Lightning Enhancement in Moist Convection With Smoke-Laden Air Advected From Australian Wildfires

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Abstract The 2019–2020 Australian wildfire crisis broke the historical bushfire record and heavily contaminated the continental and offshore atmosphere. This study found that lightning strokes increase considerably, by 73% over land and 270% over ocean, during the wildfire season. Thermodynamic parameters support a weaker forcing, unfavorable for frequent lightning activity over ocean. Clear augmentation of smaller cloud ice particles is identified with aerosol, while cloud liquid water path changes are feeble over ocean. Added aerosol invigorates positive intra-cloud (IC) strokes and negative cloud-to-ground (CG) strokes in moist oceanic convection and facilitates a noticeable positive correlation between precipitation and lightning strokes. Rainfall events accompanied by lightning increase by 240% with added aerosol. Aerosol advected from land to ocean can lead to a larger hydrometeor concentration and smaller-size ice crystals above the freezing level and thereby, invigorate convective strength systematically to stimulate more frequent and more robust mixed-phase development, energizing the lightning discharge process.

Plain Language Summary The notorious 2019–2020 Australian wildfire devastated >46 million acres of land and heavily contaminated the atmosphere over the Australian continent and offshore regions. In conditions of moist convection over the polluted ocean, massive heat from wildfires on land is ineffectual and aerosol effects can be disentangled from the thermodynamic factors in lightning response. This study focuses on this natural experiment and addresses the lightning changes during the wildfire season by checking both thermodynamic parameters and cloud microphysics. Results of the average surface temperature, convective available potential energy, Bowen ratio, and latent and sensible heat flux support a weaker thermodynamic condition for relatively infrequent lightning activity, crediting aerosol effects for the observed lightning enhancement of 270% over the polluted ocean. Added aerosol mainly invigorates the positive intra-cloud (IC) strokes and negative cloud-to-ground (CG) strokes in oceanic convection. A noticeable positive correlation between precipitation and lightning is identified. Rainfall events accompanied by lightning activity increase by 240% with added aerosol. Clear evidence is shown for an augmentation of smaller cloud ice particles, while changes of the cloud liquid water path are feeble over the polluted ocean. Added aerosol energizes the convective strength systematically and more frequent and robust mixed-phase development invigorates lightning discharges.

1. Introduction

Lightning activity is invigorated with the exacerbation of anthropogenic aerosol emission (Westcott, 1995). Deep convective cloud systems produce numerous lightning discharges by the main mechanism of non-inductive charge separation via rebounding collisions between graupel/hail and ice crystals in the presence of supercooled liquid water (Jayaratne et al., 1983; Reynolds et al., 1957; Saunders, 1993; Takahashi, 1978; Williams, 1985; Williams et al., 1991). Aerosol plumes can traverse the atmospheric boundary layer and participate in cloud microphysical processes by serving as cloud condensation nuclei (CCN) or ice nuclei (IN). The contamination of added aerosol particles modifies the size spectrum of hydrometeors and affects the convective strength substantially (Fan et al., 2018; Rosenfeld et al., 2008). These alterations may ultimately affect the main negative/positive charge...
reservoir in the typical “tripole” or “dipole” cloud charge structure and the associated lightning characteristics (Liu et al., 2020; Williams, 1989).

Lightning changes have been identified as a response to an addition of aerosol (Orville et al., 2001; Thornton et al., 2017; Yuan, Remer, Pickering, & Yu, 2011), but the simultaneous complex thermal convolution (e.g., urban heat island circulation, thermal energy insertion, and frictional lift) confuses the picture of lightning enhancement to added aerosol. How to disentangle the effects of aerosol and thermodynamics on lightning activity remains a challenge. Meanwhile, lightning is expected to increase non-monotonically with aerosol at higher concentrations in simulations of aerosol effects on electrification (Mansell & Ziegler, 2013). The non-linear stimulation of ice crystals to different aerosol concentrations is suspected to motivate the non-monotonic variation of lightning rate. Observations over both smoke-dominant or dust-dominant regions (Altaratz et al., 2010; Wang et al., 2018) at different aerosol optical depth (AOD) levels also show a saturation effect at an AOD value of ~0.3 (corresponding to CCN ~2000 cm⁻³ (Andreae, 2009)) in a “boomerang trend” for the response of lightning rate to aerosol concentration.

For the latter half of 2019, the combination of a positive Indian Ocean Dipole and El Niño-Southern Oscillation, together with a negative Southern Annual Mode, led to the failure of critical winter-spring rains and primed Australia for severely dry conditions. Such extreme synoptic features are the primary cause for the notorious 2019–2020 Australian bushfires (colloquially known as the “Black Summer”), during which the “Black Summer” burned >46 million acres of land, more than 5x more than the most severe wildfire in historical record. The bushfires peaked during 11/2019–02/2020 (named the “active-fire period,” hereafter) and massive wildfires stand out for >1,000 km along the coast of Australia (Figure 1a), coincident with the rich vegetation distribution along the coast and the sparsely inhabited desert territory further inland. In contrast, the fire counts are much reduced during 11/2018–02/2019 in Figure 1b (and the fire climatology during 2016–2017, 2017–2018, 2016–2019 in Figure S1 of the Supporting Information), especially along the coast of New South Wales. The wildfire smoke also heavily contaminated the atmosphere offshore to the southeast of Australia (as characterized by the index of AOD in Figures 1c and 1d), where the AOD gets enhanced significantly from an average of ~0.1–~0.38. But, the attendant massive heat is beyond reach due to rapid dissipation with distance, offering a natural experiment to understand the aerosol effects on lightning. Additionally, the dense smoke pall blown over ocean offers a natural validation of the aforementioned “boomerang trend” in an environment with ample moisture supply, for which such a moist oceanic AOD anomaly (AOD > 0.3) is still lacking in studying the impact of aerosol on lightning activity.

This work focuses on this exceptional natural aerosol-lightning experiment to address the lightning response to added aerosol during the “Black Summer” through a comprehensive examination of both the thermodynamic parameters and cloud microphysics. Taking advantage of the high-resolution lightning data, alterations of lightning characteristics induced by the aerosol effects are discussed for both dry and moist conditions. Possible mechanisms are elaborated to study the complex interactions of aerosol contamination of the cloud convective system and the charge separation process in the mixed-phase region.

2. Methods and Data

The fire location data are derived from the NASA Fire Information for Resource Management System (FIRMS) database, which monitors hotspots in near real-time and has been providing information on active fire from the satellite observation of NASA’s Visible Infrared Imaging Radiometer Suite (VIIRS) for more than a decade (Riggs et al., 2017). The VIIRS is a whiskbroom scanning radiometer on board the Suomi National Polar-orbiting Partnership and observes active fires based on the I-bands (375 m) and M-bands (750 m) fire detections. The active fire product suite maps global fire activity at ≤12h intervals systematically.

The pollutants are mainly characterized by AOD, SO₂, and black carbon, which are measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Sun-synchronous Terra and Aqua platforms (Bosilovich et al., 2016; Platnick et al., 2015; Remer et al., 2008). The data on the thermodynamic parameters and cloud parameters are collected from the MODIS (Collection 6, Level 3) and the reanalysis database of the European Center for Medium-Range Weather Forecasts (ERA5, ECMWF) (Berrisford et al., 2009).
Lightning activity is detected by ENGLN, an integrated system with wideband (1 Hz–12 MHz) electric field detectors in the Earth Networks Total Lightning Network (ENTLN) and the VLF (3–30 kHz) sensor network in the World Wide Lightning Location Network (WWLLN). Lightning discharge type and polarity are determined by the sign of the initial half cycle of bipolar pulses and the waveform characteristics in the measured electric field (Mallick et al., 2015) thereby, providing the distinguished data for intra-cloud (IC)/cloud-to-ground (CG) and positive/negative strokes. The sensor network in Australia has been very stable since 2017 and the stroke detection efficiency is uniformly higher than 80% over the land and oceanic region of interest for this study based on comparison with the measurement from the Lightning Imaging Sensor on board the International Space Station. Additionally, we consider the masquerading of compact intracloud discharges (CIDs) as + CG strokes, for which the +CG stroke statistics are corrected by the misclassified rate of 3.7% for current intensity <30 kA and 55% for current >30 kA (Leal et al., 2019; Liu et al., 2020).

The precipitation observations are derived from the NASA data set known as Integrated Multi-satellite Retrievals for Global Precipitation Measurement Mission (GPM-IMERG) (Huffman et al., 2014), which provides high-resolution observations of rain and snow worldwide every three hours. The GPM Core Observatory inherits the merits on the sampling strategy of TRMM and advances the rain-sensing package with two active radars, capable of probing precipitation particles within clouds layer-by-layer, and a passive microwave imager for sensing the total precipitation within all cloud layers.

Figure 1. Fire count distribution (numbers of fires per grid square of 0.2° × 0.2°) over Australia during (a) the active-fire period of 11/2019–02/2020 and (b) the reduced-fire period of 11/2018–02/2019. Massive wildfires stand out along the coast during the active-fire period. The contamination is characterized by the index of aerosol optical depth (AOD)$_{550}$ (AOD at 550 nm, an aerosol index, spatial resolution 1 × 1°). The AOD$_{550}$ contrast over the regions during (c) the active-fire period of 11/2019–02/2020 and (d) the reduced-fire period of 11/2018–02/2019. A significant accumulation of fire smoke in the atmosphere offshore can be inferred by the noticeable increase of the AOD. Most AOD values over the offshore region exceed the saturation point of 0.3.
3. Results

3.1. Muting of Thermodynamic Factors Offshore

The AOD enhancement is mainly caused by the massive fire complex over Australia and the smoke advected eastward to the marine atmosphere over the Tasman Sea. Meanwhile, SO$_2$ and black carbon mass density distribution show localized emission along the coastline and are confined within a region of radius $\sim$300 km centered on fire plumes (see Figure S2 in the Supporting Information). The low concentrations of SO$_2$ establish a distinct pollution condition in comparison with that of ship tracks (Liu et al., 2020; Thornton et al., 2017), offering a favorable condition for understanding the aerosol effects without strong SO$_2$ and black carbon perturbation. Over the continent, massive heat from combustion is injected into the local environment. Numerous hot fire plumes stimulate pyroconvection, through both thermodynamic and aerosol effects, with the extensive combustion-related emission of heat and moisture in the fire-atmosphere feedback processes (Lang et al., 2013). While for oceanic regions, the heat emission dissipates rapidly with distance from the continental fire source and consequently, greatly reduces any thermodynamic entanglement. The muting of the thermodynamic factors offshore can be verified from the difference in the measured data between the active-fire and reduced-fire period.

Surface temperature shows a slight increase over northern and southeastern Australian coastlines and a part of the central continental region during the active-fire period, consistent with the geolocations of wildfires (Figures 1a and 2a). The surface temperature manifests a clear decrease ($\sim$1°C) for the oceanic region southeast of Australia, and shows a transition from a decrease to an increase across the heavily contaminated regions (AOD $> 0.3$). This temperature decrease over the polluted ocean is caused by an increase in the amount of low-level cloudiness (by drizzle reduction) with added aerosol and regional albedo to enhance the reflectivity of cloud (Albrecht, 1989, see Figure S3 in the Supporting Information). Figure 2b shows a noticeable decrease of Convective Available Potential Energy (CAPE) over the heavily contaminated regions, both for land and ocean, during the active-fire period compared to the reduced-fire period. Moreover, the biggest CAPE reduction is located in the regions with the greatest AOD value. An increase in the CAPE can be identified over northern Australia and the adjacent oceanic regions.

Additionally, regions with low latent heat flux, such as the desert region in the central continent of Australia, are known to show modest lightning activity. The sensible heat flux indicates the vigor of vertical motions from Earth surface to the lower atmosphere, which are vital to deep convection and lightning formation (Williams and Stanfill, 2002). The wildfire conditions are characterized by a pronounced decrease in the latent heat flux and an increase in the sensible heat flux over northeastern and southeastern Australia (Figures 2c and 2d), with an attendant drier land surface and an increase in dry thermal buoyancy. While for the oceanic regions with heavy pollution, the latent heat flux manifests a reduction due to a weaker shortwave solar radiation reaching the sea surface. The sensible heat flux also shows a moderate decrease and these changes together result in an insignificant change in the Bowen ratio. Relative humidity has an impact on the moist convection and cloud development process, thereby, affecting lightning activities (Derbyshire et al., 2004; Redelsperger et al., 2002; Williams et al., 2005; Xiong et al., 2006). The massive wildfires cause a reduction in the relative humidity on land, while the relative humidity shows an insignificant bipolar change over the polluted oceanic region (Figure 2e), where the aerosol is advected from the fire plumes on land, but the heat emission dissipates rapidly with distance from the continental fire source. These measurement results support a weaker thermodynamic forcing propitious for relatively infrequent lightning activity over the ocean, efficiently suppressing the contributions from the thermodynamic effects to lightning activity.

3.2. Lightning Enhancement and Its Correlation with Precipitation

The lightning difference maps are drawn on 0.1° × 0.1° grids during the “Black Summer” in comparison with the reduced-fire period. As shown in Figure 3a, the total stroke density (both ICs and CGs) during the active-fire period is enhanced over the wildfire complex on land and the smoke-laden regions over the ocean when compared with the reduced-fire period. The increase in the total stroke density can reach as high as 58 strokes·km$^{-2}$ yr$^{-1}$ (increased by 73%) over land and 43 strokes·km$^{-2}$ yr$^{-1}$ (increased by 270%) over ocean. Detailed maps of lightning increase with the distinguished IC/CG and negative/positive strokes are given in Figure S4 of the Supporting Information, and briefly summarized here. The increase of IC strokes dominates the lightning enhancement.
in contrast to the growth of CG stroke numbers, especially for the continental condition. The increase in total positive strokes is dominated by positive IC strokes. In contrast, the enhancements of negative IC and CG strokes together are the main contributors to the increased total negative strokes. Furthermore, negative CG strokes dominate the total CG stroke increase, while positive IC strokes are prevailing in the total IC stroke enhancement. The two kinds of discharges (−CG and +IC) are also the most prevalent in the traditional non-inverted polarity thunderstorms.

Figure 2. Difference of averaged (a) surface temperature, (b) Convective Available Potential Energy, (c) latent heat flux, (d) sensible heat flux, and (e) relative humidity comparing the active-fire period with the reduced-fire period, for example, Averaged surface temperature difference = Averaged surface temperature (11/2019–02/2020) - Averaged surface temperature (11/2018–02/2019). “+” marks denote the regions with AOD > 0.3.
Figure 3.

(a) Increased total strokes

(b) Comparison of the changes in lightning characteristics over land and ocean

(c) Scatter plot of the stroke number and precipitation rate in the rainfall-lightning events within the selected red oceanic region in December 2017-2019. The N value indicates the total number of points in the scatter plot.

(d) Precipitation distribution for the selected oceanic region (2019-2020 for the active-fire period and 2010-2019 for the reduced-fire period) and the region outside of wildfire conditions during November-February in the years 2010-2020. Filled circles and squares represent the 99.9th and 99.99th percentile of each distribution, respectively.
Convoluted with the substantial thermodynamic effects over land (Lyons et al., 1998; Steiger et al., 2002), the variations in continental lightning characteristics cannot be understood conclusively in the context of the aerosol-lightning causality. Liu et al. (2020) found that oceanic lightning can be a sensitive indicator for aerosol effects, as the thermodynamic contrast is always indistinct over adjacent oceanic regions. For oceanic conditions, negative strokes increase significantly by 340% compared with the positive stroke enhancement of 130%. Both negative IC (increased by 440%) and CG strokes (increased by 280%) contribute to this noticeable enhancement in the negative discharges. Total IC strokes grow by 392% with respect to the total IC amount during the reduced-fire period. Negative IC strokes are prevailing in the total IC stroke enhancement. Total CG strokes increase by 190% compared with the CG stroke counts in the reduced-fire period. Negative CG stroke counts dominate the enhancement of total CG strokes.

In contrast (Figure 3b), for continental conditions, the positive strokes increase by 97% in contrast to the negative stroke enhancement of 46%. The increase of the positive IC strokes (by 103%) is prominent in positive stroke invigoration compared to the moderate increase of positive CG strokes (by 22%). The enhancement of negative strokes has contributions from both the negative IC (by 78%) and CG strokes (by 30%). IC strokes change more conspicuously over ocean than over land. Positive strokes increase noticeably over both oceanic and continental domains.

We check the information of precipitation and its correlations with lightning on a 0.1° × 0.1° grid resolution during the “Black Summer”. The correlation between daily precipitation and lightning is poor over the Tasman Sea (the red box region in Figure 3c) in the Decembers of 2017–2018. However, during the active-fire period, a noticeable positive correlation is identified (Figure 3c). Moreover, by matching the data of precipitation and lightning, we checked the rainfall-lightning events with one or more lightning strokes (matched in both time and geolocation) and compared them with all rainfall events regardless of lightning. The rainfall-lightning events in 2019–20 increase by 100% (from 7.04 to 14.13 mm/day) for the entire domain, including both the Australian continent and the adjacent ocean, and by 240% (from 12.23 to 41.84 mm/day) for the selected oceanic region compared to the reduced-fire period. Added aerosol enhances the precipitation rate in the rainfall-lightning category, consistent with the intensifying positive correlations between precipitation and lightning. These findings suggest that the abundance of aerosol plays a role in converting electrified shower clouds over ocean to thunderstorms.

Intense precipitation is usually associated with strong convection or large-scale upwelling, with both processes being favorable for lightning discharges. As shown in Figure 3d, more extreme precipitation occur during November–February., 2010–2019 over the outside region (blue dash line) compared to 11/2019–02/2020 (red dash line), as the period of 2010–2019 is much longer and thus, naturally incorporates more extreme events due to atmospheric variability. In contrast, the precipitation with a high rate (>100 mm/day) is noticeably enhanced by 90% in the smoke-laden oceanic atmosphere during 11/2019–02/2020 compared to that during the reduced-fire period (November–February., 2010–2019). One possible explanation for this increase in high-rate precipitation is a greater concentration of large graupel formed aloft in polluted conditions, as added aerosol can suppress the warm rain process and stimulate the growth of larger hydrometeors (e.g., graupel) in upper regions of the storm (Rosenfeld et al., 2008). This circumstance found in the polluted oceanic atmosphere also contributes to the occurrence of lightning activity.

### 3.3. Cloud Microphysical Response to Added Aerosol

Lightning manifests a clear enhancement relative to the reduced-fire period off the southeast coast of Australia over the Tasman Sea, even though the earlier examination of thermodynamic factors suggested a weak convective vigor. Due to the observed AOD anomaly during the active-fire period, aerosol effects are speculated on to
explain this lightning enhancement. To provide further evidence, we checked the cloud microphysical parameters from the satellite measurements.

Ice phase hydrometeors within convective clouds are the main source for charge separation in cloud electrification (Williams, 1985). A larger cloud ice water path (IWP) and liquid water path (LWP) can stimulate charge separation and enhance the total lightning activity in cumulonimbus clouds (Petersen et al., 2005). From the MODIS measurement shown in Figure 4, the precipitation IWP exhibits a noticeable increase over the polluted regions, both on land and ocean. The LWP presents a clear enhancement only over land and the changes are feeble over the polluted oceanic regions. For the polluted regions on land, the IWP and LWP manifest a concordant enhancement, indicating larger numbers of hydrometeors to promote more charge separation in the mixed-phase region. Thus, the lightning activity is invigorated at the locations where both the IWP and LWP increase. In contrast, over the oceanic regions, abundant water vapor is available to condense in the moist convection. The LWP shows weak changes in response to polluted conditions, but the IWP can benefit from the added aerosol and a clear enhancement can be identified even when the AOD exceeds the saturation point of 0.3. Meanwhile, lightning activity increases noticeably over the oceanic regions where the IWP is enhanced.

During the active-fire period, the cloud liquid water particle effective radius (LWPR) is clearly reduced over the moderately polluted land regions characterized by AOD < 0.3, but shows an indistinct response over the heavily smoke-laden regions (AOD > 0.3), over land and ocean alike. The average cloud ice particle effective radius
(IPER) shows a remarkable decrease over the smoke-contaminated regions for both land and ocean, even in heavily polluted conditions (AOD > 0.3). A slight increase is observed only over the moderately polluted oceanic regions, which may be caused by a predominant thermodynamic effect (the increase of surface temperature and total sensible heat flux in Figure 2). This clear evidence for the decrease in cloud IPER is consistent with the earlier findings of Sherwood et al. (2006), Liu et al. (2020), and Yuan, Remer, Pickering, and Yu (2011). It is worth noticing that in the “Black Summer” the AOD rises above the saturation point of 0.3 over oceanic regions. Under this AOD anomaly, the cloud liquid water particle radius shows a modest increase, but lightning activity is still increased, indicating that the decrease of ice particle radius in response to added aerosol plays a more important role in invigorating lightning discharges.

4. Discussion

We find clear evidence of a noticeable increase in the precipitation ice water path and a decrease in the ice particle effective radius over the polluted regions, both on land and ocean. The cloud liquid water path presents a clear enhancement only over land, but the changes are feeble over the polluted oceanic regions. The cloud liquid water particle radius is clearly reduced over the moderately polluted land regions (AOD < 0.3), while an indistinct change is noted over the heavily smoke-laden regions (AOD > 0.3). Added aerosol will slow the coalescence rate into raindrops to suppress warm rain formation in the convective cloud systems (Rosenfeld et al., 2008). These numerous but smaller cloud droplets will prevent precipitation from relatively shallow and short-lived clouds (Twomey, 1977; Rosenfeld & Lensky, 1998). More abundant water vapor is conveyed into the mixed-phase region to provide rime for ice hydrometeors (i.e., graupel and hail) and promote charge separation in rebounding collisions through the non-inductive charging pathway. Therefore, although the ample water vapor supplement in moist convection subdues the changes in the cloud liquid water path and liquid water particle radius with added aerosol, the augmentation in the concentration of the cloud ice particles with a reduced size spectrum can still cause a noticeable lightning enhancement.

Meanwhile, added aerosol could invigorate convection, although the mechanisms of this convection-intensifying effect are still in contention due to the complicated dynamics and microphysics. Three possible microphysical mechanisms modify the cloud convective vigor with added aerosol. The first mechanism is through the “cold-phase” pathway (Rosenfeld et al., 2008). Greater latent heat release within the cloud can occur from the freezing of supercooled cloud water above the freezing level in an inhibition of “warm rain.” The second mechanism emphasizes aerosol impacts on condensational heating. Numerous ultrafine aerosol particles can activate the additional formation of cloud droplets by reducing high supersaturation in liquid clouds and increase condensational heating to intensify convection (Fan et al., 2018). The third mechanism considers the “humidity-entrainment” process. Environmental humidity will increase with the cloud droplet number concentration enhanced by added aerosol and thereby, boost convection through the “humidity-entrainment” mechanism (Abbott & Cronin, 2020). The intensified convection can enhance the impact speed in the graupel/ice crystal electrification process and energize the graupel-ice crystal electrification process, as demonstrated in the laboratory riming electrification experiments (Jayaratne et al., 1983; Takahashi, 1978). In this manner, the convection-intensifying effect can further increase the lightning discharge activity.

Moreover, for oceanic conditions, aerosol in enhanced concentrations can activate the “aerosol-cloud dynamic-thermodynamic feedback effects” and strengthen the evaporation-entrainment feedback to decrease the number of moderately precipitating stratocumulus clouds and increase the number of the deep convective clouds (Saleeby et al., 2015). This process can stimulate the transition from shallow cumulus clouds to deep convective clouds. The transition is dependent on the competing effects of cloud top cooling and surface heating, when sensible heating at the surface dominates, and more broken marine convective clouds occur (Rosenfeld et al., 2006). Other studies also consistently support the aerosol-convection invigoration and the associated deepening of warm clouds (Christensen & Stephens, 2011; Yuan, Remer, & Yu, 2011). The more frequent and vigorous maritime convection stimulated by added aerosol can promote more frequent and robust mixed-phase development, important conditions for lightning formation. These more frequent lightning-viable deep convective clouds transitioning from shallow cumulus clouds can provide another mechanism for initiating lightning discharges.
In consideration of the changes in lightning characteristics to added aerosol over the polluted ocean (Figure 3b), the ratio of the enhanced negative to positive strokes is 2.6 during the Black summer. In contrast, on land the ratio is only 0.47, showing a stronger positive stroke enhancement over land than that over the ocean. Total IC strokes grow by 392% over oceanic regions and by 97% over land regions during the reduced-fire period. Meanwhile, the ratio of IC/CG is increased to 2.1 over the polluted ocean and this ratio increases to 3.4 over land. Accordingly, a more significant enhancement of CG discharges is in evidence over the oceanic regions with added aerosol. The contrast of the increase of negative CGs over ocean and land is more conspicuous than the increase of positive CGs. Therefore, the charge structures become robust over ocean and facilitate more IC discharges in response to the advected aerosol. The positive charge reservoir in the “normal” tripole charge structure is more invigorated over land compared with that of the ocean in polluted conditions. Additionally, the chemical contamination and the size spectrum of cloud droplets can remarkably influence the charge reversal temperature in the non-inductive charging process (Jayaratne et al., 1983; Saunders, 1993). Pollutants emitted from massive wildfires are injected into cloud systems and the associated smaller particle size spectrum will alter the charge reversal temperature documented in laboratory experiments (Avila et al., 1999), supporting a stronger and larger lower positive reservoir. This can be exploited as a candidate mechanism for the observed positive stroke enhancement over land.

The response of lightning flash rate to aerosol concentration is not expected to be monotonically increasing, but instead to have a “boomerang shape” with a saturation effect near the AOD value of 0.3 (Altaratz et al., 2010; Wang et al., 2018). The AOD anomalies during the active-fire period exceed this saturation point, meanwhile, both IC and CG strokes (in negative and positive polarity) are enhanced significantly. The changes of the cloud liquid water path and liquid water particle radius under different AOD values are indistinct over the selected regions. The cloud ice water path shows a decreasing trend and the effective radius of cloud ice particles is reduced over the heavily contaminated region (AOD > 0.3) on land. But, regarding the ocean condition, the cloud ice water path still increases perceptibly and the effective cloud ice particle radius decreases in the heavily contaminated condition. These alterations of the cloud microphysical parameters during the active-fire period support the observed lightning response to the different levels of AOD. Therefore, it is considered that the saturation point of the “boomerang trend” will increase beyond AOD~0.3 with humidity in moist conditions. Moist convection can supply abundant water vapor for condensation compared to the dry continental condition, producing a larger concentration of liquid water/ice particles with added CCN or IN from the abundant aerosol. The increase in the concentration of cloud ice particles takes place even for heavily contaminated conditions (AOD > 0.3). More non-inductive charging is stimulated via rebounding collisions between graupel/hail and ice crystals in the presence of supercooled liquid water and this translates into more lightning discharges. This hypothesis is different from the findings of Wang et al. (2018) over central Africa, as no appreciable role for thermodynamic factors is contributing to the lightning enhancement in our oceanic case. Our study emphasizes that an ample water vapor supplement can change the AOD saturation point on the basis of aerosol-induced increases in ice hydrometeors and intensified convection.

5. Conclusion

For oceanic regions overlain by pollution advected from the fire complex during the 2019–2020 Australian wildfire season, the surface temperature manifests a clear decrease (~1°C) and the CAPE decreases noticeably over the contaminated regions. The latent heat flux and sensible heat flux exhibit a moderate reduction. Such a thermodynamic contrast efficiently suppresses the thermodynamic contributions to lightning activity and lays a valuable foundation for tangible aerosol effects in the smoke-laden oceanic atmosphere. Lightning activity increases by 270% over the polluted ocean southeast of Australia. Added aerosol mainly invigorates positive IC strokes and negative CG strokes in moist oceanic convection and facilitates a noticeable positive correlation between precipitation and lightning. Rainfall events accompanied by lightning activity increase by 240% with added aerosol. Clear evidence has shown that advected aerosol can lead to greater concentrations of ice particles and smaller-size ice crystals above the freezing level, even though the cloud liquid water path shows an indistinct change in moist conditions. Added aerosol can invigorate convective strength systematically and stimulate more frequent and more robust mixed-phase development, energizing the lightning discharge process.
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References
Abbott, T., & Cronin, T. (2020). A humidity-entrainment mechanism for microphysical invigoration of convection. arXiv preprint arXiv:2002.06056.
Albrecht, B. A. (1989). Aerosols, cloud microphysics, and fractional cloudiness. Science, 245(4923), 1227–1230. https://doi.org/10.1126/science.245-4923-1227
Alluartz, O., Koren, I., Vair, Y., & Price, C. (2010). Lightning response to smoke from Amazonian fires. Geophysical Research Letters, 37(7), L07801–L07806. https://doi.org/10.1029/2010GL042679
Andreae, M. O. (2009). Correlation between cloud condensation nuclei concentration and aerosol optical thickness in remote and polluted regions. Atmospheric Chemistry and Physics, 9(2), 543–556. https://doi.org/10.5194/acp-9-543-2009
Avila, E. E., Pereya, R. G., Varela, G. A., & Caranti, G. M. (1999). The effect of the cloud-droplet spectrum on electrical-charge transfer during individual ice-ice collisions. J. Roy. Met. Soc., 125(557), 1669–1679. https://doi.org/10.1002/jq.49712555709
Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., & Uppala, S. (2009). The ERA-interim archive. ERA report series (1), 1–16. Retrieved from http://www.ecmwf.int/publications/library/do/refer
Bosilovich, M., Luccchessi, R., & Suarez, M. (2016). MERRA-2: File specification. GMAO office note no. 9 (Version 1.1). 73. available from http://gmao.gsfc.nasa.gov/pubs/office_notes
Christensen, M. W., & Stephens, G. L. (2011). Microphysical and macrophysical responses of marine stratocumulus polluted by undershipping ships: Evidence of cloud deepening. Journal of Geophysical Research, 116(D3), D03201. https://doi.org/10.1029/2010JD014638
Derbyshire, S. H., Beau, I., Bechtold, P., Grandis, J.-Y., Pirioi, J.-M., Redelsperger, J.-L., & Soares, P. M. M. (2004). Sensitivity of moist convection to environmental humidity. Quarterly Journal of the Royal Meteorological Society, 130(604), 3055–3079. https://doi.org/10.1256/qj.03.130
Fan, J., Rosenfeld, D., Zhang, Y., Giangrande, S. E., Li, Z., Machado, L. A. T., et al. (2018). Substantial convection and precipitation enhancements by ultrafine aerosol particles. Science, 359, 411–418. https://doi.org/10.1126/science.aan8461
Huffman, G., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R., & Xie, P. (2014). Integrated multi-satellite retrievals for GPM (IMERG), version 4.4. NASA's Precipitation Processing Center.
Jayaratne, E. R., Saunders, C. P. R., & Hallett, J. (1983). Laboratory studies of the charging of soft-hail during ice crystal interactions. Quarterly Journal of the Royal Meteorological Society, 109(461), 609–630. https://doi.org/10.1002/qj.49710946111
Lang, T., Rutledge, S., Dolan, B., Krebbel, P., Rison, W., & Lindsey, D. (2013). On the electrification of pyroccumulus clouds. AGU Fall Meeting. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20140006415
Leal, A. F. R., Rakov, V. A., & Rocha, B. R. P. (2019). Compact intraccloud discharges: New classification of field waveforms and identification by lightning locating systems. Electric Power Systems Research, 173, 251–262. https://doi.org/10.1016/j.epsr.2019.04.016
Liu, Y., Guha, A., Said, R., Williams, E., Lapierre, J., Stock, M., & Heckman, S. (2020). Aerosol effects on lightning characteristics: A comparison of polluted and clean regimes. Geophysical Research Letters, 47(9), 1–12. https://doi.org/10.1029/2020GL086825
Lyons, W. A., Nelson, T., Williams, E., Cramer, J., & Turner, T. (1998). Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke from fires. Science, 282(5386), 77–80. https://doi.org/10.1126/science.282.5386.77
Mallick, S., Rakov, V. A., Hill, J. D., Ngin, T., Gamarota, W. R., Pilkey, J. T., et al. (2015). Performance characteristics of the ENTLPN evaluated using rocket-triggered lightning data. Electric Power Systems Research, 118, 15–28. https://doi.org/10.1016/j.epsr.2014.06.007
Mansell, E. R., & Ziegler, C. L. (2013). Aerosol effects on simulated storm electrification and precipitation in a two-moment bulk microphysics model. Journal of the Atmospheric Sciences, 70(7), 2032–2050. https://doi.org/10.1175/JAS-D-12-0264.1
Orville, R. E., Huffman, G., Nielsen-Gammon, J., Zhang, R., Ely, B., Steiger, S. A., et al. (2001). Enhancement of cloud-to-ground lightning over Houston, Texas. Geophysical Research Letters, 28(13), 2597–2600. https://doi.org/10.1029/2001GL012990
Petersen, W. A., Christian, H. J., & Rutledge, S. A. (2005). TRMM observations of the global relationship between ice water content and lightning. Geophysical Research Letters, 32(14), L14819. https://doi.org/10.1029/2005GL023236
Platnick, S., Ackerman, S., King, M., Meyer, K., Menzel, W., Holz, R., et al. (2015). MODIS aerosol identification processing system. USA: NASA Goddard Space Flight Center. https://doi.org/10.5067/MODIS/MOD06_L2.006
Redelsperger, J.-L., Parsons, D. B., & Guichard, F. (2002). Recovery processes and factors limiting cloud-top height following the arrival of a dry intrusion observed during TOGA COARE. Journal of the Atmospheric Sciences, 59(16), 2438–2457. https://doi.org/10.1175/JAS-3041.1
Remer, L. A., Kleidman, R. G., Levy, R. C., Kaufman, Y. J., Tanré, D., Mattoo, S., et al. (2008). Global aerosol climatology from the MODIS satellite sensors. Journal of Geophysical Research, 113(D14). https://doi.org/10.1029/2007JD009661
Reynolds, S. E., Brox, M., & Gourley, M. F. (1957). Thunderstorm charge separation. Journal of Meteorology, 14(5), 426–436. https://doi.org/10.1175/1520-0469(1957)014<0426:TCS>2.0.CO;2
Riggs, G. A., Hall, D. K., & Romaní, M. O. (2017). Overview of NASA's MODIS and visible infrared imaging radiometer suite (VIIRS) snow-cover earth system data records. Earth System Science Data, 9(2), 765–777. https://doi.org/10.5194/essd-9-765-2017
Rosenfeld, D., Kaufman, Y. J., & Koren, I. (2006). Switching cloud cover and dynamical regimes from open to closed Benard cells in response to the suppression of precipitation by aerosols. Atmospheric Chemistry and Physics, 6(9), 2503–2511. https://doi.org/10.5194/acp-6-2503-2006
Rosenfeld, D., & Lensky, I. M. (1998). Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. Bulletin of the American Meteorological Society, 79(11), 2457–2476. https://doi.org/10.1175/1520-0477(1998)079<2457:SBIIFP>2.0.CO;2
Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., et al. (2008). Flood or drought: How do aerosols affect precipitation? Science, 321(5894), 1309–1313. https://doi.org/10.1126/science.1160606
Saleeb, S. M., Herbener, S. R., van den Heever, S. C., & L’Ecuyer, T. (2015). Impacts of cloud droplet-nucleating aerosols on shallow tropical convection. *Journal of the Atmospheric Sciences*, 72(4), 1369–1385. https://doi.org/10.1175/JAS-D-14-0153.1

Saunders, C. P. R. (1993). A review of thunderstorm electrification processes. *Journal of Applied Meteorology*, 32(4), 642–655. https://doi.org/10.1175/1520-0450(1993)032<0642:.AROTEP>2.0.CO;2

Sherwood, S. C., Phillips, V. T. J., & Wetlaufer, J. S. (2006). Small ice crystals and the climatology of lightning. *Geophysical Research Letters*, 33(5), L05804. https://doi.org/10.1029/2005GL025242

Steiger, S. M., Orville, R. E., & Huffines, G. (2002). Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000. *Journal of Geophysical Research*, 107(D11), 2–1.ACL-2. https://doi.org/10.1029/2000JD001142

Takahashi, T. (1978). Rimming electrification as a charge generation mechanism in thunderstorms. *Journal of the Atmospheric Sciences*, 35(8), 1536–1548. https://doi.org/10.1175/1520-0469(1978)035<1536:REAACG>2.0.CO;2

Thornton, J. A., Virts, K. S., Holzworth, R. H., & Mitchell, T. P. (2017). Lightning enhancement over major oceanic shipping lanes. *Geophysical Research Letters*, 44(17), 9102–9111. https://doi.org/10.1002/2017GL074982

Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *Journal of the Atmospheric Sciences*, 34(7), 1149–1152. https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2

Wang, Q., Li, Z., Guo, J., Zhao, C., & Cribb, M. (2018). The climate impact of aerosols on the lightning flash rate: Is it detectable from long-term measurements? *Atmospheric Chemistry and Physics*, 18(17), 12797–12816. https://doi.org/10.5194/acp-18-12797-2018

Westcott, N. E. (1995). Summertime cloud-to-ground lightning activity around major midwestern urban areas. *Journal of Applied Meteorology*, 34(7), 1633–1642. https://doi.org/10.1175/1520-0450-34.7.1633

Williams, E., Mushak, V., Rosenfeld, D., Goodman, S., & Boccioppio, D. (2005). Thermodynamic conditions favorable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate. *Atmospheric Research*, 76(1–4), 288–306. https://doi.org/10.1016/j.atmosres.2004.11.009

Williams, E., & Stanfill, S. (2002). The physical origin of the land-ocean contrast in lightning activity. *Comptes Rendus Physique*, 3, 1277–1292. https://doi.org/10.1016/S1631-0705(02)01407-X

Williams, E. R. (1985). Large-scale charge separation in thunderclouds. *Journal of Geophysical Research*, 90(D4), 6013–6025. https://doi.org/10.1029/JD090iD04p06013

Williams, E. R. (1989). The tripole structure of thunderstorms. *Journal of Geophysical Research*, 94(D11), 13151–13167. https://doi.org/10.1029JD94iD11p13151

Williams, E. R., Zhang, R., & Rydock, J. (1991). Mixed-phase microphysics and cloud electrification. *Journal of the Atmospheric Sciences*, 48(19), 2195–2203. https://doi.org/10.1175/1520-0469(1991)048<2195:MPMACs>2.0.CO;2

Xiong, Y.-J., Qie, X.-S., Zhou, Y.-J., Yuan, T., & Zhang, T.-L. (2006). Regional responses of lightning activities to relative humidity of the surface. *Chinese Journal of Geophysics*, 49, 311–318. https://doi.org/10.1002/cjg.2840

Yuan, T., Remer, L. A., Pickering, K. E., & Yu, H. (2011). Observational evidence of aerosol enhancement of lightning activity and convective invigoration. *Geophysical Research Letters*, 38(4), L04701. https://doi.org/10.1029/2010GL046052

Yuan, T., Remer, L. A., & Yu, H. (2011). Microphysical, macrophysical and radiative signatures of volcanic aerosols in trade wind cumulus observed by the A-Train. *Atmospheric Chemistry and Physics*, 11, 7119–7132. https://doi.org/10.5194/acp-11-7119-2011