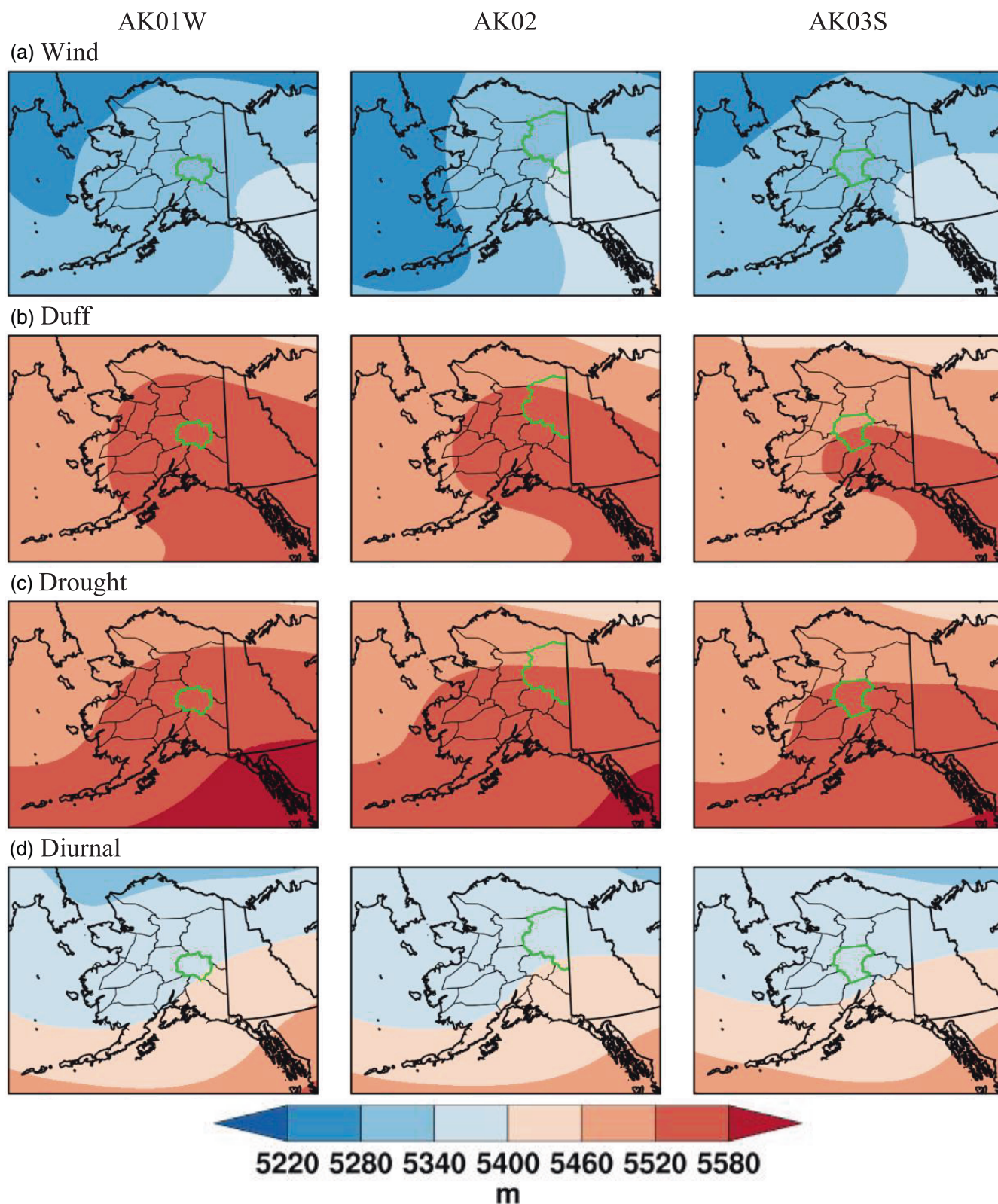


FIGURE 7 500 hPa geopotential height fields (in meters (m)) for respective fire season phases for high (>75th percentile) MODIS count years. The three respective CEI PSAs focused upon are labelled by column and are outlined in green with fire season phase shown row wise as (a) wind, (b) duff, (c) drought and (d) diurnal.

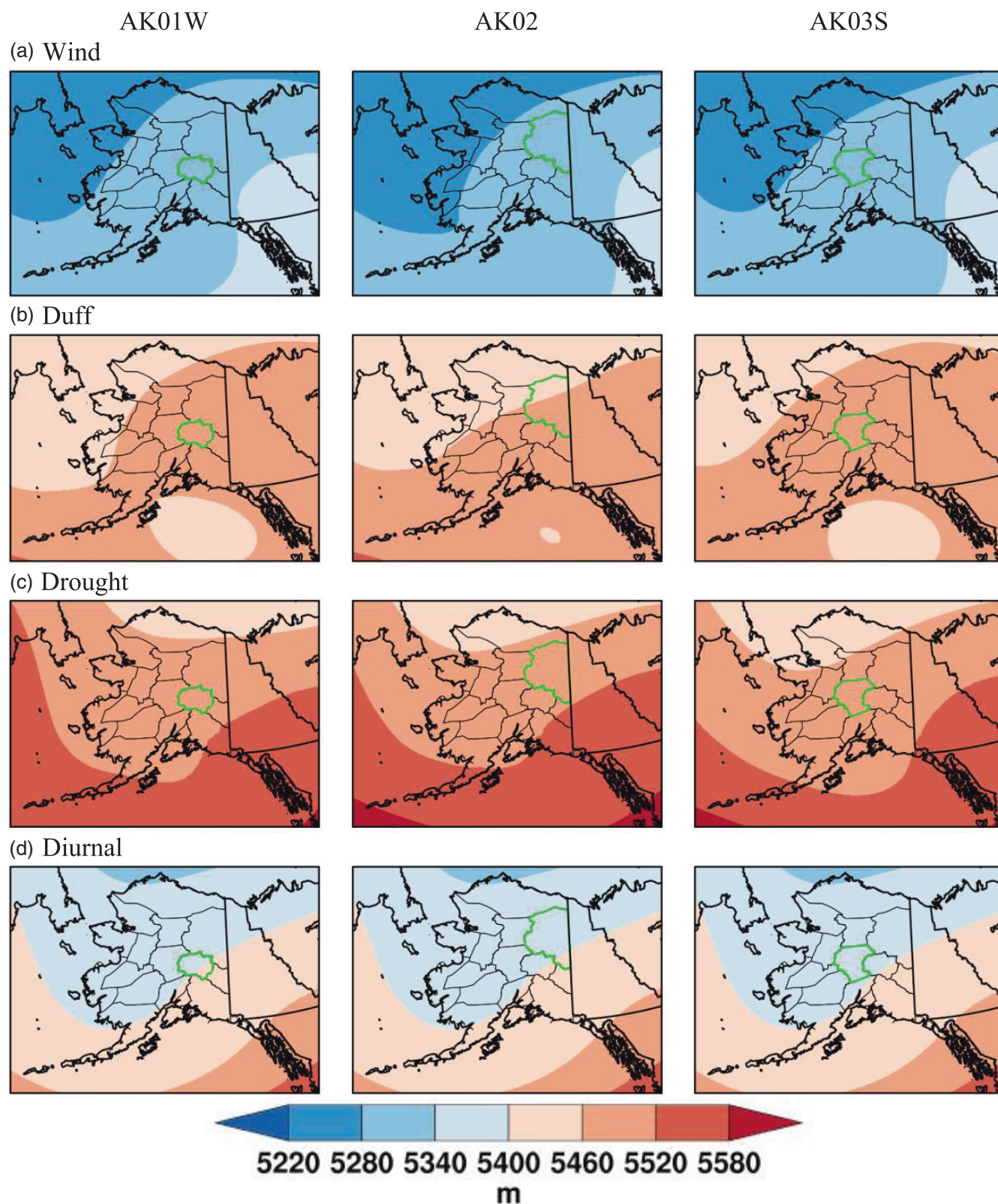


FIGURE 8 500 hPa geopotential height fields (in meters (m)) for respective fire season phases for low (<25th percentile) MODIS count years. The three respective CEI PSAs focused upon are labelled by column and are outlined in green with fire season phase shown row wise as (a) wind, (b) duff, (c) drought and (d) diurnal.

3.2 | Atmospheric composites based on high and low fire years

Recognizing the inherent interannual variability and nonlinearity within and between fire seasons (e.g., onset and conclusion of each fire season, and total acres burned between each phase within a season and between consecutive full fire seasons), we identify years of high and low MODIS-identified fire activity and the surface-atmosphere conditions associated with them. To this end, we examine mean BUI and ABI daily values based on <25th (low/no) and >75th (high) percentile fire occurrences in each fire season phase (these years are explicitly listed in Table S2).

Figure 6 shows these composite BUI and ABI values following the aforementioned composite criteria. In each case, high fire cases have elevated BUI with the largest, statistically significant departures from average BUI values ($p \leq 0.05$) shown in the duff and drought phases across each of the PSAs (Figure 6a,c,e). Within these phases, generally the largest BUI values (BUI >45 indicative of at least moderate surface conditions for potential wildfire activity) are shown at AK01W and AK02, while AK03S comparatively exhibits smaller values in high fire years suggesting a more impactful fire season can occur with less dry conditions. Of note, AK02 BUI values stand out in these high fire years, delving into the high category (BUI ~70). Attendant ABI values shown in Figure 6b,d,f are significantly higher than average ABI values at AK01W and AK02 in the duff and drought periods suggesting these anomalous years are associated with higher than average 500 hPa geopotential heights and potential blocking anticyclone presence aloft. Diurnal period ABI values at AK02 and AK03S are also significantly higher than average during high fire years, but not at AK01W. Differences in BUI and ABI in high versus low fire years are pronounced across PSAs in the duff and drought phases (Figure S3a,b).

Building upon these index composites, in Figures 7 and 8 we display 500 hPa geopotential height spatial fields by the same high and low MODIS observed fire activity criteria, respectively. For the duff period, a northwest to southeast tilted ridge aloft (5520–5580 m) across AK01W, AK02, and most of AK03S characterizes years of higher fire activity (Figure 7b). Midtropospheric ridges of similar magnitude characterize the drought period (Figure 7c). A clear distinction between the duff and drought high fire years is the extent of the ridge in the latter period, which engulfs most of south-central Alaska including the Aleutian Islands.

Synoptic circulation patterns associated with years of low fire activity are most clearly differentiated from those of high fire activity also in the duff and drought periods

(Figure 8b,c). For the duff period, the geopotential heights are comparatively lower with a less pronounced ridge across the CEI (Figure 8b). For the drought period, low fire years tend to have lower relative pressure aloft and the pattern configuration shows a trough across Alaska that supports cooler temperatures and end-of-season rains over the state's interior (Figure 8c). In line with composite analyses presented in Figures 6b,d,f and S3b, when comparing high versus low fire seasons anomalously high 500 hPa geopotential height fields are found especially for the duff season and to a lesser extent the drought season across the CEI PSAs analysed (Figure S4b,c).

3.3 | Extreme event associations and hindcasts

As previously discussed and shown, elevated BUI tends to signal high fire activity in the CEI. Therefore, we build upon the previous analyses of anomalous fire weather conditions by extending the ERA5 reanalysis-derived BUI back to 1979 and examine associations between extreme frequencies of both the daily BUI values and the ABI (i.e., BUI and/or ABI ≥ 95 th percentile for the day of year) within each phase. It is important to note that this correlation reflects counts of these days within the period and not their co-occurrence in time. Figure 9 reveals the within period correlations. Similar to the previous section, there are robust Kendall's tau correlations, most notably in the duff and drought periods (Figure 9b,c). During these two phases the total BUI extreme days are significantly and positively correlated with the total ABI extreme days considering either parameter's raw or detrended count values (the latter is listed in parentheses in each figure panel). This suggests that changes in the variability and trends of the ABI or CEI BUI extremes tends to be mirrored by the other variable. Further, while similar magnitude ABI and BUI correlation coefficients are found when averaged across the three CEI PSAs comparing the drought period raw ($\tau \geq 0.32$) versus detrended ($\tau \geq 0.31$) values, the detrended duff correlations are comparatively higher ($\tau \geq 0.47$ vs. $\tau \geq 0.32$) suggesting a closer relative coupling of interannual extreme surface–atmosphere interactions than trends in such behaviours.

Given the synoptic settings (Figure 6) and atmospheric indices' magnitudes are generally aligned with CEI fire activity (Figures 7 and 9), we further examine how ABI values may relate to the BUI 95th percentile extremes within the duff and drought periods (Table 1). In summary, the ABI is distinguished as a more robust predictor of CEI duff period versus drought period BUI

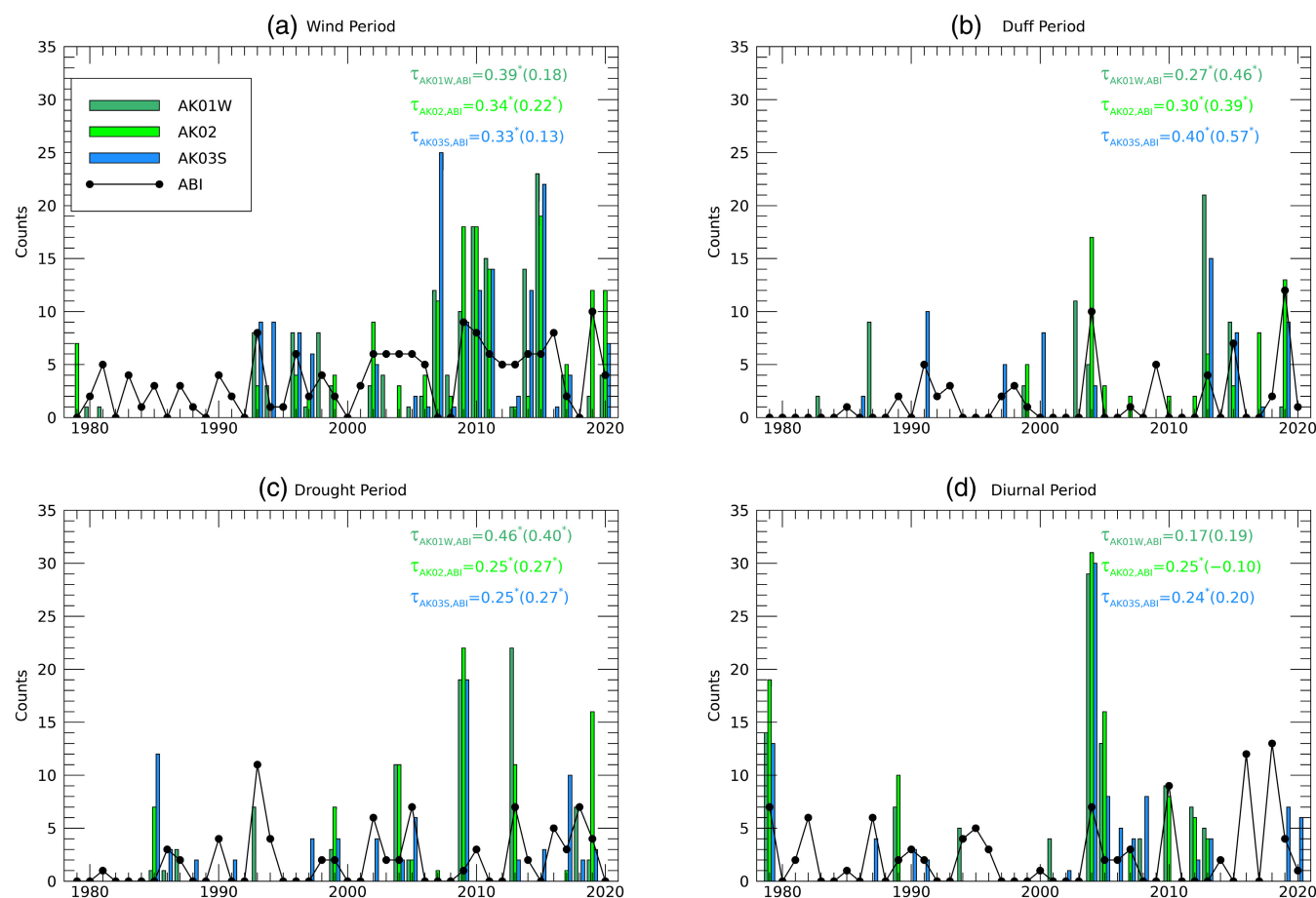


FIGURE 9 Counts of (a) wind, (b) duff, (c) drought and (d) diurnal AK01W, AK02 and AK03S 95th percentile BUI and ABI days since 1979. Kendall's tau (τ) correlations are shown and detrended correlations are provided in parentheses. Statistically significant correlations ($p \leq 0.05$) are marked with a plus (+) superscript symbol.

extremes (compare rows 3–6 vs. 9–12 in Table 1). For the AK02 duff period, mean ABI conditions at 6–10 day leads explain $\sim 14\%$ ($\sim 20\%$) of the raw (detrended) extreme BUI variance with smaller BUI variance ($\tau^2 > 12\%$) explained by raw and detrended ABI at 1–5 days and detrended ABI at 11–15 day leads. At AK01W, raw and detrended ABI values explain $\sim 13\%$ of the variance, respectively. BUI predictability by mean ABI is otherwise relatively weak ($\tau^2 < 10\%$) at AK03S during the duff and drought periods as well as at AK01W and AK02 during the drought period.

4 | SUMMARY AND CONCLUSIONS

Alaska's CEI is a hotspot of fire activity within the state, making it imperative to identify the physical mechanisms that precondition and sustain fire activity. Development of new meteorological tools and indices combined with

TABLE 1 The explained variance of CEI PSA duff and drought period BUI extremes by short-term ABI values.

Period/PSA	AK01W	AK02	AK03S
Duff			
1–5 days	0.8 (6.4)	12.4 (12.3)	<0.1 (0.5)
6–10 days	7.5 (0.8)	14.4 (20.3)	6.9 (5.1)
11–15 days	13.4 (12.7)	7.4 (13.1)	0.8 (0.8)
16–20 days	3.6 (3.6)	1.4 (0.7)	0.2 (0.3)
Drought			
1–5 days	2.9 (9.6)	2.1 (1.7)	0.1 (0.1)
6–10 days	3.9 (7.9)	0.9 (2.7)	1.6 (3.1)
11–15 days	0.2 (0.1)	0.1 (1.3)	0.1 (0.1)
16–20 days	7.3 (5.5)	0.3 (0.1)	0.6 (1.3)

Note: AK01W, AK02 and AK03S 95th percentile BUI variance are associated with mean ABI values in the preceding days (e.g., the 1–5 day mean ABI values serve as predictors of ensuing 95th percentile AK01W duff extreme days spread across the 1979–2020 period). The squared Kendall's tau correlations, where τ^2 is shown in %, are presented for raw (detrended) data.

applications of existing products may therefore represent an important path forward to short-term forecasting within the fire season, especially as Alaska's air temperatures, precipitation and overall seasonality are expected to continue to change in the warming climate (Lader et al., 2018).

In our study, we use a relatively new atmospheric metric, the ABI, toward understanding linkages between CEI fires and surface fire weather indices and the overlying upper-air pattern. Key results and their interpretations include:

1. Strong correlative relationships ($\tau \geq 0.46$) are found between the CEI MODIS fire counts and BUI values, and the ABI during the wind and diurnal phases as increasing (decreasing) fire incidence and drying (wetting) of surface layers reflected in rising (falling) BUI and ABI values as the season commences (concludes; Figures 3–5). These indices' climatological values thus provide some potential forecast skill at the tails of the fire season.
2. Years of high (i.e., >75th percentile) fire counts since are associated with above-average BUI with the largest departures from average BUI conditions found in the duff and drought phases across PSAs (Figure 6a,c,e). Within these phases, the largest BUI values (BUI >45) are shown at AK01W and AK02, while AK03S comparatively exhibits smaller values in high fire years. ABI values are higher than average when BUI is elevated at each CEI PSA in the duff and drought periods (Figure 6b,d,f), Composite 500 hPa maps of atmospheric circulation atop Alaska confirm that excessive fire years are associated with higher heights and atmospheric ridging aloft (Figure 7).
3. Covariability of extreme ABI and BUI occurrences (≥ 95 th percentile for the day of year) since 1979 is notable when detrended correlations are averaged across CEI PSAs for the duff period ($\tau \geq 0.47$; Figure 9). This suggests a moderate linkage between the most anomalous atmospheric circulation patterns (e.g., strong anticyclonic systems) and surface BUI responses. Most notably, at meteorological scales, mean ABI conditions at 6–10 day leads explain roughly 14% (20%) of the raw (detrended) 95th percentile duff period BUI variance at AK02 (Table 1).

Taken as a whole, these results suggest that the ABI is a useful index that can be applied toward identifying fire weather conditions and extremes in Alaska's CEI, especially during the core of the fire season in the duff and drought periods. Moreover, at 6–10 day lead times, the mean ABI over this period offers modest statistical skill toward indicating extreme surface conditions during the duff phase at AK02 (the Upper Yukon Valley). In the

context of these findings it is important to note that the vastness of the Alaskan landscape means that each PSA has different fuels and topography. Therefore, as is shown in our study, fire behaviour will vary between PSAs even under similar BUI or ABI values.

It is acknowledged that atmospheric blocking life cycles, and the frequency, intensity, and persistence of these systems are not consistently represented in numerical weather and climate models (Kautz et al., 2022). However, when these systems are resolved by such models their linkages may be more clearly connected with surface weather extremes (Ferranti et al., 2018). Therefore, as numerical models continue to improve depictions of blocking characteristics, future work can more clearly define atmospheric processes relating observations of the upper-level atmospheric processes associated with blocking patterns to surface conditions conducive to fire. To this end, building upon historical studies like ours, future work could integrate the ABI along with other new and existing ocean–atmosphere–land indices (e.g., El Niño–Southern Oscillation and other tropical/extratropical Pacific indices) in a multivariate, machine learning and/or nonlinear framework to better understand and predict Alaska fire weather. Recent work using these methods has shown promise toward a more integrated, system-level understanding of fire weather amidst Arctic change (Coffield et al., 2019; Langford et al., 2019).

AUTHOR CONTRIBUTIONS

Thomas J. Ballinger: Conceptualization; investigation; formal analysis; visualization; writing – original draft; data curation. **Rick T. Lader:** Formal analysis; visualization; writing – review and editing. **Peter A. Bieniek:** Visualization; writing – review and editing. **Heidi Strader:** Writing – review and editing; conceptualization. **Robert Ziel:** Writing – review and editing; conceptualization; data curation. **Uma S. Bhatt:** Conceptualization; writing – review and editing; data curation; funding acquisition. **Cecilia Borries-Strigle:** Writing – review and editing. **Joshua Hostler:** Writing – review and editing. **Eric Stevens:** Writing – review and editing. **Christine F. Waigl:** Writing – review and editing. **Alison York:** Conceptualization; writing – review and editing.

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DATA AVAILABILITY STATEMENT

ERA5 data is available from the Copernicus Climate Data Store: <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview>. The BUI data is available from <https://zenodo.org/records/3626193>. The ABI is available from the lead author upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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