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Observations of Emissions and the Influence of Meteorological Conditions during Wildfires: A Case Study in the USA, Brazil, and Australia during the 2018/19 Period

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Abstract: Wildfires can have rapid and long-term effects on air quality, human health, climate change, and the environment. Smoke from large wildfires can travel long distances and have a harmful effect on human health, the environment, and climate in other areas. More recently, in 2018-2019 there have been many large fires. This study focused on the wildfires that occurred in the United States of America (USA), Brazil, and Australia using Cloud-Aerosol Lidar with Orthogonal Polarisation (CALIOP) and a TROPOspheric Monitoring Instrument (TROPOMI). Specifically, we analyzed the spatial-temporal distribution of black carbon (BC) and carbon monoxide (CO) and the vertical distribution of smoke. Based on the results, the highest detection of smoke (~14 km) was observed in Brazil; meanwhile, Australia showed the largest BC column burden of $\sim 1.5 \text{ mg/m}^2$. The meteorological conditions were similar for all sites during the fires. Moderate temperatures (between 32 and 42 °C) and relative humidity (30–50%) were observed, which resulted in drier conditions favorable for the burning of fires. However, the number of active fires was different for each site, with Brazil having 13 times more active fires than the USA and five times more than the number of active fires in Australia. However, the high number of active fires did not translate to higher atmospheric constituent emissions. Overall, this work provides a better understanding of wildfire behavior and the role of meteorological conditions in emissions at various sites.

Keywords: air pollution; smoke; CALIPSO; Sentinel-5P; biomass burning; black carbon

1. Introduction

Approximately 90% of global wildfires are attributed to anthropogenic activities such as the burning of debris, equipment use and malfunctions, campfires left unattended, negligently discarded cigarettes, and intentional acts of arson. On the other hand, ~10% of wildfires are due to natural causes such as lightning and volcanic eruptions. Wildfires have adverse effects that include air pollution, deteriorated human health, loss of ecosystems and biodiversity, forest degradation, and economic losses [1–4]. However, controlled ignited fires by humans can be used for the management of non-agricultural objectives such as fuel reduction, ecosystem management, and restoration [5,6]. However, this event also contributes to increased air pollution and a decrease in air quality.

Wildfires inject vast amounts of gaseous components such as carbon dioxide (CO₂) and carbon monoxide (CO) and particles such as black carbon (BC) and brown carbon into the atmosphere [7]. These emissions affect radiation, clouds, air quality, and climate on regional and global scales [8]. The composition and amount of fire emissions into the atmosphere depend on a wide range of variables associated with fuel characteristics such as loading, structure, type, chemistry, moisture, and fire behavior [9]. These emissions have substantial impacts on the atmospheric and chemical composition of the atmosphere [10].



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Copyright: © 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/ licenses/by/4.0/). The burning of biomass during wildfires produces, amongst other things, large amounts of CO and smoke [11,12]. Generally, smoke contains the unburnt portion of aerosol particulate produced by chemical reactions during biomass burning. Moreover, smoke from biomass burning also comprises of organic carbon and black carbon. However, the palpable composition of smoke depends on the type of vegetation burnt, the temperature of the fire, and the wind conditions. Contrarily, CO is produced by the incomplete combustion of carbon-containing fuels. CO mass concentration is highest when the fire is smoldering [11]. CO also contributes to the formation of tropospheric ozone and has a lifetime of ~30 to 40 days in the troposphere [13]. As a result, CO can be transported long distances by winds, but not long enough to mix evenly throughout the atmosphere.

In situ instruments inarguably provide the most detailed information on emissions; however, they are spatially and temporally limited. Additionally, the cost of operating and maintaining such instruments is high, and thus unsustainable. Satellites have been extensively used for the monitoring, detection, observation, and studying of wildfires. These provide a cost-effective and spatially and temporally comprehensive alternative and have been found to correlate well with in situ measurements. Some of the satellites that have been used include the Moderate Resolution Imaging Spectroradiometer (MODIS) [14], the Visible Infrared Imaging Radiometer Suite (VIIRS) [15], the Satellite FIre Detection (SFIDE) [16], Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) [17], Sentinel-2A [18], and Sentinel-5P. These above-mentioned satellites give a comprehensive understanding of the distribution, intensities, and emissions from wildfires. For example, the Cloud-Aerosol Lidar with Orthogonal Polarisation (CALIOP) instrument on board CALIPSO provides information on the vertical and spatial distribution of smoke. The MODIS onboard NASA's Terra and Aqua satellites provide information on the burned area and fire intensity, while the TROPOspheric Monitoring Instrument (TROPOMI) on board of the Copernicus Sentinel-5P satellite can give the spatial distribution of the gases emitted from wildfires such as carbon monoxide (CO). Furthermore, reanalysis data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), are very useful in studying emissions from wildfires. Several works have used MERRA-2 products such BC and CO to investigate emissions from wildfires [4,19,20].

Studying and managing wildfires is important for maintaining resources; protecting people, properties, and ecosystems; and reducing air pollution. Wildfire effects are influenced by forest conditions before the fire and management action taken or not taken after the fire. Major forest fire disasters were reported in the United States of America (USA), Brazil, and Australia during the years of 2018 and 2019. These fires caused enormous losses of vegetation, lives, and property and the destruction of infrastructure and thus attracted global attention [21–23]. Most importantly, tons of toxic gases and particles were released into the atmosphere, thus adversely compromising air quality, water quality, and visibility (especially for aircrafts). Therefore, the main purpose of this study is to investigate (1) the horizontal and vertical distributions of smoke resulting from these wildfires and (2) compare the fire parameters from the three fires and determine if there are any similarities and/or differences. The study aims to understand the role of meteorological conditions in these fires and relate them to the observed emissions. The emissions from these mega-fires are studied using the Sentinel-5P, MERRA-2, and CALIPSO datasets. Specifically, we investigate the USA fires (mainly in the state of California) that occurred in August 2018, the Brazil fires that occurred in August 2019, and the Australia fires that occurred in December 2019.

2. Study Sites

This study focused on three study areas selected based on the recent occurrence of major wildfire disasters—i.e., the USA, Brazil, and Australia (see Figure 1). The state of California (36.78° N, 119.42° W) in the western USA is characterized by a dry season from May to October. During this period, California experiences low rainfall, warm temperatures, strong winds, and stable atmospheric conditions. The fires of August 2018 were amongst

the worst fires recorded in California (https://news.sky.com/story/scorched-earth-howthe-australia-fires-compare-to-us-and-brazil-11904192). Brazil (14.24° S, 51.93° W), on the other hand, has a tropical climate with a dry season, usually between May and November. Fires commonly occur in the Amazon between July and October. One of the worst fires in the Amazon occurred in August 2019. In the same year in December 2019, Australia (25.27° S, 133.76° E) also experienced one of the most catastrophic fires. December is part of the dry season in southwestern Australia and occurs in the spring and summer season (September to February). During this period, vegetation (fuel) is dry following the winter rains, and the surge of hot air from the interior produces dangerous weather conditions suitable for fire.



Figure 1. Land cover distributions at the three study areas: (**a**) the USA, (**b**) Brazil, and (**c**) Australia. The land cover distributions are derived from Climate Change Initiative Land Cover (CCI-LC) [24].

3. Data and Methods

3.1. CALIPSO

CALIPSO was launched in April 2006 to study the roles of clouds and aerosols in the atmosphere. The CALIPSO mission, the Cloud-Aerosol Lidar with Orthogonal Polarisation (CALIOP) instrument, data products, and the algorithms are discussed in detail by [25]. CALIOP has a two-wavelength laser (532 and 1064 nm) operating at a pulse repetition rate of 20.16 Hz [26]. CALIOP has proven over the years to be one of the critical instruments in studying emissions from wildfires [4,19,27], thus making it an ideal instrument for this study. Some of the advantages of the CALIOP is its ability to classify aerosol subtype, its proficiency in producing high-resolution aerosol profiles, and its ability to determine the height distributions of aerosols. Some of its limitations, however, include its narrow swath width and longer revisit times, and the differences in the day and night signal. The solar background signal is higher during the day than night, which leads to more background noise during the day [28].

In this study, we use the CALIOP aerosol subtype and the backscatter coefficient data products (CAL_LID_L1-ValStage1-V3-40) to (1) identify the aerosols released into the atmosphere (CALIPSO STANDARD Browse Images-Versions 3.40 and 3.45) and to (2) determine the heights of the aerosols during the wildfires in the USA, Brazil, and Australia.

3.2. Sentinel-5 Precursor (5P)

Sentinel-5P was launched in October 2017 with a mission to carry out global atmospheric measurements (for air quality, ozone, UV radiation, and climate monitoring and forecasting) with a high spatio-temporal resolution. Sentinel-5P carries the TROPOspheric Monitoring Instrument (TROPOMI) sensor, which provides high-resolution measurements in the ultraviolet (UV), visible (VIS), near-infrared (NIR), and shortwave-infrared (SWIR) part of the spectrum. This broad spectral range allows numerous atmospheric trace gases such as ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and formaldehyde (HCHO) from the UV-VIS and carbon monoxide (CO) and methane (CH₄) from the SWIR to be retrieved. Further details on the characteristics of instrument and retrieval settings are provided by [29].

In this study, TROPOMI was used to map the spatial distribution of CO over the periods of the wildfire observations at each study area. The data used in this study were processed in the Google Earth Engine (GEE) Javascript platform. The product type used was L2_CO_, which can be found at this link (https://code.earthengine.google.com). Further analysis of the data was carried out in the QGIS software.

3.3. MERRA-2

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), provides data from 1980 to the present. MERRA-2 was introduced to replace and extend the original MERRA dataset [30], which ended in February 2016. It was produced using version 5.12.4 of the Goddard Earth Observing System Model (GEOS) Data Assimilation System (DAS). Gridded data are released at a 0.625° longitude $\times 0.5^{\circ}$ latitude resolution on 72 sigma–pressure hybrid layers between the surface and 0.01 hPa. A detailed description and data assimilation of MERRA-2 is described by [31,32]. BC is derived from MERRA-2 and is one of the byproducts of biomass burning. In this study, we use MERRA-2 data to study the time series of BC column burden before, during, and after the wildfire disasters at each study area. BC data were retrieved from the Goddard Earth Sciences Data and Information Services Center Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni) (https://giovanni.gsfc.nasa.gov/giovanni/). The black carbon column burden, time average (M2T1NXAER v5.12.4), surface skin temperature (M2TMNXSLV v5.12.4), and total latent energy flux (M2TMNXFLX v5.12.4) products were used in this study.

3.4. AIRS

The Atmospheric Infrared Sounder (AIRS) is a satellite that gathers the infrared energy emitted from the Earth's surface and atmosphere globally to provide temperature and water vapor measurements. AIRS provides atmospheric temperature profiles with an average accuracy of 1 K in 1 km (km) layers in the troposphere, humidity profiles to a 10% accuracy, and surface temperatures with an average accuracy of 0.5 K. More details on AIRS can be found in [33,34]. In this study, the relative humidity product was used.

4. Results

4.1. Observation of the Atmospheric Pollutants from Wildfires

4.1.1. USA Fires (August 2018)

A time series of the hourly BC column burden $(32^{\circ} \text{ N}, 45^{\circ} \text{ N}; 125^{\circ} \text{ W}, 115^{\circ} \text{ W})$ from 1 August 2018 to 31 October 2018 is shown in Figure 2a. It must be emphasized that the BC column burden is not a direct observation but rather modeled fields from assimilation calculation. Two strong peaks at ~0.6 mg/m² are observed on 5 and 22 August 2018, indicating the high intensity of the wildfires. It is anticipated that some or all fire conditions (such as high fuel load, low humidity, and strong winds) were favorable at this period, influencing a rapid spread of the fire. However, days after 8 August 2018 showed lower (decreasing) values of the BC column burden, thus indicating the decrease in fire intensity. This decrease could be from (1) the efforts of firefighters in controlling the fire outbreak and/or (2) changes in fire conditions such as humidity, precipitation, and winds. Moreover, Figure 2b,c show the spatial distribution of CO, which is associated with the burning of carbon-based materials. Figure 1a shows that the region in northern California is covered by forests—i.e., where most of the CO is observed. Therefore, it can be assumed that forests form the main fuel loading in this study area (see Figure 1). During the period of 1–4 August 2018 (see Figure 2b), fires on the north coast had begun but were not widespread to the central and south coast. Furthermore, CO was observed in the neighboring states, thus signifying that fires could have spread to those areas as well or through transportation by strong winds. However, during the period of 5–8 August 2018 (see Figure 2c), CO is mostly confined in the north and central coast of California. A plume of CO is also observed in the southwest of the Oregon state.



Figure 2. (a) Hourly averaged BC column burden for the period of 1 August 2018 to 30 September 2018 from MERRA-2. CO distribution in (b) 1–4 August 2018 and (c) 5–8 August 2018.

Figure 3 shows the vertical distribution of constituents from wildfire as observed by CALIOP on 6 August 2018. This date was chosen because it is the closest overpass during the study period. The CALIOP aerosol subtype product (see Figure 3a) shows the dominance of smoke, polluted dust, and dust constituents, which are signatures of biomass burning. Polluted dust and smoke are observed up to heights of ~4 km. Val Martin et al. [35] have shown that the smoke injection height from biomass burning varies with geographic location, vegetation type, and season. Polluted dust from wildfires consists of (but not limited to) black carbon aerosols, brown carbon aerosols, and organic carbon. These have a negative effect on the climate, air quality, and human health. Figure 3b shows the backscatter coefficients from aerosols and smoke. However, there are precursors (such as hydrocarbons, nitrogen oxides, and other associated gases) that are emitted during biomass burning. Nevertheless, in this work only aerosols and smoke are discussed because CALIOP does not provide information on any of the precursors mentioned.



Figure 3. (a) CALIOP 532 nm aerosol subtype and (b) total attenuated backscatter coefficient $(km^{-1}sr^{-1})$ on 6 August 2018.

4.1.2. Brazil Fires (August 2019)

The BC column burden time series over Brazil (30° S, 5° N; 70° W, 45° W) for the period of 1 July 2019 to 30 November 2019 is shown in Figure 4a. Two distinct peaks are observed in August and September 2019, corresponding to the high intensity of the wildfires. August had the highest BC column burden of $\sim 0.46 \text{ mg/m}^2$, while September had a BC column burden of ~ 0.50 mg/m^2 . On the other hand, October had a BC column burden > 0.3 mg/m^2 , corresponding to moderate fire intensities. The BC time-series indicates that the fires began in early August and peaked to high intensities in mid-August. The gradual decrease in the BC column burden began in mid-August and was stable at a BC column burden of $\sim 0.3 \text{ mg/m}^2$ for most of early September. However, in mid-September the fire intensity increased again, releasing more BC into the atmosphere. This was followed up by another decrease in the BC column burden in late September until November. This occurrence is also observed in Figure 4b, which shows the high concentrations of CO (0.05 mol/cm²) in August and October and the moderate to high CO concentration (0.04 mol/cm²) in September and November. The high CO concentration in October is also observed in the neighboring countries, Bolivia and Peru. This indicates that the wildfires might have spread to these countries. The wildfires in Brazil's Amazon rainforest may be attributed to deforestation motivated by industrial activities and large-scale agriculture [36].



Figure 4. (a) Hourly averaged BC column burden for the period of 1 July 2019 to 1 January 2020 Figure 2. (b) Averaged monthly CO distribution over South America in August, September, October, and November 2019.

Figure 5 shows the vertical distribution of constituents released into the atmosphere by forest fires, as observed by CALIOP over Brazil on 24 August 2019. Figure 5a shows smoke and polluted dust as the dominant constituents which are produced from biomass burning. The highest polluted dust is observed at ~9 km, while the highest smoke is observed at \sim 17 km (see purple circles in Figure 5a). The CALIOP data can be noisy at times and can therefore give false information. This is likely to be due to misjudged pixels. The high solar background signal present during daylight measurements makes the daytime data much noisier than the nighttime data. Consequently, the quality of the data acquired in the latitude/longitude region will fluctuate according to the local diurnal cycle. The additional noise in the daytime data is especially prominent when CALIOP passes over bright clouds, where the noise magnitude above the stratus clouds is significantly larger than over the ocean surface. The retrievals of spatial and optical properties of layers lying above these clouds is typically much more uncertain than the retrievals for layers lying above a dark ocean. There is a known flaw in the aerosol subtyping scheme that sometimes causes a misidentification of lofted smoke layers as marine layers. There is a geographical bias to the occurrence of this error, as it happens most frequently in those regions where dense smoke is transported out over the ocean. Therefore, the highest smoke height can be estimated at ~14 km. This aerosol injection into the upper troposphere and lower stratosphere (UTLS) occurs sporadically and is discussed in detail by [26]. However, most of the smoke and polluted dust aerosols are observed up to heights of ~5 km. The backscatter coefficient profile in Figure 5b confirms and clearly shows a smoke and aerosol plume extending from the ground to ~5 km. Additionally, dust aerosols are also observed but are likely to originate from the Saharan desert [37]. Dust aerosols are observed at heights of up to ~4.5 km.



Figure 5. (a) CALIOP 532 nm aerosol subtype and (b) total attenuated backscatter coefficient $(km^{-1}sr^{-1})$ on 24 August 2019.

The BC column burden time series over southeast Australia (40° S, 28° S; 145° E, 155° E) for the period of 1 December 2019 to 1 January 2020 is shown in Figure 6a. A sharp peak at ~1.43 mg/m² BC column burden is observed between 21 and 24 December 2019 due to large episodes of biomass burning. However, a gradual decrease in the BC column burden is observed from 25 December 2019. This decrease might be attributed to (1) the decrease in fuel load and/or (2) the effectiveness of fire management interventions by the fire authorities. Peaks at 1.07 mg/m² and 1.5 mg/m² are also observed on 29 December 2019 and 5 January 2020, respectively. Figure 6b,c show the distribution of CO for November and December 2019, respectively. The figures clearly show that fires began in November 2019 in the northern coastlines of the New South Wales (NSW) state. The vegetation along the coastline in the NSW state is different in the northern and southern parts. The northern part mostly consists of grassland, dry sclerophyll shrub/grass forests, and semi-arid woodlands, while the southern part is mostly made up of dry sclerophyll shrub forests [38] (also see Figure 1c). These vegetation types serve as good fuel sources for large wildfires. In December 2019, the CO concentration is observed from the northern to the southern coastline of the NSW state. This indicates that the fires spread in a southerly direction, thus destroying more vegetation.



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Figure 6. (a) Hourly averaged BC column burden over Australia for the period of 1 September 2019 to 1 January 2020 from MERRA-2. (b) Monthly averaged CO distribution in November and December 2019.

The vertical distribution of constituents from biomass burning over Australia is shown in Figure 7. The CALIOP's overpass in this study is on 22 December 2019, which corresponds to the period when large amounts of BC aerosols are observed (Figure 7a). The aerosol subtype (see Figure 7a) shows the dominance of smoke and polluted dust emitted from biomass burning. The highest smoke and polluted dust heights are observed at ~6 km (see orange box). The backscatter coefficient profile in Figure 7b shows two dominant plumes at the 25.49° S and 34.45° S regions. The 25.49° S region is mostly shrubland, while the 34.45° S region is covered by forests (see Figure 1c). The different land cover types influence the emission height of smoke and aerosols. A large amount of smoke aerosols has implications for atmospheric chemistry, cloud properties, Earth radiation budget, air quality, and climate [8,39–41]. Generally, this study was limited by the temporal resolution of the CALIOP data—i.e., 16 days—hence multiple observations were not possible. The results presented here show the best overpass time during the fires. Moreover, the smoke heights, which vary remarkably throughout the fire life cycle, are difficult to record adequately using satellite measurements.

4.2. Similarities and Differences in the Fire Parameters over USA, Brazil, and Australia

Meteorological conditions play a very important role in determining the behavior of fires (i.e., the intensity and rate of spread of wildfires). The three main meteorological conditions that influence wildfires are temperature, humidity, and wind. In general, the ignition of a fire is related to both the prevailing atmospheric conditions and the local geomorphological structure, among other anthropogenic factors that are not easily quantified. Meteorological conditions and other fire parameters for the three study sites are shown in Table 1. As can be seen in Table 1, there are some similarities and differences in the parameters. One of the major differences between the wildfires in the three sites is the number of active fires. Brazil has a ~13 times higher number of active fires than the USA, and a ~2.5 times higher number of active fires in Australia. This is directly translated in the burnt area (BA), were Brazil has a 5 times larger BA than the USA and a 1.4 times larger BA than the Australia fires. Interestingly, there were no major differences in the meteorological

conditions during the fire periods in the three study sites. Low wind speeds of 4 and 6 m/s were observed across all the sites. Wind speed is an important parameter because wind does not only transport wildfires across landscapes but also supplies oxygen that propagates them. Additionally, wind can blow embers for long distances, igniting new spot fires. Moderate temperatures of 32 °C and 42 °C and a moderate relative humidity (RH) (30–50%) were also observed during the fires. It is known that high temperatures and low humidity cause vegetation to dry and wildfires to burn rapidly. During biomass burning, constituents such as the BC, smoke + aerosols, and CO are released into the atmosphere. The USA and Brazil showed low BC column burden values of 0.5 and 0.6 mg/m^2 , respectively. Australia, on the other hand, showed a BC column value ~3 times higher than that of the USA and Brazil. Since the meteorological conditions were similar during the respective fires, another factor such vegetation type could have played a role in the difference in BC emissions [9]. CO column densities (~0.05 mol/m²) are similar in all the study sites. In the USA and Brazil (smoke + aerosols) are observed at a height of 4 km, while (smoke + aerosols) in Australia are observed at a height of 6 km. The height differences could be attributed to the high BC column burden emissions and the slightly higher wind speed of 6 m/s, transporting BC to higher altitudes. Overall, there are slight similarities and differences between the three wildfires.



Figure 7. (a) CALIOP 532 nm aerosol subtype and (b) total attenuated backscatter coefficient $(km^{-1}sr^{-1})$ on 22 December 2019.

Parameter	USA	Brazil	Australia
BC column burden (mg/m ²)	0.6	0.5	1.5
Smoke + aerosol height (km)	4	4	6
$CO (mol/m^2)$	0.05	0.05	0.045
* Burnt area (km ²)	800	4000	2800
* Temperature (during the fire) ($^{\circ}$ C)	~42	~32	~42
* Relative humidity (during the fire) (%)	~30	~50	~40
* Average wind speed (m/s)	~6	~6	~4
* Number of Active Fires	1098	14,128	5613
* Mean Fire Radiation Power (MW)	762.07	356.77	494.37

Table 1. Summary of wildfire parameters for the USA (i.e., August–September 2018), Brazil (i.e., August–September 2019), and Australia (i.e., November–December 2019).

The asterisk (*) indicates parameters published in a study by Kganyago and Shikwambana [24].

4.3. Analysis of the Meteorological Conditions during the Period of the Wildfires

The effect of meteorological conditions on fires is well established. Despite the fuel conditions and topography, the meteorological conditions affect the ignition, rate of spread, intensity and suppression of the fires. Here, we analyze the relative humidity (RH, %), latent energy flux (LE, W/m⁻²) and surface temperature (T_s , °C) in the year of the wildfires (i.e., 2018 for the USA and 2019 for Brazil and Australia) and previous year (i.e., 2017 for the USA and 2018 for Brazil and Australia), representing the current (during the year of fires) and antecedent conditions, respectively. The changes between the current and antecedent conditions were also assessed using difference. The meteorological conditions presented for the USA, Brazil, and Australia are not averaged for the whole year but for the months of the wildfires. These months coincide with the fire season of these respective areas. The fire seasons in the western USA and Brazil are typically in August and September. Meanwhile, the fire season for Australia is typically between October and March.

In the western USA, the results (Figure 8) indicate a reduction in RH between 2017 and 2018 of between 5–10%, thus indicating lower atmospheric moisture in the year of fires—i.e., 2018 which promoted drier conditions. A low RH allows for rapid evapotranspiration, causing drier vegetation conditions, thus making it easier for fires to start. The slight increase in LE (Figure 8) further supports this observation. In the surface energy balance, LE directly relates to evaporation, which causes a loss of moisture from the surface and an increase in the atmosphere [42]. The drying of the atmosphere releases the latent energy into the atmosphere, causing a strong heating source and moisture convection. This is also seen in the T_s measurements, which show a decrease due to the increase in the LE. On the other hand, for high relative humidity, it is harder for the moisture to evaporate into the air. Meteorological drought happens when dry weather patterns dominate an area. This condition usually favors the start and spread of wildfires.

In Brazil, the results (Figure 9) show a decrease in the RH in the year 2019 (i.e., year of the mega-fires). Similar to the USA results, a relatively low RH results in drier fuels and increases their flammability. In contrast, the T_s over the Brazilian Amazon was higher in 2019 than in the previous year, shown by the positive difference. The higher temperatures result in a decrease in RH. Figure 9 also shows that LE was more or less similar to the previous year, with some areas showing an increase and others a decrease.



Figure 8. August-averaged spatial distribution of relative humidity (RH), latent energy flux (LE), and surface temperature (T_s) over the USA (California and Nevada) for the year 2018, the year 2017, and the difference.



Figure 9. August-averaged spatial distribution of relative humidity (RH), latent energy flux (LE), and surface temperature (T_s) over Brazil for the year 2018, the year 2019, and the difference.

In Australia, the decrease in the LE is mostly due to the fire-induced damage in the vegetation canopy from wildfires. This, in turn, causes an increase in the T_s . This phenomenon is observed in the Australian fires in Figure 10. As can be seen in Figure 10, T_s was higher in 2019 (year of the fires), while a decrease in LE is observed. It is anticipated that the record high temperatures in Australia resulted in a reciprocally high T_s and lowered RH, as observed in Figure 10.



Figure 10. December-averaged spatial distribution of relative humidity, latent energy flux, and surface temperature over Brazil for the year 2018, the year 2019, and the difference.

Across all the study areas, the current (during the fires) and antecedent meteorological conditions provided suitable conditions for fire ignition and propagation. Generally, they created drier fuel and atmospheric conditions ideal for intense wildfires. Kganyago and Shikwambana [24] also showed moderate winds of ~5 m/s during the fire period. In general, the wind increases the supply of oxygen, which results in the fire burning more rapidly and for more extended periods. Additionally, several studies [24,43] suggest a relationship between the drought conditions and fire occurrence and intensity. For these fires, Kganyago and Shikwambana [24] demonstrated based on the vegetation condition index (VCI) that moderate to extreme dry conditions existed at the three study areas, thus explaining the high emissions observed in this study. In fact, Figure 11 shows that the period of these wildfires corresponds to a weak El Niño-Southern Oscillation (ENSO) based on classes by [44]. Generally, a weak El Niño contributes to below-normal rainfall, higher temperature, and low relative humidity. These are the perfect meteorological conditions that favor fuel load accumulation during the wet season and the start and spread of wildfires during the dry season. The wildfires in the USA, Brazil, and Australia were subjected to a weak El Niño event, which resulted in drier conditions, thus making them ideal environmental candidates for a successful biomass burning event.



Figure 11. Historical sea surface temperature (SST) anomaly.

5. Conclusions

This study investigated emissions from the recent wildfire disasters in 2018 and 2019 in the USA, Brazil, and Australia. In the USA, we observed a high BC column burden, peaking at approximately 0.6 mg/m², during early and late August—i.e., 5 and 22 August 2018, respectively. Comparatively, these peaks were more or less similar to Brazil, which had BC column burden peaks of approximately 0.46 to 0.5 mg/m² in August and September 2019, respectively. Alarmingly, Australia showed BC column burden peaks of 1.43 and 1.5 mg/m^2 (i.e., three times those of the USA and Brazil) in late December 2019 (i.e., 25th) and early January 2020, respectively. These differences can be attributed to various fuel conditions, fuel types, meteorological conditions, and anthropogenic activities [24,45]. Across the study sites, the results also showed widely distributed CO, as measured by Sentinel-5p TROPOMI. Specifically, during early August (i.e., 1-4 August) in the USA the CO was predominant over the north coast in California, Washington, and Oregon, and later (i.e., 5-8 August) was mainly concentrated over Washington and California. According to Brewer and Clements (2020), these fires were mainly preceded by dry seasonal conditions, which resulted in record low vegetation (fuel) moisture contents. In contrast, high concentrations of CO (0.05 mol/cm²) were observed in August and October over Brazil, mainly driven by policy changes that favor agricultural expansion over forest conservation. The neighboring countries, such as Bolivia and Peru also had high CO concentrations. This is consistent with the BA estimations reported by Lizundia-Loiola et al. [21], who show that burned areas in Bolivia increased by three times in 2019. On the other hand, the spatial distribution of CO showed the fire origin during November 2019 in the northern coast of New South Wales, where the vegetation is predominantly grassland, shrubs, and forests. During December 2019, the CO emissions were concentrated across all the NSW coast. The wildfires in these regions also resulted in the deposition of smoke and polluted dust aerosols at various heights into the atmosphere, peaking at approximately 4 km in the USA, 9 km-14 km in Brazil, and 3-6 km in Australia, as observed by CALIOP. A large amount of smoke aerosols has implications for atmospheric chemistry, cloud properties, Earth radiation budget, air quality, and climate. Overall, despite the wildfire being over a relatively smaller area, the emissions in Australia were higher than those in Brazil and the USA, while those in the USA were similar to those in Brazil. This can be attributed to the burning of predominantly high biomass fuel types—i.e., forests—in Australia and the USA, versus the relatively low biomass types such as cultivated lands and grasslands in the Brazilian Cerrado [24].

All the study sites showed low RH values during the wildfires. However, the surface temperature and latent energy flux varied in the different sites. For example, an increase in the latent energy flux in the USA resulted in a decrease in surface temperature, while in Australia a decrease in the latent energy flux was influenced by an increase in surface temperature. As Kganyago and Shikwambana [24] note, these conditions resulted in the largest BA recorded in Brazil, followed by Australia and the USA, respectively. Their results show that the number of active fires is directly proportional to the BA. Across all sites, wind speed was low, thus indicating its limited role in the propagation of these fires. A more comprehensive analysis of additional parameters such as topography, long-term trends, and causal statistical relationships should be explored in future studies. Generally, this study is in good agreement with other similar wildfire studies that have been conducted in Brazil [46], Australia [47], and the USA [48]. Overall, this work provides a better understanding of wildfire behavior and the role of meteorological conditions in emissions at various sites.

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