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ORIGINAL ARTICLE

Identifying local-scale meteorological conditions favorable to large fires in Brazil

Sihan Li[1,2] | **Sami Rifai**[1,3] | **Liana O. Anderson**[4] | **Sarah Sparrow**[2]

[1] Environmental Change Institute, School of Geography and the Environment, Oxford, United Kingdom

[2] Oxford e-Research Centre, Engineering Science, Oxford, United Kingdom

[3] ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, Australia

[4] National Centre for Monitoring and Early Warnings of Natural Disasters (Cemaden), São José dos Campos, Sao Paulo, Brazil

Correspondence
Sihan Li, Environmental Change Institute, School of Geography and the Environment, South Parks Road, Oxford OX1 3QY, United Kingdom.
Email: sihanli@ouce.ox.ac.uk

Abstract

This study aims to investigate local-scale meteorological conditions associated with large fires in Brazil during recent decades. We assess whether there are large fire types with preceding predictors. Our results show that large fires, defined with a threshold of a daily burned area >95th percentile of the historical record, mainly occur in August and September in Brazil, and Amazônia and Cerrado experience much higher numbers of large fires than the other biomes. There are two large fire types that have robust meteorological signatures: (1) a wind driven type, characterized by peak wind speed on the day of the fire, and anomalously high wind speed a few (~3) days before and after the fire; and (2) a Hot-Drought driven type, characterized by anomalously high temperature, low relative humidity, and consistent drought conditions indicated by anomalously high fuel aridity starting as far back as 5 months prior to the fires. A third one is characterized by no anomalous meteorological conditions. The wind driven type most frequently occurs in southern and southeastern Amazônia, Pantanal, and western and northern-to-central Cerrado, with some occurrences over the western Caatinga region bordering Cerrado, southern Cerrado, and southern Mata Atlântica; whereas the Hot-Drought driven type most frequently occurs in southern and southeastern Amazônia, Pantanal and western and northern-to-central Cerrado, with some occurrences over the western Caatinga region bordering Cerrado, southern Cerrado, central-to-southern Mata Atlântica, and a few occurrences over Northern Brazil where the Amazônia meets Roraima. Southern and southeastern Amazônia, Pantanal and western and northern-to-central Cerrado are the major large fire prone regions. Our results highlight that understanding the temporal and spatial variability of the meteorological conditions associated with large fires is essential for developing spatially explicit forecasting, and future projections of large fire hazards under climate change in Brazil, in particular the Hot-Drought driven type.

KEYWORDS
Brazil, large fires, large-fire-meteorology, local-scale, meteorological forcings

1 | INTRODUCTION

Brazil is characterized by a large variety of vegetation types, including rainforests, deciduous forests, dry forests, shrubs, savannahs and grasses, which harbor great biodiversity. Fire has been a significant factor in shaping the vegetation landscapes (Mistry, 1998; Pivello, 2011). Fires can occur naturally in Brazil due to lightning, and have been used to modulate the vegetations and local landscapes, especially in the Cerrado (Durigan, 2020; Pivello, 2011). However, humans have significantly increased Brazilian fire activities in both the fire-adapted biomes such as the Cerrado and the fire-sensitive biomes such as the Amazônia (Caúla et al., 2015; Eloy et al., 2019; Pivello, 2011). Humans can influence fires directly by burning the native vegetations through slash-and-burn practices for agropastoral purposes, whereas the recent burns in the Amazônia are the sole doing of human actions (Caetano, 2021; Caúla et al., 2015; Durigan, 2020; Pessôa et al., 2020a; Reddington et al., 2015). Fires are also indirectly influenced by humans by anthropogenic warming leading to increased drought frequency (Swetnam and Anderson, 2008), as fire activities tend to increase in drought years (Aragão et al., 2018; Barbosa et al., 2019; Nepstad et al., 2004; Silva Junior et al., 2019; Swetnam and Anderson, 2008). All the above mentioned aspects make Brazil a very unique, interesting and challenging backdrop for fire meteorology. Especially the more recent 2019 and 2020 fires have brought discussions on fires in Brazil to the forefront (Durigan, 2020; Silveira et al., 2020). In 2019, fire smoke darkened South American skies, grabbing the whole world's attention when the smoke got to São Paulo, inciting discussions on the causes and effects of the fires. A total of 34% of the total fire hot spots detected were in the Amazon rainforest, 50% in the Cerrado, and 5% or less burned in the Brazilian Pantanal (https://earthobservatory.nasa.gov/images/146355/reflecting-on-a-tumultuous-amazon-fire-season). Fire activity increased significantly in 2020 in the southern Brazilian Amazon, with deforestation fire activity increasing by 23% and active fire detections from understory fires by 60%, compared to 2019 (https://earthobservatory.nasa.gov/images/147946/fires-raged-in-the-amazon-again-in-2020). Fires burned approximately 28% of the Pantanal, with record high hot spots between January and August in 2020, an increase of 211% over the same period in 2019 (Marengo et al., 2021).

Although heated debates still remain about the effects of fire on natural ecosystems (Durigan, 2020, and the references within), and admittedly there are no universal fire management policies that will fit the whole country, there is good agreement in the scientific community that large fires are very destructive events, with very severe and detrimental consequences. These range from high economic costs (Campanharo et al., 2019; Gill et al., 2013), deteriorating air quality which has adverse impacts on human health (Reddington et al., 2015), biodiversity loss, loss of carbon stock and increased greenhouse gas emissions (Hardesty et al., 2005; Pivello, 2011; Pessôa et al., 2020a), which could pose threats to the global climate and conservation due to the compromised ecosystem services resulting from large fires.

The important role that weather and climate play in fires has been widely discussed by previous work, especially the varying effects on different timescales (Barbero et al., 2015; Gouveia et al., 2016; Ruffault et al., 2016, 2018). Meteorological conditions on longer (interannual, annual, and seasonal) timescales are essential to the production of biomass, following that the drying of fuels, and once fuel conditions are sufficient (abundant and dry) to sustain burning, is a matter of fire ignition which can occur either naturally (e.g., lightning) or human induced. After fire ignition, instantaneous weather conditions (e.g., high temperature and strong winds) could promote fire growth in intensity and fire spread into wider regions which could lead to exceptionally destructive fire seasons.(Barbero et al., 2015; Riley et al., 2013). In the recent decades, there have been many studies focusing on the relationship between large fires and meteorology, mostly motivated by single large fire events with devastating impacts. Most of these studies are focused on large fires that occurred in Europe and North America. Large fires have been linked to the occurrence of extreme episodes of heatwaves (Dimitrakopoulos et al., 2011), drought conditions in prefire seasons (Riley et al., 2013; Russo et al., 2017; Turco et al., 2017), very intense wind conditions (Dimitrakopoulos et al., 2011; Ruffault et al., 2018), and the convergence of these anomalous meteorological conditions (Barriopedro et al., 2011; Gouveia et al., 2016; Koutsias et al., 2012; Ribeiro et al., 2020; Tedim et al, 2013; Trigo et al., 2006).

In the Amazon region, land use variables have been identified as a better fire predictor than climatic variables (Fonseca et al., 2016, 2017), although water deficit and previous months precipitation also perform well. Since fires in this region occur in the driest period of the year, there is a reduced chance of natural fire ignitions by lightning (Barbosa and Fearnside, 2005). Fires in this biome are strongly related with deforestation (Aragão *et al*., 2008), forest fragmentation (Silva Junior et al., 2018), and land management (Zarin et al., 2005). Nonetheless, extreme droughts have led to major fire events (Anderson et al., 2015; Aragão et al., 2018), and areas under water deficit have been more affected by fires than areas under normal climate, once fire ignition is present (Aragaõ *et al*., 2007). Other studies have used climatic variables, such as precipitation, temperature, and relative humidity (RH) (Cardoso et al., 2003; Sismanoglu and Setzer, 2005) or forest flammability derived from plant available soil water (Nepstad et al., 2004) or vapor pressure deficit (Silvestrini et al., 2011) for modelling fire activity. However, up until now, a systematic study on Brazil large-fire-meteorology is still missing. Our study aims to fill in this gap.

There have been growing interests and great efforts (e.g., Ruffault et al., 2016, 2018, 2020) in developing a systematic framework to examine and define fire-meteorology, and growing realization that it is of great importance to examine fire-meteorology, to better understand the underlying relationships between fires and meteorological conditions, in order to help explain the different spatial distribution of fires (i.e., why fires tend to occur more frequently over certain regions), and to improve forecasting capacities and future projections of fire hazards, which could guide fire management decision-making, fire-fighting preparation, and disaster preparedness (Ruffault et al., 2016, 2020; Vieira et al., 2020).

This study, focusing only on the meteorological aspects of large fires, aims to (1) provide a holistic characterization of different large fire types (characterized by distinct fire-weather relationships) across Brazil and for each major biome; (2) identify the features of large fire occurrences, that is, are there any dominant types of large fires when considering the whole of Brazil and for each biome, and where they most frequently occur; (3) gain better insights into the underlying relationship between robust meteorological features and large fires; (4) find potential preceding predictors that can be incorporated to improve forecasting of large fires and future predictions of large fire hazards, and thus can provide useful information for fire-fighting and disaster preparedness strategies at local and regional scales.

The rest of the article is structured as the following: section 2 describes datasets used for investigating the daily burned area (BA) and meteorological conditions, as well as the two complementary methods applied to identify the different large fire types and the meteorological conditions associated with them. The identified large fire types, geographical locations with similar local-scale forcing conditions, along with the composite analysis results demonstrating the temporal variability of local-scale meteorological forcing are shown in section 3. Section 4 presents further discussions and reflections on our results and section 5 summarizes the main conclusions.

2 | MATERIALS and METHODS

2.1 | Burned area

Daily BA is extracted from the Global Fire Emissions Database(GFED), version 4 (GFED4, Giglio et al., 2013) which has a spatial resolution of 0.25°, derived from the 500 m MCD64A1 BA product aggregated to 0.25° spatial resolution on a daily basis (Giglio et al., 2013). The GFED product is widely used in the Earth System Science community (e.g., Global Carbon project https://www.globalcarbonproject.org/RECCAP/products.htm), as well as the Fire Modeling Intercomparison Project (Li et al., 2019).

We used the higher temporal resolution daily BA covering the period between 2001 and 2015. From this database, across Brazil large fires were defined as fires burning at least 66,452 ha over a 0.25° by 0.25° grid cell, a threshold corresponding to the 95th percentiles of all fire sizes, referred to as the country-wide analysis from here on. Given that using a single percentile threshold to characterize a fire as being large or not across Brazil could mask potential interesting regional differences due to landscape, climatology, local fire practices, management policies, etc., especially across different biomes, where fires play significantly different roles (Durigan, 2020; Pivello, 2011). We also performed additional analysis, using a different threshold value for each major biome, that is, using the 95th percentile from each biome as the threshold, to characterize a fire as being large or not for Amazônia (a threshold value of 53,590 ha), Caatinga (38,585 ha), Cerrado (79,313 hPa), Mata Atlântica (17,149 ha), and Pantanal (1,17,898 ha), separately. In Pampa, large fires rarely happen (not shown here), so was excluded from the analysis. These are referred to as the biome-wise analysis from here on. The country-wide analyses are presented as the main results since the overarching goal of this study is to provide a systematic view on Brazil large-fire-meteorology, but we discuss how the country-wide results compare to the biome-wise results throughout.

2.2 | Meteorological variables

The meteorological variables used to characterize the near surface local-scale conditions before, during, and after large fires are extracted from the Fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate—ERA5 (from https://cds.climate.copernicus.eu/, Copernicus Climate Change Service), with a horizontal resolution of 0.25° by 0.25°. The daily surface variables over Brazil extracted were: 2 m temperature (T) and dewpoint temperature, surface pressure, zonal (U) and meridional (V) wind components at 975 hPa. In addition, RH was computed using T and surface pressure, and vapor pressure deficit (VPD) was computed using T and dewpoint temperature. The wind speed (Wspd) was calculated from the zonal and meridional wind components for each grid point.

Besides these surface variables, to approximate fuel moisture conditions, we chose two fuel moisture codes: Duff Moisture Code (DMC) and Drought Code (DC) of the Fire Weather Index (VanWagner, 1987), taken from the ERA5 fire danger indices (available on the Copernicus Emergency Management Services, https://doi.org/10.24381/cds.0e89c522), as generic indicators of medium- and longer-term drought, for which higher numbers denote drier conditions. The DMC and DC represent the moisture content of fuels at different depths of the soil layers (Van Wagner, 1987), with DMC representing moisture availability of the loosely compacted layer of approximately 3 inches, and DC representing the moisture availability of deep, compacted layers of approximately 10 inches (Ruffault et al., 2018; Van Wagner, 1987; Vieira et al., 2020). Interested readers are referred to Van Wagner (1987) for detailed calculation methodology of DMC and DC. These two indices are chosen over other drought indicators, because: (1) although the FWI system was originally developed for the Canadian forests as a numerical indicator of potential fire intensity, it has been shown to be an effective indicator of fire activities across other climatic regions and vegetation types of the world (e.g., Abatzoglou et al., 2019; Krikken et al., 2019; van Oldenborgh et al., 2021); (2) daily DMC is computed from daily rainfall, RH, and temperature and DMC from the prior day, and daily DC is computed from daily rainfall and temperature and DC from prior day (Van Wagner, 1987), so both indices contain information of water deficit; and (3) as pointed out by Van Wagner (1987), DMC represents fuel moisture of "loosely compacted decomposing organic matter" underneath the litter, providing insight to live fuel moisture stress, whereas and DC approximates moisture conditions of "a deep layer of compact organic matter," representing drying deep into the soil. Thus DMC and DC are good representations of fuel aridity.

In total these five variables: Wspd, T, RH, DMC, and DC are used together for identifying meteorological conditions for large fire types. We also examined VPD in the process, but since its inclusion did not appreciably change the results, in terms of the proportion of large fires represented by each identified type and the overall features of each type, the results are presented in the Supplementary information (Figures S12-S15).

2.3 | Methods

The different large fire types are identified objectively through two methods. The first method aims to robustly determine the association between large fire types with anomalous meteorological conditions, and to provide a classification grounded in physical characteristics as shown by previous studies (Ruffault et al., 2016, 2018, 2020; Vieira et al., 2020), which are known to be related to fire occurrence. Thus, the first method can be considered as the reference method. The second method aims to apply an unsupervised learning method with no prior knowledge or assumption of what large fire types might emerge. By comparing the results from the reference method with those from an object method could help identify which large fire types are robust, as well as whether the features of meteorological forcings are robust.

It would be ideal to have a clear distinction between human-induced and natural fires. However, to our knowledge there isn't any existing dataset that provides this separation systematically across Brazil over the historical record. Hence, in this study we do not provide this difference because ignition is almost exclusively human (other than those ignited by lightning); and the meteorological conditions are considered as the variables that enhance the hazard of large fires, rather than the ignition itself in this study.

The standardized anomaly for each meteorological variable was calculated before the rest of the analysis. For each grid cell, the standardized anomaly is calculated by dividing the daily anomalies by the climatological standard deviation, using the whole 2001-2015 as the reference period. Standardized anomalies are used instead of raw meteorological values because in the multivariate *k*-means analysis, the five variables are used as inputs together, where each data point contains the five-variable, to characterize the meteorological conditions more comprehensively. These five variables have different units, and are on different magnitude scales, using the standardized anomalies ensures that the five variables account for the same weight (contribute equally) in the analysis, so that the result is not disproportionately influenced by the inherent magnitude differences of the five variables. Details are provided below.

2.3.1 | Absolute thresholds

The first method is applying absolute thresholds for the different meteorological variables. Since large fires have been associated with episodes of extreme heatwaves, drought conditions in prefire seasons, intense high winds, and the synergy between these anomalous meteorological conditions, it is expected that these variables could lead to exceptionally severe fires. Here, we explore the anomalous condition classified in standardized anomaly terms (Table 1). Same as done in many previous studies (e.g., Ruffault et al., 2016, 2018, 2020; Vieira et al., 2020), the large fire types are named according to their main meteorological characteristics and grouped into these broad categories to make

TABLE 1 Classification of large fire types in standardized anomaly terms of temperature (T), relative humidity (RH), Duff Moisture Code (DMC), Drought Code (DC), and wind speed (Wspd)

Large fire type	Classification (in standardized anomaly terms)				
	T	RH	DMC	DC	Wspd
Wind driven	–	–	–	–	>2*
Heatwave driven	>1	–	–	–	–
Hot-Drought driven	>1	←1	>1	>1	<1
Drought driven	<1	←1	>1	>1	–
Near-normal	<0.5*	<0.5*	<0.5*	<0.5*	<0.5*

Blue numbers represent absolute values, and those marked with *indicate that an alternative value 1 was also tested and shown in Figure 2.

the description easier, as the following: (1) Wind driven large fires, (2) Heatwave driven large fires, (3) Hot-Drought driven large fires, (4) Drought driven large fires, and (5) Near-normal large fires.

It is worth noting that the fraction of fires in each fire type is highly dependent on the choice of threshold values. Therefore, the fraction in each type can be altered through this choice. Weakening the threshold value will increase the number of fires classified as each type, but also means that any meteorological signature will be weakened. In this article, we selected relatively strict threshold values to allow for less “mixing” between types, giving the clearest meteorological signature. Hence, the data samples retained are small for the absolute thresholds method.

2.3.2 | Multivariate *k*-means clustering

The second method is to use multivariate *k*-means clustering (Singhal and Seborg, 2005) based on the meteorological variables associated with each large fire record, using T, RH, Wspd, DMC, and DC. This method partitions the five multivariate dataset into *k* (pre-defined) distinct clusters, where each data point belongs to one cluster. Practically, it allocates each data point such that the sum of the distance between the data points and the cluster's centroid is minimal. In essence, it tries to achieve maximum intracluster similarity and minimum intercluster similarity. Similar to many other clustering methods, *k* needs to be predefined. *k* is often defined as a trade-off between: (1) being large enough to differentiate between different large fire types associated with distinct and robust meteorological features, and (2) being small enough so that the results are not cumbersome and impractical beyond interpretation. The ultimate goal is to get a set of clusters that sufficiently represent the different large fire types, with a solid physical interpretation of the relationships between large fires and meteorological conditions. The robustness of the clusters is verified by rerunning the algorithm, each time with different initial random seeds, same as done by previous studies (e.g., Ruffault et al., 2020). We run the algorithm with $k = 3$, 4, 5, and 6, but choose $k = 5$; the detailed rationale is discussed in section 4. In the multivariate *k*-means method, all the data points (defined as large fires) are used, hence, the data samples are much bigger compared with the absolute thresholds method.

Taking a similar approach as introduced by Ruffault et al. (2016, 2018, 2020), we characterize the large fire meteorological forcings by performing a composite analysis. We mainly focus on prefire conditions, because anomalous conditions on lead times could indicate potential prior warning. Composites are examined over two timescales to capture the short-term day-to-day, and seasonal variability associated with large fire occurrences. We use an 11-day window (from 7 days before to 3 days after a fire) for all the variables (T, RH and Wpsd, DMC and DC) and a 9-month window (from 7 months before to 1 month after a fire, using calendar months) for the fuel aridity variables. We look at these time windows to get a fuller picture of the temporal variability of the meteorological conditions, and to get the right approximate time frame of when peak fire weather would occur. We also look at the meteorological conditions postfire because of the important roles weather and climate—especially drought, play in how quickly the ecosystems can recover after fire (Gouveia et al., 2012; Wilson et al., 2015). It is worth noting that both methods are applied on the day 0 of the temporal window.

3 | RESULTS

In Brazil, there is a marked annual cycle of large fire occurrences, peaking during the Southern Hemisphere winter season (Figure 1A), with the vast majority of the large fires occurring in August and September, accounting for 32.78% and 46.37% of the total number of large fires, respectively. The total BA during the peak months (August plus September, hereafter AugSep) accounts for 81.61% of annual BA. The temporal distribution of large fires show very high interannual variability (Figure 1B), with very high occurrences in 2007 and 2010, followed by 2012 and 2015; 2009 is the year with the lowest large fire

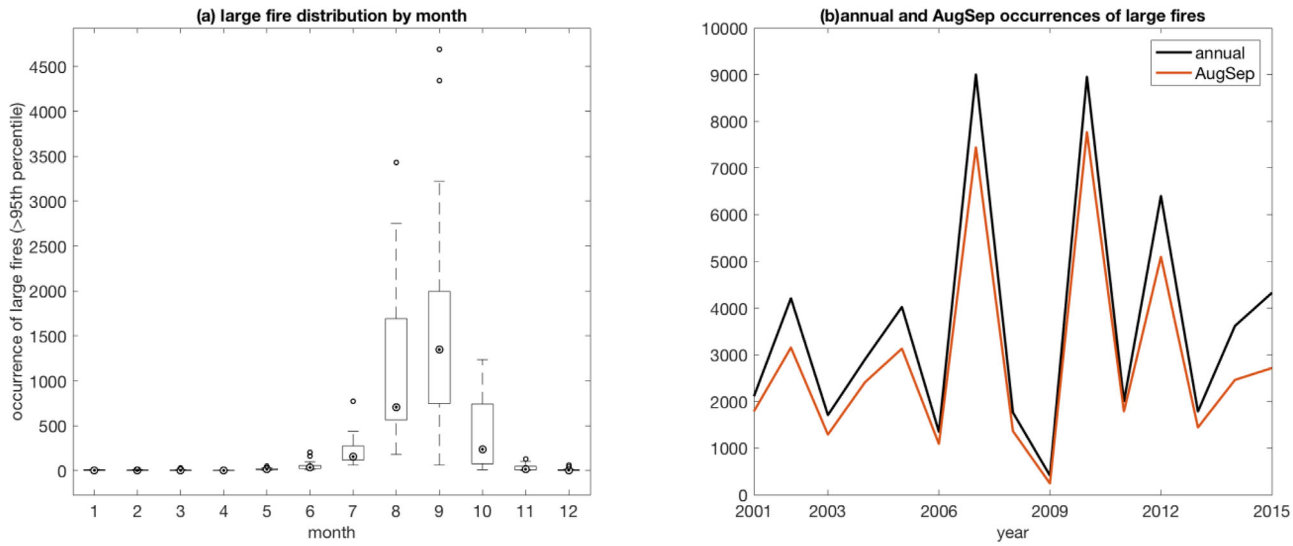

FIGURE 1 Statistics on large fires (with a daily burned area >95th percentile of historical record) in Brazil for the period 2001-2015. (A) Box plots showing the annual cycle of the variability of the number of large fires in each month, and (B) the number of large fires in the yearly annual and high fire months (August plus September)

occurrences. The AugSep cumulative frequency of large fires is highly correlated with the yearly frequency (rho = 0.9918, $p < 0.05$). Therefore, we only examine AugSep for the country-wide analysis, that is, using the single percentile threshold value to characterize a fire as being large or not across Brazil. When using a different threshold value for each major biome (shown in Supporting information Figure S1) for the biome-wise analysis, the vast majority of the large fires also occur in August and September in most of the biomes (Amazônia, Cerrado, Mata Atlântica, and Pantanal), except Caatinga where the peak months are September and October. Hence, we focus on AugSep for Amazônia, Cerrado, Mata Atlântica, and Pantanal, and SepOct for Caatinga. It is worth noting that, in Amazônia and Cerrado, the number of large fires are much higher compared with the other biomes.

First, we examine the country-wide results from the absolute threshold method, since the absolute thresholds are based on sound physical understanding. Using this method, on the day of the fire, the meteorological conditions reflect the absolute threshold chosen to define each fire type as expected (Figure 2). The days leading up the fire day (up to 7 days lead time) for each meteorological variable are also assessed, which is of greater interest because anomalous conditions on lead times could indicate potential prior warning. The main features of the Wind driven type are anomalously high Wspd on the day of the large fires compared with the preceding and following days, and the anomalously high Wspd are also seen ~3 days before and after the fire. The strong anomalous winds are accompanied by a slight drought condition, indicated by slightly lower RH and higher DMC, although T becomes anomalously low on the days of and after the fire. The main feature of the Heatwave driven type is anomalously high T on the day of the large fire compared with the preceding and following days. The Near-normal type is characterized by little to no change in all the meteorological variables throughout the 11-day time period. The main features of the Hot-Drought driven type are very anomalously high DMC and DC (although not as high as DMC) throughout the 11-day time period, with anomalously high T, and low RH. The Drought driven type is characterized by very anomalously high DMC and DC (although not as high as DMC) throughout the 11-day, with anomalously low RH. Given that DMC and DC are representative of fuel aridity, and have a longer memory as generic indicators of medium- and longer-term drought, we also look at months before and after large fires for all the fire types. As shown in Figure 2 (bottom 2 rows), for the Hot-Drought type DMC and DC start to become anomalously high as far back as 5 months before the large fires, gradually rising then rise steeply 1 month before, and DMC peaks during the large fire month whereas DC continues to rise in the month after; whereas for the Drought type, DMC and DC also start to become anomalously high as far back as 5 months before, and continue to rise during the month after. For the Wind driven and Near-normal types, DMC and DC also start to show anomalously high conditions a few months prior, but the anomalous states are not as strong as seen for the Hot-Drought and Drought types; the month-to-month variations of the Wind driven type resemble those of the Hot-Drought type. Whereas for the Heatwave type, DMC and DC do not show any consistent anomalously high conditions, and they are even anomalously low in some of the

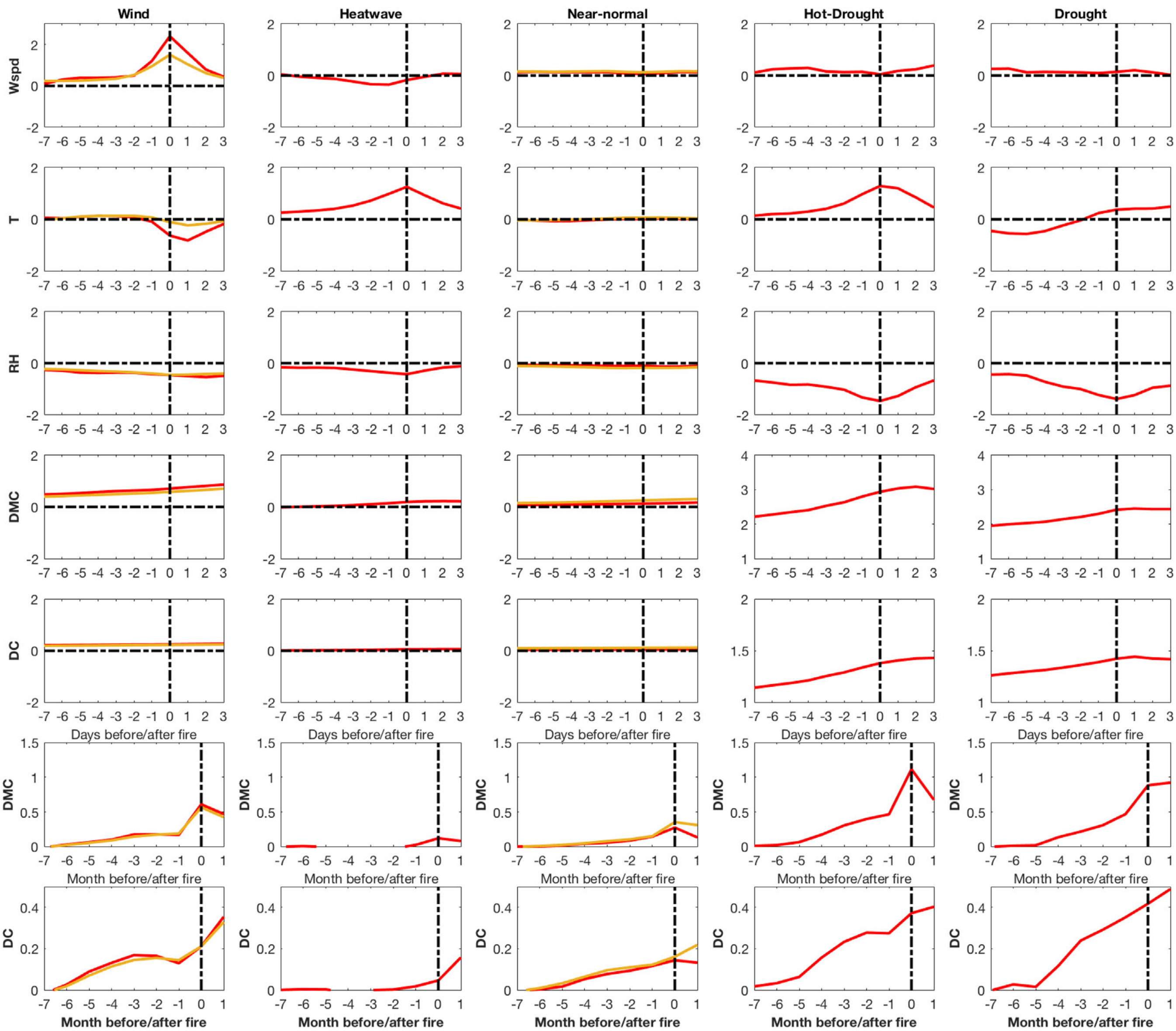

FIGURE 2 The characteristics of different large fire types derived from using the absolute thresholds. Lead (7 days before) and lag (3 days after) composites of meteorological variables with respect to big fire days on daily (shown in the top panels, for Wspd, T, RH, DMC, and DC) and monthly (shown in the bottom four panels, 7 months before and 1 month after, only for DMC and DC) timescales. Results are derived by pooling AugSep, and the results of using an alternative value of 1 are shown as orange lines. The country-wide analyses results are shown

months prior. It is worth highlighting that these results are from pooling August and September, and the feature of the Hot-Drought driven type is more reflective of September due to its higher frequency of occurrence in September (shown in Supporting information Figure S3); whereas the feature of the Drought driven type is more reflective of August, again due to its higher frequency of occurrence in August (shown Supporting information Figure S2).

The results from applying the absolute threshold method on each major biome, using a different threshold value per biome to define large fires (as described above), are presented in Supporting information Figures S4-S8 (Amazônia, Caatinga, Cerrado, Mata Atlântica, and Pantanal, respectively). The main features of all the fire types for each biome remain relatively the same as the country-wide results for the short-term 11-day time window, with Amazônia and Cerrado results being mostly similar in terms of day-to-day variation. On longer lead times (up to 7 months prior), the country-wide results are reflective of the features seen for Amazônia and Cerrado (Supporting information Figures S4 and S6, respectively), which is not that surprising given these two biomes experience much higher numbers of large fires.

The above results suggest that for the Hot-Drought and Drought driven type, DMC and DC could serve as more relevant fire risk indices to develop large fire forecasting models, given their longer-term memory, hence, better predictability.

To verify the absolute threshold results, we then apply the multivariate *k*-means method. By comparing the two methods, we can determine which large fire types are robust, as well as whether the features of meteorological forcings are robust. The absolute threshold method serves as a reference and provides guidance on reasonable naming and grouping of the *k*-means results into broad categories to make the description easier. Again country-wide analysis results from pooling August and September are presented here.

The results from the multivariate *k*-means algorithm run with $k = 3, 4, 5$, and 6 are compared as a sensitivity test to arrive at the optimal number of clusters to retain. The three-cluster results are presented in Supporting information Figure S9. The first cluster resembles the Hot-Drought driven type, the second cluster resembles the Wind driven type, and the third cluster resembles the Near-normal type; by increasing the number of clusters to 4 (Supporting information Figure S10), on top of these three clusters, an extra cluster emerges with no resemblance to any clusters from the absolute threshold method, with wet conditions indicated by anonymously low DMC, dubbed as Wet-condition type from here on. By increasing to five clusters (Figure 3), the Wind, Hot-Drought, and wet-condition clusters remain more or less the same features, whereas the Near-normal type seem to have been split into two different categories, one with even closer resemblance to the Near-normal type as identified from the absolute threshold method, one with anonymously low Wpds on the day of the large fire compared with the preceding and following days as well as slightly higher DMC throughout the 11-day period, dubbed as Slow-Wind type from here on. Finally, by increasing to six clusters (Supporting information Figure S11), the Hot-Drought and wet-condition clusters remain more or less the same feature, whereas the clusters that resemble Wind and Near-normal type seem to have been rearranged into four clusters, making the description less clear and more difficult to generalize the results. Therefore, we choose $k = 5$, as increasing from 3 to 5 brings forward different categories thus adding to our understanding of different variables which contribute to large fire types. Adding more clusters beyond 5 makes the results less generalizable for interpretation.

To summarize, the most prominent features of meteorological forcings from the multivariate *k*-means method for each cluster are described below:

- cluster (1): corresponding to the Wind driven type (accounting for 21.23% of the large fires), is mainly characterized by peak wind speed (Wspd) on the day of the fire, and anomalously high Wspd a few days (~3) before and after the fire, with little change in RH, DMC and DC, although T becomes anonymously low on the days of and after the fire, which are consistent with the above absolute threshold results. DMC and DC, especially DC, start to show anomalously high conditions a few months prior, but the anomalous states are not as strong as seen for the Hot-Drought type, which is also consistent with the absolute threshold results.
- cluster (2): corresponding to the Hot-Drought driven type (12.73%), is characterized by drought conditions, as shown by the very anomalously high DMC and slightly higher DC throughout the 11-day period, and anomalously higher T and lower RH, also consistent with the above absolute threshold results. Same as the absolute threshold results, DMC and DC start to become anomalously high as far back as 5 months before the large fires, then rise steeply 1 month before and DMC peak during the large fire month, whereas DC continues to rise in the month after.
- cluster (3): the Wet-condition type (12.67%), is mainly characterized by anonymously low DMC throughout the 11-day period.
- cluster (4): corresponding to the Near-normal type (29.5%), is characterized by little to no change in all the meteorological variables.
- cluster (5): the Slow-Wind type (21.77%), is predominantly characterized by anonymously low Wspd on the day of the fire.

The results from applying the multivariate *k*-means method on each major biome, using a different threshold value per biome to define large fires (as described above), are presented in Supporting information Figures S16–S20 (Amazônia, Caatinga, Cerrado, Mata Atlântica, and Pantanal, respectively). Again, the country-wide results are reflective of the features seen for Amazônia (Supporting information Figure S16) and Cerrado (Supporting information Figure S18). In Amazônia/Cerrado, the same five types emerge: the Near-normal type (cluster 1/cluster 2, accounting for 29.89%/33.93% of the large fires), the Hot-Drought driven type (cluster 2/cluster 4, 17.11%/13.25%), the Wind driven type (cluster 3/cluster 1, 11.72%/19.18%), the Slow-Wind type (cluster 4/ cluster 5, 19.88%/19.60%), and the Wet-condition type (cluster 5/cluster 3, 12.85%/10.64%). The prominent features for each type resemble those from the country-wide results. In Caatinga, the same five types also emerge, however, the main features are slightly different: for the Hot-Drought driven type (cluster 4, 9.59%), on longer lead times (up to 7 months), DMC and DC do not show anomalously high conditions; and for the Slow-Wind type (cluster 3, 11.27%), anomalously high T condition can be seen throughout the 11-day window (Supporting information Figure S17), and DC starts to show anomalously

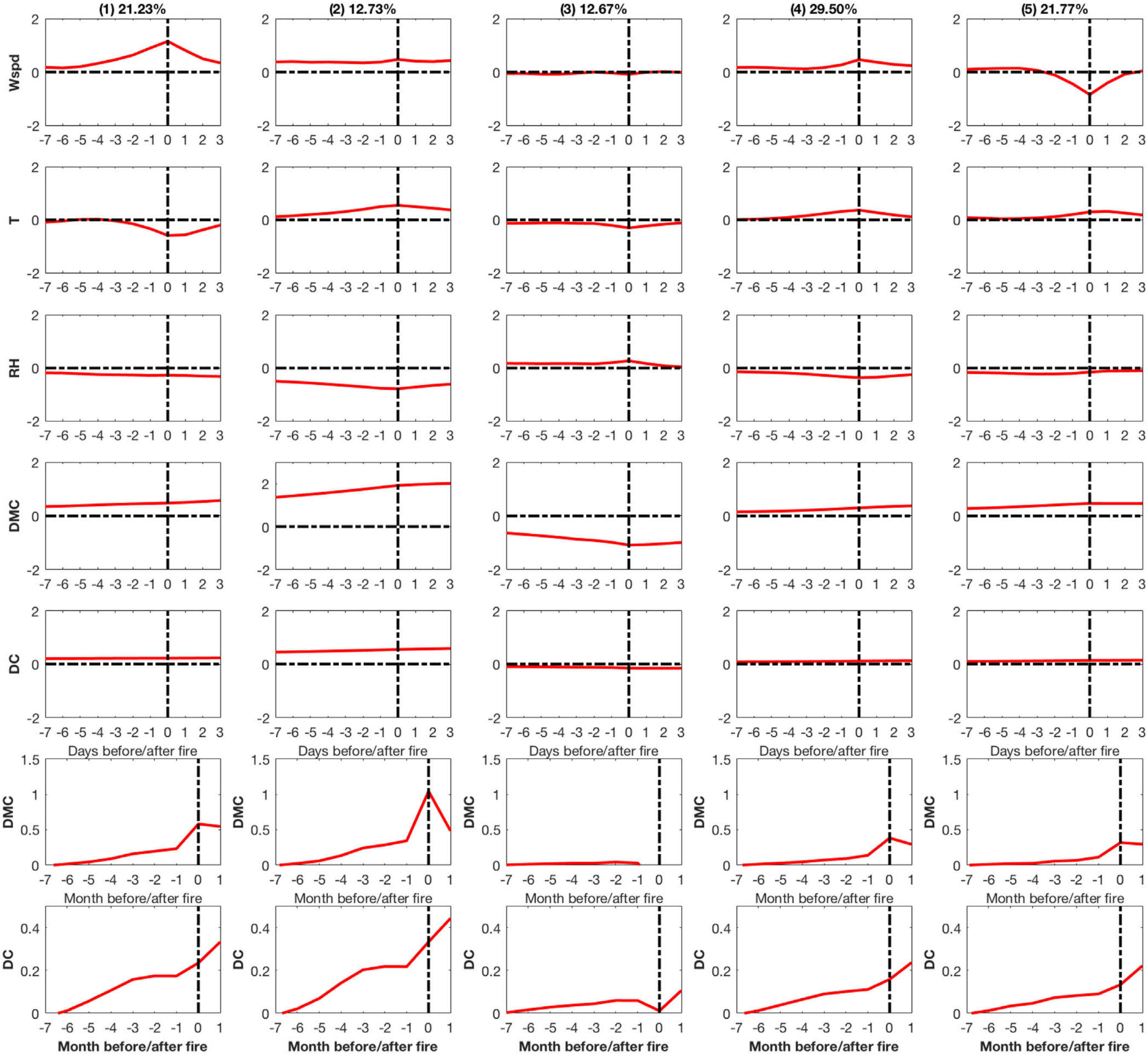

FIGURE 3 The characteristics of different large fire types derived from the multivariate *k*-means clustering ($k = 5$). Lead (7 days before) and lag (3 days after) composites of meteorological variables with respect to big fire days on daily (for Wspd, T, RH, VPD, DMC, and DC) and monthly (shown in the bottom 2 panels, 7 months before and 1 month after, only for DMC and DC) timescales. Results are derived by pooling August and September, and the proportion of large fires represented by each classified group is highlighted in the title of each column. The country-wide analyses results are shown

high conditions a few months prior (~5 months). In Mata Atlântica (Supporting information Figure S19), the Hot-Drought driven type (cluster 1, 14.44%), the Near-normal type (cluster 3, 11.46%), and the Wind driven type (cluster 5, 10.66%) are still present, although with slightly different features compared with the country-wide results: anomalously DMC and DC not as high on longer lead times for the Hot-Drought, and stronger anomalously high DMC and DC conditions for the Wind driven type; cluster 2 (11.46%) is characterized by slightly low Wpds, cool T and wet conditions denoted by anomalously high RH; and cluster 4 (19.86%) resembles the Heatwave driven type from the absolute threshold results. In Pantanal (Supporting information Figure S20), although the Hot-Drought (cluster 1, 10.15%) and the Wind (cluster 2, 19.58%) types are still present, the other types along with the prominent features further diverge from the country-wide results; we do not discuss the finer details of each type for brevity and refer interested readers to Supporting information Figure S20 for further details.

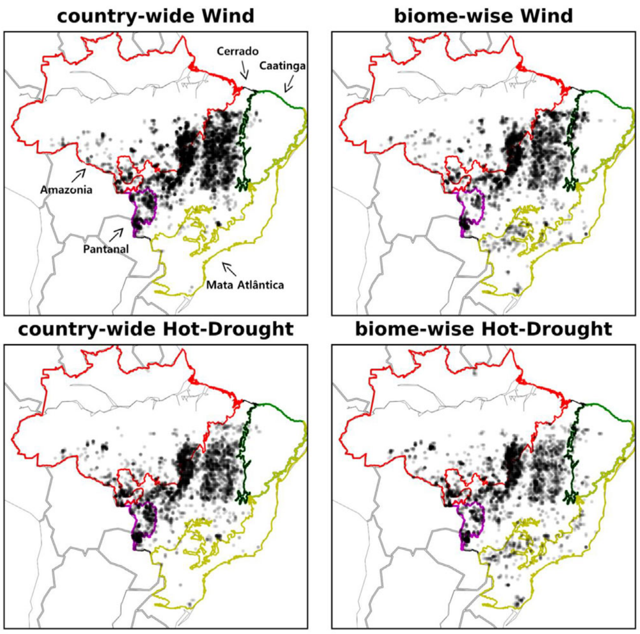

FIGURE 4 Spatial distribution of the Wind driven large fires (top row) and Hot-Drought driven large fires (bottom row) from the country-wide analysis (left column) and the biome-wise analysis (right), respectively. The results from the multivariate *k*-means method applied on the two peak fire months (as described previously) are shown, respectively. Each dot denotes one large fire occurrence, and the denser the dots the more occurrences over that region. The colored shape files denote the major biomes investigated in this study

In summary, the common large fire types and meteorological forcings identified through the two different methods, from both the country-wide analysis and the biome-wise analysis, are the Wind driven, Hot-Drought driven, and Near-normal types (in all biomes but Patanal), indicating these are robust characteristics of large-fire-meteorology. Since the Near-normal type has no clear meteorological signature, and we are interested in identifying anomalous meteorological features (which could indicate potential prior warning), we focus on the Wind and Hot-Drought types for the remaining analysis.

Figure 4 shows the spatial distribution for the two large fire types from the country-wide and the biome-wise analyses, both using the *k*-means method. As mentioned in the previous section, in the *k*-means method, all the data points (defined as large fires) are used, providing a complete view of spatial distribution. Whereas in the absolute method, the data points retained are small due to the strict threshold values, which is applied in order to give the clearest meteorological features. Therefore, the *k*-means results are presented here (the comparison between the absolute thresholds and *k*-means are shown in Supporting information Figure S21). The results from the country-wide and biome-wise analyses both show that the Wind driven large fires mainly occur in southern and southeastern Amazônia, Pantanal, and western and northern-to-central Cerrado, with some occurrences over western Caatinga in the region bordering the Cerrado, southern Cerrado, and southern Mata Atlântica. The country-wide analysis results show more occurrences over northern-to-central Cerrado and Pantanal, and less over western Caatinga and southern Mata Atlântica compared with the biome-wise results. The biome-wise results reveal some occurrences over central Mata Atlântica whereas the country-wide results show none over this region. For the Hot-drought driven large fire, both sets of analysis show that large fires are concentrated in southern and southeastern Amazônia, Pantanal, and western and northern-to-central Cerrado, with some occurrences over western Caatinga in the region bordering the Cerrado, southern Cerrado, central-to-southern Mata Atlântica, and a few occurrences over Northern Brazil where the Amazônia meets Roraima. Similar to the Wind drive large fires, the country-wide analysis results show more occurrences over northern-to-central Cerrado and Pantanal, and less over western Caatinga and central-to-southern Mata Atlântica compared with the biome-wise results. The biome-wise results reveal more occurrences over central Mata Atlântica than the country-wide results, and a few more occurrences over the Roraima border. Comparing the spatial differences between Wind driven and Hot-Drought driven large fires shows that Wind driven type occurs more frequently over northern-to-central Cerrado, and less frequently over central-to-southern Mata Atlântica.

Comparing the absolute threshold and *k*-means methods (Supporting information Figure S21) show that the Wind driven large fire mainly occurs in southeastern Amazônia, Pantanal, and western-to-central Cerrado. For the Hot-drought driven large fire, both the absolute threshold and *k*-means methods show concentrated large fire occurrences over southernmost Amazônia, Pantanal, and southern Cerrado. Together with the country-wide and biome-wise comparisons as described above, these results suggest that southern Amazonia, Pantanal, and Cerrado are the big fire-prone regions although large fires do occur over other Roraima border, western Caatinga, and central-to-southern Mata Atlântica, with much less frequency.

4 | DISCUSSION

Southern Amazonia, Pantanal, and Cerrado are the big fire-prone regions as shown above, and with droughts projected to occur more frequent/intense, as well as extended periods of consecutive dry days (Avila-Diaz et al., 2020; Betts et al., 2018; Marengo et al., 2017; Sillmann et al., 2013) in these regions, our results here are of particular relevance within the context of climate change, because such changes in drought conditions could facilitate increased dryness of fuel leading to an increase in large fire activities in the future. The fuel aridity indices (as generic indicators of droughts) identified here serve as promising predictors for projecting future large fire hazards with ongoing climate change in these ecosystems.

Gaining insights into the spatially explicit information on where each large fire type occurs is particularly useful, to determine where it would be more meaningful to invest in or allocate resources to develop local and regional forecasting and projection capacities for large fires, and building postfire resilience. Especially for the Hot-Drought driven type, since one of the key characteristics is the anomalously high DMC and DC on mid- to longer-time scales, indicating the strong influence of medium and longer-term drought from a few months leading up to the large fire occurrences. Because these fuel aridity indices have longer memories, they could serve as more relevant fire risk indices to develop spatially explicit large fire forecasting models, and to predict large fire hazards over southern and southeastern Amazônia, Pantanal, and western and northern-to-central Cerrado, where the Hot-Drought driven large fires frequently occur. Information like these are particularly useful for spatially explicit fire management policies and actions.

It is very important to highlight some key caveats of the present study. First and foremost, in this study we do not explicitly differentiate between large fires by: deforestation fire, agricultural/land management fire, and forest fires/wildfires (Barlow et al., 2020; Berenguer et al., 2020). It must be acknowledged that the most BA products underestimate the total fire affected areas in the Amazon region in a spatially-dependent way (Pessôa et al., 2020b), with the western Amazonia highly underestimated, especially related with forest fires (Anderson et al., 2017), which was therefore not assessed in this study. Potentially, anomalous weather and climate conditions can promote any of the fire types to grow into large fires, increasing the hazard for this type of disaster. Second, we do recognize the limitation of the results due to the relatively short length of available dataset (2001-2015), which misses the more recent large fires in 2019 and 2020 (Marengo et al., 2021; Silveira et al., 2020). As this analysis relies on using daily GFED dataset, currently updated to 2015 (http://globalfiredata.org/pages/data/), but there is planned work to update the results as soon as the daily product is released post-2015. The analysis presented here might be further improved by the use of other global fire databases, such as the FRY database (a global database of fire patch functional traits derived from space-borne BA products, Laurent et al., 2018), but is beyond the scope of this study. Last, the identification of large fire types is based only on the day of the large fire as indicated by BA, without considering the potential lead/lag day of when the BA is registered or recorded in the database, thus, the potential mismatch of fire ignition day.

Nonetheless, the identified large-fire-meteorology offers a holistic view of country-wide large-fire-meteorology in Brazil as well as a biome-wise perspective, and provides a sound physical basis for the selecting relevant fire risk indices, to develop spatially explicit large fire forecasting capacity and future projection of large fire hazards.

5 | CONCLUSIONS AND FUTURE WORK

This study characterizes the different types of large fires in Brazil over the recent decades, and investigates the temporal and spatial variability of meteorological conditions that promote the large fires. Our results show that the large fires in Brazil mainly occur in August and September (September and October in the Caatinga biome), and Amazônia and Cerrado experience much higher numbers of large fires than the other biomes. Both the country-wide and biome-wise results show that two large fire types exhibit clear meteorological signatures, one being the Wind driven large fires, and the other one being the Hot-Drought driven large fires, with a third one accompanied by no anomalous meteorological conditions. The Wind driven type is characterized by peak wind speed on the day of the fire, anomalously high compared with the preceding and following days, most frequently occurring in southern and southeastern Amazônia, Pantanal, and western and northern-to-central Cerrado, with some occurrences over western Caatinga in the region bordering the Cerrado, southern Cerrado and southern Mata Atlântica; whereas the Hot-Drought driven type is characterized by consistent anomalously high DMC and DC, with anomalously high T, and low RH, and the drought condition (as indicated by high fuel aridity) starts as far back as 5 months before the large fires, most frequently occurring in southern and southeastern Amazônia, Pantanal, and western and northern-to-central Cerrado, with some occurrences over western Caatinga in the region bordering the Cerrado, southern Cerrado, central-to-southern Mata Atlântica, and a few occurrences over Northern Brazil where the Amazônia meets Roraima. Our results suggest that southern and southeastern Amazônia, Pantanal, and western and northern-to-central Cerrado are the major large fire prone regions. The identified aridity metrics have longer memories and better predictability, thus, could serve as predictors for forecasting large fires over these regions, in particular for the Hot-Drought driven large fires. Our results indicate that large fires could be predicted several months in advance in these regions.

As an interesting next step, it will provide additional insights on the matter to perform the analysis as laid out in this study on a finer regional scale, for example, on state levels, or subecosystems, to assess how the large-fire-meteorology relationships vary from state to state and across different subecological systems. A more comprehensive assessment would be beneficial for local fire management and mitigation strategies. Another interesting next step is to investigate the synoptic-scale conditions to check whether there are any dynamic signatures in particular that promote large fire occurrences. As previous studies (e.g., Ruffault et al., 2017; Trigo and Palutikof, 2001; Duane and Brotons, 2018) have pointed out, synoptic variables are often better simulated by models than surface climatic variables, suggesting that under the contexts of climate change and future projection, they are more suitable to use. Last but least, as mentioned previously, our results here are particularly important within the context of climate change for Brazil. The regions identified here could be exposed to increased large fire activities in the future, with the projected increases in drought frequency and intensity as well as extended periods of consecutive dry days (Avila-Diaz et al., 2020; Betts et al., 2018; Marengo et al., 2017; Sillmann et al., 2013) facilitating increased fuel dryness. Therefore, as future work, the identified aridity indices (as generic indicators of droughts) could be incorporated into future projections to estimate the variability of these meteorological conditions, in order to improve our grasp on future large fire hazards in Brazil and to inform science-based fire and land management decision-making.

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AUTHOR CONTRIBUTIONS

Sihan Li: conceptualization; data curation; formal analysis; funding acquisition; methodology; software; visualization; writing-original draft; writing-review and editing. Sami Rifai: data curation; formal analysis; funding acquisition; methodology; writing-review and editing. Liana O. Anderson: data curation; formal analysis; funding acquisition; methodology; writing-review and editing. Sarah Sparrow: formal analysis; funding acquisition; project administration; supervision; writing-review and editing.

ORCID

Sihan Li https://orcid.org/0000-0002-2479-8665
Liana O. Anderson https://orcid.org/0000-0001-9545-5136

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SUPPORTING INFORMATION

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

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