Spatio-Temporal Assessment of Thunderstorms’ Effects on Wildfire in Australia in 2017–2020 Using Data from the ISS LIS and MODIS Space-Based Observations

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Abstract: The impact of thunderstorms on the wildfire situation in Australia in 2017–2020 was investigated using data from the ISS LIS and MODIS space-based observations. To determine lightning-caused wildfires, a Geographic Information System (GIS) method was carried out, which consisted of a combined investigation of the spatial and temporal distributions of strikes and ignition hotspots. The seasonal variability of thunderstorms and wildfire activity was analyzed. It was established that the maximum seasonal distribution of thunderstorm activity does not coincide with wildfire activity. The interannual changes in strikes were recorded, but this was not revealed for the major vegetation types. Of 120,829 flashes, recorded by the ISS LIS sensor, only 23 flashes could be characterized as lightning-caused wildfire events, i.e., the frequency of lightning ignition was equal to 0.00023 fires/stroke. The lightning ignitions usually took place along the boundary of a thunderstorm, in semiarid areas covered by open scrublands. During the dry Australian period (April–September), very few lightning events were detected by the ISS LIS sensor, while fire activity was quite high. Additionally, it was concluded that the impact of thunderstorms on the fire situation is too small to explain the numerous wildfires during the wet period.

Keywords: Australia; lightning-caused fire; ISS LIS flash; MODIS active fire; land cover; GIS system

1. Introduction

In recent years, there has been an increase in the number of wildfires, including in California, Australia, and Siberia. As is known, wildfires can occur for various reasons. This work explores the relationship between landscape wildfires and lightning cloud–ground (CG) strikes. In this work, wildfire and thunderstorm events in Australia in the period 2017–2020 are selected as the object of research.

Lightning is a common cause of wildland fires; however, a significant increase in the number of ignitions in wildland in the dry period, in the absence of thunderstorms, raises many questions. Some suggest that wildland fire activity has already increased due to climate change. In particularly, Flannigan et al., in [1], indicated that a warmer climate will increase evapotranspiration, since the ability of the atmosphere to retain moisture increases rapidly at higher temperatures, thereby reducing the groundwater level and reducing fuel moisture. In addition, higher temperatures lead to more lightning activity, which usually leads to an increase in fires [2–5]. The interannual variability of lightning-induced fire activity in western US was investigated by Abatzoglou et al. in [6].

Stock et al., in [7], noted that lightning fires predominate in the northern Canada, and they account for 80% of the total area burned by large fires. Later, in [8], it was also reported that in North America, most recent large forest fires were caused by lightning. According to [9], lightning wildfires represented 16% of all wildfires in the Continental United States from 1992 to 2013, and accounted for 56% of the total burned area. In [10,11], it was mentioned that in Canada, igniting lightning is responsible for 45% of all wildfires and accounts for more than 85% of the total area burned. In the work of Abdollahi et al.,
in [11], the applicability of a remote sensing normalized difference water index (NDWI) as an indicator of vegetation/fuel water content to model lightning-caused forest wildfires in Northern Alberta, Canada, was investigated.

The processes of thunderstorm electrification were described in detail in the reviews [12–15]. In our study, it is expedient to allocate the following types of lightning wildfires: those caused by wet thunderstorms; sloping or boundary thunderstorms; and dry thunderstorms. These types of lightning wildfires are presented in Figure 1a–c. Usually, wet lightning wildfires take place during strong thunderstorms in forests. In this type of lightning wildfire, the strikes hit objects which have bulk dry material inside, so the objects are usually dead trees, haystacks, and wood buildings. With this type of lightning wildfire, ignitions often do not spread because the area covered by the thunderstorm is wet (Figure 1a).

Figure 1. The schemes of the main lightning wildfire types are as follows: (a) wet lightning wildfire of objects which contain loose, dry materials, such as a dead tree, haystack, or house; (b) edge lightning or sloping lightning wildfire; (c) a dry thunderstorm wildfire that mainly takes place over hot deserts. The investigation scheme is additionally presented in (d).

The next type of lightning wildfire is an edge or sloping lightning wildfire, sometimes called a sheet lightning wildfire. This type usually takes place at the boundary of a thunderstorm’s front. Because rain does not cover the strike area, the burning materials are dry and the wildfires can extend slowly or quickly, depending on the wind conditions (Figure 1b).
The last type of lightning wildfire is the dry thunderstorm lightning wildfire. This kind of lightning wildfire mainly occurs in hot desert areas. Raindrops evaporate as they fall, so there is a lot of dry vegetation in desert or semi-desert areas under a thundercloud, which can ignite when a thunderstorm hits them. Note that with this type of lightning ignition, the increase in clouds does not occur due to the convection process, but as a result of the advection process of passing the air mass over a mountain range (Figure 1c).

As discovered in our research, it appears that a lightning fire study was conducted recently [16], so we pay more attention to this. Schumacher et al., in [16], during their investigation of lightning fires, combined cloud–ground (CG) lightning and CG dry lightning (CGDL), detected by a ground network with fire pixels mapped by satellite remote sensing (AQUA, S-NPP, and NOAA-20) in Central Brazil, between 2015 to 2019. During the study, the lightning ignition candidates were selected based on the distance between fires and lightning in time and space. It was stated that lightning ignition has a higher impact compared to that caused by humans; this is because it occurs mainly in a forest in the remote wildland, making it difficult to manage fire suppression, which leads to a more significant burned area. Moreover, it was noted in [16] that satellite detection of active fires is a useful tool to identify lightning-induced wildfires.

Discussions of wildfires in Australia, the features of Australian thunderstorms, rainfall, and dry and wet lightning can be found in [17–20], and in other sources cited therein. In addition, there are several reviews that describe the relationship between climate and Australian megafires. Harris and Lucas, in [21], investigate the variability of Australian fire weather in the period from 1973 to 2017. It was shown that Australian fire weather shows spatio-temporal variability on interannual and multi-decadal time scales. Using correlation analysis, the authors examined the relationship of these time series with the El Niño Southern Oscillation (ENSO), the Southern Annular Mode (SAM), and the Indian Ocean Dipole (IOD). On a time scale from 1973 to 2017, the linear trends in the Forest Fire Danger Index (FFDI) increased at most observation stations, but this trend was strongest in the southeast and in spring. However, in the different regions of Australia at different times of the year, the influence of ENSO, SAM, and IOD varied greatly. The authors also wrote that the positive FFDI trends were not driven by the trends in the climate drivers, and they were not consistent with the hypothesized impacts of the Interdecadal Pacific Oscillation (IPO).

In [22,23] the authors drew our attention to the fact that in the second half of 2019, the combination of positive IOD and ENSO, together with a negative SAM, led to the failure of critical winter–spring rains and primed Australia for severely arid conditions. The review [24] analyzed the cause of wildfires. In particular, it was written that the cause of wildfires differs from place to place all over the world. Haque et al., in [24], wrote that lightning is the main cause of ignition in Canada and northwest China. In Africa, Central America, Fiji, Mexico, New Zealand, South America, and Southeast Asia, wildfires are caused by human activities such as agricultural activities, dairy production, and land-conversion burning. In the Mediterranean Basin, human negligence is a key cause of wildfires. Lightning strikes and human activities together are the main causes of wildfires in the USA and Australia. Coal seam fires burning in New South Wales and Centralia, Pennsylvania, and different coal-sustained fires in China can also spread contiguous combustible elements.

Abram et al., in [25], indicate that anthropogenic sources in Australia—including accidental ignitions, such as fallen power lines; arson; and other professional activity by farmers, cowboys, loggers, rangers, and the travel and tourism industries—are likely to be located near populated areas. Lightning strikes can naturally cause a fire, especially in remote and impassable areas where fire detection and control are difficult. The Australian Black Summer (December 2019–February 2020) megafires in Australia were caused mainly by natural and accidental ignitions. There are indications of deliberate community misinformation attempting to attribute the Black Summer fires to arson [25]. However, we should note that an increase in temperature, even by 1.5°C, cannot lead to forest, grassland, or
scrubland wildfires. Thus, the question about whether the Australian Black Summer wildfires were caused accidentally by humans, by arson, or due to lightning-caused ignitions remains relevant.

Further, it is interesting to note that according to [22], the enhancement of negative strokes over land during the wildfire season had contributions from both negative IC (by 78%) and CG strokes (by 30%), and they were allocated along the north coast of Australia (see Figure 3a,b in [22]). The negative CG strokes, which caused lightning ignitions, had a weakly increasing frequency and mainly occurred in north part of Australia, far from the Victoria district. The major changes in the number of strokes were found over ocean, so this increase in lightning activity was not the cause of the Australian Black Summer megafires.

In this work, a study of the spatial and temporal resolution of lightning strikes and wildfires, recorded using MODIS and LIS sensors, was carried out. The goal of this study is to find an answer to the question: How many flashes, recorded between 2017–2020 by the ISS LIS, led to ignitions in Australia? It has been shown that although ignitions due to lightning strikes occur, they account for a small percentage of all wildfires. This study may be of interest to specialists in remote sensing, fire service personnel, and climatologists.

2. Materials and Methods

2.1. Lightning Imaging Sensor

The Lightning Imaging Sensor (LIS) is established on the board of the International Space Station (ISS). It is optimized to locate and detect lightning with a storm-scale resolution of 4 km at nadir (directly below the instrument), increasing to 8 km at limb at the edge of the measurement region of the satellite. The LIS sensor has a swath width of about 550 km of the Earth’s surface, and daily, covers an area with latitudes ranging from $-55^\circ$ S to $+55^\circ$ N. For more detailed information about the development and accuracy of the ISS LIS product, please see [26] and the references therein. The original ISS LIS data are available in HDF-4 and netCDF-4 formats from the Global Hydrology Resource Center (GHRC) [27]. These datasets consist of near-real-time and non-quality-controlled science and background data, while the final quality-controlled science and background datasets are continually being added after being manually reviewed by the LIS Team. In particular, note that in [28], a comparison between the lightning observations of the ground-based European lightning-location system EUCLID and the ISS LIS data was carried out. Moreover, the ground-based observed strikes and the LIS remote flashes were different parameters that described the same lightning process, so these should not be confused.

It should also be remembered that a similar LIS sensor was established early on the TRIMM (NASA Tropical Rainfall Measuring Mission), and the oldest prototype of the LIS, named the Optical Transient Detector (OTD), was on board the OrbView-1 (OV-1) satellite [29,30]. Therefore there are many publications in which validations of the LIS/OTD sensors have been carried out; please see, for example, the World Wide Lightning Location Network (WWLLN; [31,32]), the U.S. National Lightning Detection Network (NLDN; [33]), the Earth Networks Total Lightning Network (ENTLN; [34]), the Arrival Time Difference Network (UK Met Office) (ATDnet; [35]), and the Vaisala Global Lightning Dataset (GLD360; [36,37]), BrasilDAT [16], and EUCLID [28,38].

In this study, data from the period 2017–2020, were used and obtained using the LIS Space–Time Domain Search (LIS STDS) [39]. The final quality datasets were used where possible, until 2020; however, additional filtrations were carried out for several months in 2020. Thus, ISS LIS flashes with a “Duration” equal to zero milliseconds and “Events” equal to 1 were not taken into account. Additionally, on the second filtration, flashes with “Groups” and “Events” equal to 2, for satellite orbits with “Orbit ID” numbers equal to 21,552 or 21,553, were excluded. Note that pyrocumulus lightning (pyroCb) as reasons for the ignitions were discussed in [40]. These pyroCb strikes are characterized by high-intensity positive lightning density, sometimes more than 100 kA, while most cloud–ground (CG) strikes, investigated in this study, have negative polarity. Due to the positive ground–cloud polarity of pyroCb strikes, the statement that these strikes are a reason for
wildfire ignitions is disputable. The ratio of intracloud lightning (IC) to cloud–ground lightning (CG) in thunderstorms was discussed by Price and Rind in [3].

2.2. MODIS Land Cover

The definitions of the types of lightning wildfire, presented in Figure 1, require knowledge of Australian land cover. In this study, the International Geosphere-Biosphere Programme (IGBP) land mask classification schemes, which have 17 vegetation classes, were used. The original MCD12Q1 files from the C6 collection in HDF format are available from the Earth Explorer server (Earth Explorer) [41]. For more detailed information about the development and accuracy of the MCD12Q1 products, please see [42] and the references therein.

Further, the land cover HDF files were converted to GeoTIFF format by using a special HEG conversion tool, which helps to convert HDF-EOS files to GeoTIFF format and is usually used in a Geographic Information System (GIS). The HEG is a tool developed to allow a user to reformat, re-project, and perform stitching/mosaicing and subsetting operations on HDF-EOS objects. As a basis for a full GIS System, the ESRI ArcInfo system was used, the description of which can be found on the ESRI site [43].

A MODIS land cover map of the state of land cover in 2018, with a spatial resolution of 500 m, is drawn in Figure 2. For convenience, the major roads and cities are also drawn in this Figure.

![Figure 2](image-url)
Figure 3. The contributions of different IGBP classes to Australia’s land cover (MCD12Q1, 2018) are presented.

2.3. The Lightning Land-Cover Retrieval Method

In this study, the monthly land-cover distributions of lightning hotspots determined by the LIS ISS sensor were characterized by three parameters. Firstly, they were characterized by the absolute number of lightning flashes, recorded using the defined IGBP class types. Secondly, because the number of lightning flashes varied from month to month, it is of interest to study the relative contribution, which was defined by the following Equation:

$$n_i(m_j) = \frac{N_i(m_j)}{\sum_{i=1}^{17} N_i(m_j)}$$ (1)

where $m_j$ is a month ($j = 1, \ldots, 12$), $i$ is a number representing the IGBP vegetation classes ($i = 1, \ldots, 17$), and $N_i$ is the number of lightning flashes, recorded in the $i$ vegetation class. The value of $n_i$ is the monthly distribution of lightning in %, which interests us. Note that the gradation into subgroups corresponding to additional LIS attributes, such as “Events” and “Groups”, was not performed.

Thirdly, the monthly land-cover distribution was characterized by the ratio for lightning attraction. This ratio was the relative monthly distribution, normalized to the value of the defined vegetation class for the total land cover distribution, which is defined by Equation (2):

$$ratio_i(m_j) = \frac{n_i(m_j)}{\sum_i LC_i / \sum_{i=1}^{17} LC_i}$$ (2)

where $m_j$ is a month ($j = 1, \ldots, 12$), $i$ is a number representing one of the classes ($i = 1, \ldots, 17$), and $LC_i$ is the number of pixels of $i$ (the vegetation class). The ratio unit is percent to percent (%/%). Note that for uniform land cover loading, the ratio for lightning attraction is equal to 1.
2.4. MODIS Active Fires

The global monthly fire location product, referred to below as MCD14ML, was used in this study. This active fire (AF) product contained information for all Terra and Aqua MODIS fire pixels in a single monthly ASCII file. The MCD14ML files from the C6 collection are available from the University of Maryland fuoco SFTP server [45]. The description of active fire products is available in [46].

The Active Fire MODIS product included the latitude and longitude of wildfire pixels; the brightness temperatures recorded in 21/22 and 31 channels (T21 and T31), which were measured in degrees K; the Fire Radiative Power (FRP), measured in MW; and the detection of confidence, which is presented as a percentage. The datasets used in this study are presented in Table 1.

Table 1. The datasets used in this study are presented. References are given above in the text of Section 2.

| Dataset  | Satellite | Description                                      | Spatial Resolution | Spatial Cover | Time Window | Temporal Coverage               | Variables                                                                 |
|----------|-----------|--------------------------------------------------|--------------------|---------------|-------------|-------------------------------|--------------------------------------------------------------------------|
| LIS      | ISS       | Optical lightning data                           | 4 kmin nadir       | 54.3° N –54.3° S | Daily        | March 2017–present            | Time and location of groups and lightning flashes                          |
| MCD14ML  | Terra and Aqua | Wildfire hotspots          | 500 m            | World         | Daily        | Terra (1999–present) Aqua (2002–present) | Time and location of active fires                                        |
| MCD12Q1  | Terra and Aqua | Classification of vegetation type       | 1 km              | World         | Yearly       | 2018                          | IGBP classes                                                             |
| GDAS     | –         | Meteorological data                           | 1° × 1°            | World         | 3 h          | 1978–present                 | surface wind speed, cloud fraction (mcld, hcld)                          |
| ABARES   | –         | Classification of Australian forest type    | 100 m              | Australia     | 2018         | 2018                          | Eucalypt forests                                                        |

As is well known, the forest fires are characterized by high FRP and confidence values; however, in Australia, the scrubland, meadow, and savanna vegetation types prevail. The ignitions of these vegetation types are characterized by low FRP and confidence, so in our work, there was no reason to exclude low values of confidence and FRP.

2.5. Lightning Wildfire Retrieval Method

In this study, the lightning wildfires were recorded using several satellites. The usual scheme used to carry out investigations is shown in Figure 1d. The two MODIS sensors, established on Terra and Aqua satellites, and the LIS sensor, allocated on board the ISS spacecraft, have different temporal and spatial coverage. Thus, the next temporal–spatial criterion was chosen to register the fact that ignition is triggered by cloud–ground lightning strikes.

Firstly, the wildfires had to be located in a 2 km buffer from the place of registration of the lightning strikes. Secondly, the fires recorded by the Aqua and Terra sensors had to be recorded on the day that the lightning discharges were recorded, but not earlier than the ISS time of flight, or the next day. Thirdly, before the thunderstorm, there should have been no wildfires in the specified region (~10–50 km). Mixed cases, wherein ignitions in the region were observed both before and after the thunderstorm, were not included in the final treatments. Additionally, in this study, the type of vegetation was analyzed near the centers of the thunderstorm strikes.
3. Results

3.1. Seasonal Variations in Lightning Flashes

In this Section, the seasonal variations in lightning strikes, recorded in the period of 2017–2020 by LIS sensors in Australia, are investigated. The results of this investigation are presented in Table 2. As can be seen from Table 2, in Australia, the temporal distribution of thunderstorms is clearly divided into dry and wet periods. The period from April to September (4–9) corresponds to the dry period, which corresponds to the Australian autumn and winter. During the dry period, the thunderstorm activity is minimal. The thunderstorm and lightning activity increases rapidly in Australia in spring (October and November) and in summer (February and March). Further, the interannual variation in thunderstorm activity in the period of 2017–2020 is insignificant, and the maximum activity was recorded in January 2018. In this month, the number of strikes was equal to 9604 pcs.

Table 2. Seasonal variations in the number of the Australian LIS strikes. Values more than 8000 are highlighted in gray.

| Month   | Seasons in Australia | Years |
|---------|----------------------|-------|
|         |                      | 2017  | 2018  | 2019  | 2020  |
| 1       | January              | –     | 9604  | 3702  | 7191  |
| 2       | February             | –     | 6222  | 5078  | 6156  |
| 3       | March                | 5593  | 3342  | 6013  | 1250  |
| 4       | April                | 261   | 551   | 5     | 808   |
| 5       | May                  | 134   | 5     | 408   | 21    |
| 6       | June                 | 0     | 32    | 31    | 1250  |
| 7       | July                 | 22    | 11    | 13    | 47    |
| 8       | August               | 123   | 25    | 1     | 176   |
| 9       | September            | 141   | 232   | 75    | 1099  |
| 10      | October              | 2067  | 4680  | 2023  | 7118  |
| 11      | November             | 9096  | 8036  | 2587  | 6156  |
| 12      | December             | 3690  | 4440  | 8164  | 4331  |
|         | Annual               | 21,127| 37,180| 28,148| 34,374|

Within the frame of our study, it is of interest to compare storm activity with wildfire activity. The seasonal distributions of lightning flashes and wildfire hotspots are presented in Figure 4; please see green, blue, and red lines, respectively. A significant number of wildfires were observed during the dry period, while thunderstorm activity during the dry Australian period was minimal.

Further, an abnormal number of wildfires were registered in summer 2019 and spring 2020 (see black arrows in Figure 4b,d). Detailed information about the seasonal distributions of Australian wildfires can be found in Tables S2 and S3, in Supplementary Materials. In particular, it is noted that there is a difference between the number of Aqua and Terra wildfires, which is highlighted in Table S4. Since this difference is observed in autumn, at the end of the agricultural cycle in Australia, i.e., in April and May, this phenomenon can be explained by the daily burning of agricultural waste.

Summing up this section, we note that the maximum temporal distribution of thunderstorm activity does not coincide with the maximum wildfire activity. The number of thunderstorms in the dry period (April–September) is minimal, while wildfire activity is quite high.

3.2. The Lightning Flashes and Different Vegetation Classes

Next, we investigated the seasonal distribution of lightning over different underlying vegetation types. As is shown above, the main types of vegetation in Australia are shrublands, grasslands, and savannas, which cover 57.4%, 18.4%, and 14.1% of the total Australian area (Table S1). In this study, the monthly distributions of absolute and relative numbers of LIS strikes, and of the four specified major vegetation types, were investigated.
For reference, we remind the reader that the definitions of the relative amount and the ratio of lightning attraction are specified above, in Equations (1) and (2).

Figure 4. The comparison between monthly distributions of MODIS Terra (blue) and Aqua (red) wildfire hotspots, and the ISS LIS lightning flashes (green lines), for the 2017 (a), 2018 (b), 2019 (c); and 2020 (d). Abnormal numbers of wildfires in the spring and summer are marked by arrows.

The strike numbers on grasslands, shrublands, and savannas are calculated and presented in Figures 5a and 6a–d. Additionally, the relative lightning values are presented in Figures 5b and 7a–d, as a percentage of the total monthly lightning values. Due to anomalous low numbers of thunderstorms, the relative flake distributions in the dry season for grassland, savannas, and scrublands (April–September) are not mathematically reliable. Therefore, the central parts of Figures 5b and 7a–d, which contain several peaks, are not the objects of this study.

The seasonal distributions of lightning flashes over the grasslands, croplands, and savanna repeat the general distribution, presented in Figure 4. In the wet Australian season, in spring and summer—i.e., in January–March (1-2–3)—and in October–December (10-11-12), the relative number of strikes over grasslands and open shrublands are about 30–40% of the total number of thunderstorms for the same period (Figures 5b and 7c). However, unlike the grassland relative value, the relative number over grassland savannas in the wet season vary in the range of 10–20% (Figure 7b). Further, the relative number of strikes over the closed shrublands and woody savannas change in a smaller range of 5–10% (Figure 7a,d).

The interannual changes in lightning numbers in the wet season of 2017–2020 were investigated; however, no significant differences in the lightning numbers over the major types of Australian vegetation were found.

It is interesting to note that in the Australian wet season, the attraction ratio (Equation (2)) for grasslands and grassland savannas is equal to ~1.5–2 (Figures 5c and 8b). On the other hand, due to the ratio of lightning attraction for open and closed shrublands being less than 1 (Figure 8a,c), the scrublands do not attract strikes. Moreover, the ratio of lightning attraction for woody savannas is equal to ~1, i.e., the woody savannas have a neutral attraction for thunderstorm lightning.
The remaining categories of IGBP vegetation types occupy less than 3% of the Australian territory (see Table S1). Therefore, the number of lightning flashes that took place over evergreen and deciduous broadleaf forests, croplands, urban, and built-up lands are insignificant and do not exceed a few percent. Due to limited space, the seasonal distributions of lightning over evergreen and deciduous broadleaf forests, croplands, and urban and built-up lands are moved to Supplementary Materials and presented in Figures S1–S4.

Note that the ratio of lightning attraction for urban and built-up lands can significantly exceed 1 (see Figure S4c). Such attractiveness of buildings for CG strikes is an expected phenomenon. A similar phenomenon is observed for the Australian evergreen broadleaf forest (Figure S2c).

The lightning anomalies were found in two study cases, one over croplands and another over the urban and built-up lands. The anomaly in the urban category was associated with a strong thunderstorm in Sydney, which was located on the east coast of Australia. This case study is presented in Figure S5a,b. The anomaly on cropland in November 2017 was associated with a thunderstorm north-east of Melbourne (see Figure S6b). Note that both of these cases are interesting, but are not related to the wildfire anomalies observed in Australia in late 2019 and early 2020, that is, they are beyond the scope of this publication.
Figure 6. The monthly distributions of LISS ISS flashes, recorded in the open (c) and closed (a) shrublands, and in the woody (d) and grasslands savannas (b) in absolute values (pcs.) in the period 2017–2020. MODIS land cover (MCD12Q1) is used for estimations.

Figure 7. The monthly distributions of LISS ISS flashes, recorded in the open (c) and closed (a) shrublands, and in the woody (d) and grasslands savannas (b) as % of total monthly lightning flashes recorded in Australia in 2017–2020.
The interannual changes in lightning numbers in the wet season of 2017–2020 were investigated; however, no significant differences in the lightning numbers over the major types of Australian vegetation were found. It is interesting to note that in the Australian wet season, the attraction ratio (Equation 2) for grasslands and grassland savannas is equal to ~1.5–2 (Figures 5c and 8b). On the other hand, due to the ratio of lightning attraction for open and closed shrublands being less than 1 (Figure 8a,c), the scrublands do not attract strikes. Moreover, the ratio of lightning attraction for woody savannas is equal to ~1, i.e., the woody savannas have a neutral attraction for thunderstorm lightning.

Figure 8. The monthly distributions of ratios of lightning attraction of open (c) and closed (a) shrublands, and of grasslands (b) and woody savannas (d), are presented.

3.3. Spatial Distribution of Lightning Wildfires

In this Section, we present the results of a geo-information study of the relative spatial distributions of wildfires and lightning strikes. This study was carried out using a full-scale Geographic Information System (GIS) ESRI ArcInfo. Note that the sampling method for lightning wildfire retrieval is described above in Section 2.5.

The results of this investigation are summarized in Table 3. Only 23 cases of lightning wildfires were recorded in the period 2017–2020, with 120,829 total lightning flashes recorded in the same period. As can be seen from Table 3, the numbers of registered lightning ignitions are extremely small, and are equal to 6 in 2017, 3 in 2018, 11 in 2019, and 3 in 2020. As percentages of the total number of lightning flashes, these numbers are changed to a range from 0.008% to 0.039% (see Table 3). Additionally, we remind the reader that during the study period of 2017–2020, 445,139 and 599,016 wildfires (Tables S2 and S3) were defined, which is several orders of magnitude more than the value announced above in the 23 events of lightning wildfires.

Table 3. The number of ISS LIS flashes, which, according to MCD14ML wildfires, are probably sources of wildfires. The values in brackets are related to events which did not complete the requirements for selection, specified in Section 2.5. For example, single wildfire hotspots were present in the 3 h prior to the ISS spacecraft flight.

| Month | Seasons in Australia | 2017 | 2018 | 2019 | 2020 |
|-------|---------------------|------|------|------|------|
| 1     | January             | Summer | – | 0 | 2 (1) | (1) |
| 2     | February            | –    | 0 | 3 | 1 |
| 3     | March               | Autumn | 0 | 0 | 2 (1) | 0 |
| 4     | April               | 0 | 0 | 0 | 0 |
| 5     | May                 | 0 | 0 | 0 | 0 |
| 6     | June                | Winter | 0 | 0 | 0 | 0 |
Table 3. Cont.

| Month | Seasons in Australia | Years |
|-------|----------------------|-------|
|       |                      | 2017  | 2018  | 2019  | 2020  |
| 7     | July                 | 0     | 0     | 0     | 0     |
| 8     | August               | 0     | 0     | 0     | 0     |
| 9     | September            | 2     | 0     | 0     | 1     |
| 10    | October              | 0     | 0     | 2 (1) | 1     |
| 11    | November             | 3     | 3 (3) | 0     | 1     |
| 12    | December             | 2 (1) | 0     | 2 (1) | 0     |

Total lightning wildfires, pcs. 6 (1) 3 (3) 11 (4) 3 (1) 23 (9)
Total events, in % 0.028 0.008 0.039 0.009
Annual ISS LIS flashes 21,127 37,180 28,148 34,374

The 2017–2020 merged spatial distribution of the lightning wildfires is drawn in Figure 9. The MODIS land cover map (MCD12Q1, 2018) is used as a background image. The monthly distributions of lightning wildfires that occurred over the specified IGBP land cover vegetation classes are presented in Table 4.

![Figure 9](image-url)

Figure 9. The spatial distribution of the ISS LIS lightning flashes, which can be triggers for lightning-caused ignitions, is presented (see Table 3). The MODIS land cover map (MCD12Q1, 2018) is used as a background image.

The summary of Section 3.3 is as follows: No lightning wildfires were detected during the dry Australian period (April–September). As is shown in Figure 9 and Table 4, most of the lightning wildfires in the wet Australian season are concentrated in the arid northwestern part of the continent, covered with steppe and shrub vegetation. The impact of the recorded lightning wildfires is too small to explain the large number of wildfires in Australia during the wet period of 2017–2020. In Section 4, we will provide a detailed analysis of some typical cases of lightning ignitions.
Table 4. Numbers of lightning wildfires in Australia in 2017–2020, occurring in the IGBP land cover vegetation classes. The values in brackets are related to events which did not complete the requirements for selection, specified in Section 2.5.

| ID | IGBP Classes                  | Numbers of Lightning Wildfires, pcs. | 2017 | 2018 | 2019 | 2020 | 2017–2020 |
|----|--------------------------------|--------------------------------------|------|------|------|------|-----------|
| 0  | Water Bodies                  |                                      |      |      |      |      |           |
| 1  | Evergreen Needleleaf Forests  |                                      | 1    |      |      | 1    |           |
| 2  | Evergreen Broadleaf Forests   |                                      |      |      |      |      |           |
| 3  | Deciduous Needleleaf Forests  |                                      | (1)  |      |      | (1)  |           |
| 4  | Deciduous Broadleaf Forests   |                                      |      |      |      |      |           |
| 5  | Mixed Forests                 |                                      |      |      |      |      |           |
| 6  | Closed Shrublands             |                                      |      |      |      |      |           |
| 7  | Open Shrublands               |                                      | 5 (1)| 2    | 5 (3)| 1    | 13 (4)   |
| 8  | Woody Savannas                |                                      | 1    |      |      |      |           |
| 9  | Savannas                      |                                      | (1)  | 2    | (1)  | 2 (2) |
| 10 | Grasslands                    |                                      |      |      |      |      |           |
| 11 | Permanent Wetlands            |                                      | 1    | (2)  | 2    | 1    | 4 (2)    |
| 12 | Croplands                     |                                      |      |      |      |      |           |
| 13 | Urban and Built-up Lands      |                                      |      |      |      |      |           |
| 14 | Natural Vegetation Mosaic     |                                      |      |      |      |      |           |
| 15 | Permanent Snow and Ice        |                                      |      |      |      |      |           |
| 16 | Barren                        |                                      |      |      |      |      |           |
| 17 | Unclassified                  |                                      |      |      |      |      |           |
|    | Total lightning wildfires, pcs.|                                    | 6 (1)| 3 (3)| 11 (4)| 3 (1)| 23 (9)   |
|    | Annual ISS LIS flashes        |                                      | 21,127| 37,180| 28,148| 34,374| 120,829 |

4. The Spatial Distributions of Lightning Wildfires

4.1. Lightning Wildfires in the Open Shrublands

Two events of lightning wildfires in the area covered by open shrublands, with embedded closed shrubland pixels, are presented in Figure 10. The lightning wildfires in Figure 10a correspond to the event that took place on 29 October 2017, nearby Birdum, in the north of Australia. Another study case, which is drawn in Figure 10b, relates to ignitions nearby Alice Springs on 17 December 2017.

The wildfires in both events were recorded using an AF sensor the day after the thunderstorms. We remind the reader that the spatial resolution of LIS ISS is equal in nadir at ~4 km, so the radius of spatial buffer in our method was chosen to be equal to 2 km. The distances between lightning flashes (black zipper markers) and close wildfire hotspots (red points) are less than 2 km. The weather conditions in both study cases promote propagation of the wildfires to the east in the next one to two days. Additionally, note that before the strikes, the ignitions in the specified regions are not marked. The meteorological situation was analyzed by using the GDAS1 meteorological dataset, but due a lack of space, it is not demonstrated in our work. Moreover, the middle and high tropospheric cloud fraction (mcl, hclcl) and the surface wind (u10, v10) were investigated. The sample of the joint retrieval of the parameters of ISS LIS and MODUS Active Fires for these study cases are presented in Supplementary Materials, in Tables S5 and S6.

4.2. The Lightning Wildfires in Forests

The forests covered approximately 3.6% of Australia. Thus, we found only two events that occurred in the Australian forests. The spatial distributions for forest lightning wildfires are presented in Figure 11a,b. The study case, which is presented in Figure 11a, was located near Perth. It corresponded to a single ignition, which was extinguished the next day. Such behavior usually corresponds to the wet type of lightning wildfires (see Figure 1a).
The summary of Section 3.3 is as follows: No lightning wildfires were detected during the dry Australian period (April–September). As is shown in Figure 9 and Table 4, most of the lightning wildfires in the wet Australian season are concentrated in the arid northern part of the continent, covered with steppe and shrub vegetation. The impact of the recorded lightning wildfires is too small to explain the large number of wildfires in Australia during the wet period of 2017–2020. In Section 4, we will provide a detailed analysis of some typical cases of lightning ignitions.

4. The Spatial Distributions of Lightning Wildfires

4.1. Lightning Wildfires in the Open Shrublands

Two events of lightning wildfires in the area covered by open shrublands, with embedded closed shrubland pixels, are presented in Figure 10. The lightning wildfires in Figure 10a correspond to the event that took place on 29 October 2017, nearby Birdum, in the north of Australia. Another study case, which is drawn in Figure 10b, relates to ignitions nearby Alice Springs on 17 December 2017.

![Figure 10. The spatial join distributions of a couple of the lightning flashes and the wildfire hotspots, recorded together by the ISS LIS (black zipper markers) and by the MODIS Terra/Aqua (red points) sensors in the northwestern part of Australia. (a) corresponds to the study case on 29 October 2017, and (b) on 17 December 2017. In both cases, the weather conditions promoted propagation of the wildfires to the east in the next one to two days. These lightning-caused wildfires have a place in open shrublands. The MODIS land cover map (MCD12Q1, 2018) was used as a background image.](image)

Note that severe thunderstorms more often extinguish fires than contribute to their occurrence. Thus, the burning of a wet forest is a rather rare phenomenon; only isolated instances of ignition of old, dry trees are possible.

Further, the abnormal case of a massive and rapid extending wildfire triggered by lightning is presented in Figure 11b. This rapidly spreading wildfire took place in a forest near Melbourne during the next two days. The global MCD12Q1 land cover map was used in this work, but the global vegetation maps do not correctly characterize a specific type of vegetation growing in a particular area. In other words, different types of forests can correspond to the same spectral range at different parts of the planet. Therefore, to detail the Australian forests, we used the ABARES 2019 map adapted to the vegetation of Australia (ABARES) [47]. According to ABARES 2019, the forests growing between Melbourne and Canberra are characterized as Eucalypt open forests. Therefore, the rapid spread of wildfires can be explained by the fact that the leaves of Eucalyptus emit the essential oils of Eucalyptus, which can be easily ignited.
The wildfires in both events were recorded using an AF sensor the day after the thunderstorms. We remind the reader that the spatial resolution of LIS ISS is equal in nadir at ~4 km, so the radius of spatial buffer in our method was chosen to be equal to 2 km. The distances between lightning flashes (black zipper markers) and close wildfire hotspots (red points) are less than 2 km. The weather conditions in both study cases promote propagation of the wildfires to the east in the next one to two days. Additionally, note that before the strikes, the ignitions in the specified regions are not marked. The meteorological situation was analyzed using the GDAS1 meteorological dataset, but due to a lack of space, it is not demonstrated in our work. Moreover, the middle and high-tropospheric cloud fraction (mcld, hcld) and the surface wind (u10, v10) were investigated. The sample of the joint retrieval of the parameters of ISS LIS and MODUS Active Fires for these study cases are presented in Supplementary Materials, in Tables S5 and S6.

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4.3. The Sheet Lightning Wildfires at the Boundary of a Thunderstorm

We remind the reader that edge or sheet lightning wildfires are wildfires that are triggered on the boundary of a thunderstorm front (see Figure 1b). Sometimes, the thunderstorm front itself can have sufficient length. Such thunderstorms occurred in the north part of Australia on 25–26 December 2018. Several lightning wildfires were established near Darwin (Figure 12a) and Cairns (Figure 12b) at the boundary of thunderstorm fronts.

Other samples of multiple ignitions of lightning wildfires separated by a long distance (30–80 km) are presented in Figure 13a,b. In particular, the two events of lightning wildfire ignitions took place on 21 October 2019, in the northwest of Australia (Figure 13a). Further, three lightning wildfires, presented in Figure 13b, correspond to events that took place in the south of Australia on 29 December 2019.

Thus, when the dry period changes to a wet one, a special condition may be created in which strong thunderstorms can lead to numerous fires. It occurs because, firstly, during this period, the thunderstorm strikes are already strong enough, and secondly, the underlying surface layer remains dry from the previous dry period.

Figure 11. The spatial distributions of ISS LIS lightning flashes and the MODIS active fires that were recorded on 22 October 2020 (a) and on 1 March 2019 (b) in the Australian forests are shown. The study case (a) corresponds to a single active fire (AF) MODIS pixel, extinguished the next day, and (b) represents uncommon massive wildfire hotspots, which spread rapidly during next two days.
Note that severe thunderstorms more often extinguish fires than contribute to their occurrence. Thus, the burning of a wet forest is a rather rare phenomenon; only isolated instances of ignition of old, dry trees are possible.

Further, the abnormal case of a massive and rapid extending wildfire triggered by lightning is presented in Figure 11b. This rapidly spreading wildfire took place in a forest near Melbourne during the next two days. The global MCD12Q1 land cover map was used in this work, but the global vegetation maps do not correctly characterize a specific type of vegetation growing in a particular area. In other words, different types of forests can correspond to the same spectral range at different parts of the planet. Therefore, to detail the Australian forests, we used the ABARES 2019 map adapted to the vegetation of Australia [47]. According to ABARES 2019, the forests growing between Melbourne and Canberra are characterized as Eucalypt open forests. Therefore, the rapid spread of wildfires can be explained by the fact that the leaves of Eucalyptus emit the essential oils of Eucalyptus, which can be easily ignited.

4.3. The Sheet Lightning Wildfires at the Boundary of a Thunderstorm

We remind the reader that edge or sheet lightning wildfires are wildfires that are triggered on the boundary of a thunderstorm front (see Figure 1b). Sometimes, the thunderstorm front itself can have sufficient length. Such thunderstorms occurred in the north part of Australia on 25–26 December 2018. Several lightning wildfires were established near Darwin (Figure 12a) and Cairns (Figure 12b) at the boundary of thunderstorm fronts.

Figure 12. The period of lightning wildfires on 25–26 December 2018 is presented for two study cases, which took place in the north part of Australia, near Darwin (a) and Cairns (b). These Figures demonstrate that wildfires, triggered by the lightning storms, are allocated at the edge of thunderstorms.

Other samples of multiple ignitions of lightning wildfires separated by a long distance (30–80 km) are presented in Figure 13a,b. In particular, the two events of lightning wildfire ignitions took place on 21 October 2019, in the northwest of Australia (Figure 13a). Further, three lightning wildfires, presented in Figure 13b, correspond to events that took place in the south of Australia on 29 December 2019.

Figure 13. The lightning wildfires on 21 October 2019 (2 events) and on 29 December 2019 (3 events) are illustrated by multiple ignitions of the thunderstorm front in (a,b), accordingly. The lightning-caused wildfires in both study cases happened at the same time, but were separated by tens of kilometers.

5. Discussion

Romps et al. [48] proposed that the lightning flash rate per area is proportional to the precipitation rate multiplied by the convective available potential energy. In mathematical form, this looks like following:
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Romps et al. [48] proposed that the lightning flash rate per area is proportional to the precipitation rate multiplied by the convective available potential energy. In mathematical form, this looks like following:

\[ F_l = \frac{\eta}{E} \times P \times \text{CAPE} \]  

where \( F_l \) is the lightning flash rate per area (m\(^{-2}\) s\(^{-1}\)), \( P \) is the precipitation rate (kg m\(^{-2}\) s\(^{-1}\)), \( \text{CAPE} \) is the convective available potential energy, and is measured in J kg\(^{-1}\). The constant of proportionality, \( \frac{\eta}{E} \), contains the dimensionless conversion efficiency \( \eta \), and \( E \) is the energy discharge per flash in joules.

On the other hand, the frequency of ignition is determined by the type of vegetation and the aridity of the season. Thus, the frequency of fires can be determined by the following:

\[ F_f = \alpha_i \times \frac{VI}{I_a} \]  

where \( F_f \) is the frequency of wildfires per pixel, \( VI \) is the burn-sensitive vegetation index (VI) [49], and \( I_a \) is the aridity index. We remind the reader that that the aridity index is defined in [40]:

\[ I_a = \frac{P_{\text{total}}}{EV} \]  

where \( P_{\text{total}} \) is the monthly total precipitation (mm/month), and \( EV \) is the potential evaporation (mm/month). The aridity index is unitless. Note that the \( I_a \) index is usually classified as arid \((I_a \leq 0.2)\), semiarid \((0.2 < I_a \leq 0.5)\), or humid \((I_a > 0.5)\).

From Equations (3)–(5), it follows that in general, for thunderstorms—and consequently, for lightning-caused ignitions—significant rain masses with a high relative humidity (RH) of \( \sim 100\% \) are required to present at the meteor formation level, that is, at high altitudes \( \sim 4–10 \) km; on the other hand, for burning, the underlying vegetation layer must be dry. Thus, these two factors are mutually exclusive, and so, “a priori”, lightning-caused ignitions are a very rare phenomenon. Therefore, it is not surprising that in this study, the ratio of lightning-caused events is varied in the range of 1/12,400 to 1/2560, from total remote flakes, recorded by ISS LIS.

In this study, we found that the ignition probability in Australia in 2017–2020 was in the range of 0.00008–0.00039 fires/stroke, with an average value of 0.00023. It is interesting to compare our result with the results of previous studies. Our average value is similar to that of 0.00015, obtained in Finland by Larjavaara et al. [50], and of 0.00071 in Alberta Canada, reported by Wierzchowski et al. [51]. However, our result is less than that of 0.0017 in Alberta and Saskatchewan [52], 0.0022 in Portugal [53], 0.02 in British Columbia [51], and 0.03 in Greece [53].

Further, based on Dowdy and Mills [17], it could be found that in Victoria, southeastern Australia, the average probability of a fire caused by dry lightning (334 pcs.) and wet lightning (332 pcs.) is equal to 0.014 at a total lightning value of 46,488. What is the reason for such divergence? In [50,53] Perez-Invernon et al. and Larjavaara et al. used the following proximity index \( A \) to search for lightning candidates:

\[ A = \left(1 - \frac{D}{D_{\text{max}}}\right) \times \left(1 - \frac{T}{T_{\text{max}}}\right) \]  

where \( D \) is the distance between each fire and each lightning discharge, with a delay between them of \( T \) (days or hours). The parameters \( T_{\text{max}} \) and \( D_{\text{max}} \) correspond to the maximum holdover and distance between a fire and a lightning discharge, to consider the latter as the cause of ignition. In [53], \( T_{\text{max}} \) was set to 14 days and \( D_{\text{max}} \) was equal to 10 km, with an upper limit of \( A > 0.7 \). However, in [50], the fires judged to be ignited by lightning were linked to strokes occurring within 10 km and 50 h of ignition, see Equation (6). Hence, it is possible to assume that the result can depend not only on the weather conditions and
features of the landscape, but also on the parameters of selection. We remind the reader that in this study, we selected lightning-caused ignition within a radius of 2 km, with a delay probably less than 48 h, i.e., a more severe constraint than in previous studies (see Figure 1d and Section 2.5).

It should particularly be noted that during the Australian Black Summer in Victoria, the southeastern province of Australia, not a single forest fire caused by lightning was recorded.

6. Conclusions

In this study, the impact of the thunderstorm factor on the wildfire situation in Australia in the period of 2017–2020 was investigated. To determine lightning wildfires, a combined study of spatial distributions CG strikes and ignition hotspots, which were obtained from ISS LIS and MODIS Terra and Aqua datasets, was conducted. A total of 23 lightning wildfire events were detected: 6 in 2017, 3 in 2018, 11 in 2019, and 3 in 2020. The total number of lightning strikes, recorded in 2017–2020 by the ISS LIS sensor, was equal to 120,829 flashes. As a percentage of the total strike number, the annual lightning wildfire value varied from 0.008% to 0.039%. Further, by using MODIS sensors in Australia, in the time period from 2017 to 2020, 445,139 (Aqua) and 599,016 (Terra) hotspots were identified, which is several orders of magnitude more than the number of lightning wildfires. Thus, the impact of thunderstorms on fire situation is too small to explain a large number of wildfires during the wet period. Moreover, no thunderstorms were detected during the dry period.

An analysis of the seasonal variability of thunderstorms and fire activity was carried out. It was established that the maximum temporal distribution of thunderstorm activity does not coincide with the maximum wildfire activity. The number of thunderstorm flashes in the dry period (April–September) was minimal, while fire activity was quite high. Additionally, the interannual changes in the number of thunderstorms during the wet period were researched, but significant differences were not revealed in the number of thunderstorms that took place over the major types of Australian vegetation.

In Section 4, we studied, in more detail, the ignition mechanisms, with several particular examples. It was shown that lightning ignitions usually take place along the boundary of thunderstorm fronts, mainly in the arid regions of Australia. In the author’s opinion, the dominant type is edge or sheet lightning wildfires, occurring between the dry and wet Australian period in the area covered by open scrublands. Additionally, two forest lightning wildfires were detected, with one of each occurring in the eucalyptus forest near Melbourne, followed by a rapid spread of forest fire during the next two days. However, during the Australian Black Summer in Victoria in the southeastern province of Australia, not a single forest fire caused by lightning was recorded.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos13050662/s1, Figure S1: The monthly distributions of lightning hotspots (LIS ISS), recorded in deciduous broadleaf forests in pieces (pcs.), as a percentage (%) of total monthly lightning hotspots, and ratio of lightning attraction are drawn in the (a–c), respectively; Figure S2: Same monthly distributions of lightning hotspots of LIS ISS, but recorded in the evergreen broadleaf forests: the amount of lightning (a) in pcs. and (b) in %; (c) the ratio of lightning attraction for evergreen broadleaf forests; Figure S3: The monthly distributions of lightning hotspots of LIS ISS, but recorded in the croplands: the amount of lightning (a) in pcs. and (b) in %; (c) the ratio of lightning attraction for croplands; Figure S4: The monthly distributions of lightning hotspots of LIS ISS, but recorded in urban and built-up lands: the amount of lightning (a) in pcs. and (b) in %; (c) the ratio of lightning attraction for urban and built-up lands; Figure S5: (a) monthly distributions of ISS LIS lightning flashes for Croplands are at maximum in November 2017; (b) the map of spatial distribution of anomalous lightning flashes in November 2017 in the south-east part of Australia. The purple points indicate the lightning flashes in croplands, and black points indicate the lightning flashes in other vegetation classes; Figure S6: (a) monthly distributions of ISS LIS lightning flashes for urban and built-up lands have an anomaly maximum in March 2019; (b) the spatial distribution of thunderstorm flashes in March 2019 in Sydney (Australia). The purple points
indicate the lightning flashes. Table S1: The Australia MODIS land cover vegetation quotes (2018) according by the International Geosphere Biosphere Programme (IGBP) legend and class descriptions; Table S2: The monthly distributions of Australian MODIS Terra wildfires, 2017–2020; Table S3: The monthly distributions of Australian MODIS Aqua wildfires, 2017–2020; Table S4: The differences between the numbers of Australian Aqua and Terra wildfires, 2017–2020; Table S5: The LIS ISS and MODIS parameters for lightning-caused wildfire event (29 October 2017), presented in Figure 10a; Table S6: The LIS ISS and MODIS parameters for lightning-caused wildfire event (17 December 2017), presented in Figure 10b.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data used in this manuscript are available on the official websites of MODIS and the ISS LIS.

**Conflicts of Interest:** The author declares no conflict of interest.

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