A Review of the Physics of Lightning in a Polluted Atmosphere: How It Works, What We See, and What It Does

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Abstract: Aerosols made by people have a big effect on how thunderstorms move and how lightning strikes. This review tries to bring together what we know about how pollution in the air, notably aerosol concentrations, changes how lightning starts and spreads through physical processes like convective invigoration, cloud microphysics, charge separation dynamics, and radiative impacts. We look at how polluted environments affect lightning activity based on aerosol regimes and weather conditions. We do this by looking at observational research, numerical simulations (like WRF-ELEC), and theoretical models. We look at documented links between urban megacities, shipping routes, and areas where biomass is burned. Finally, we talk about the effects of lightning on the environment and climate, such as how it affects the generation of nitrogen oxide (NO_x) in the area. We also point out gaps in our knowledge and suggest areas for future research in atmospheric physics.

Keywords: Lightning physics, aerosol pollution, convective invigoration, cloud microphysics, charge separation, NO_x emissions, WRF-ELEC, and atmospheric electrification.

Introduction

Lightning is a strong natural electrical discharge that happens in storm clouds when charge separation causes dielectric breakdown. But now we know that human-made aerosols, like those from cities, burning biomass, and shipping lanes, are changing how storms and lightning behave through physical pathways called aerosol-cloud-lightning interactions. Not only is it important for atmospheric physics to understand these systems, but it is also important for forecasting, air quality, and climate change mitigation.

Cloud Microphysics and Pollution:

Understanding of aerosols:

Aerosols are tiny solid or liquid particles suspended in the air, ranging in size from a few nanometres to several micrometres. They can come from natural sources (like dust, sea salt, volcanic ash, pollen, forest fires) or human activities (like vehicle emissions, industrial pollution, biomass burning

- **Size:** Typically, 0.001–10 μm in diameter.
- **Types:**
  - **Natural** — sea spray, desert dust, volcanic particles, pollen.
  - **Anthropogenic** — sulfate particles from fossil fuel burning, black carbon (soot), industrial emissions.

Aerosols as Cloud Condensation Nuclei: Fine particles like PM2.5 and sulfate aerosols act as cloud condensation nuclei (CCN). Higher levels of concentration of aerosols cause a lot of tiny cloud droplets to form, which stops rain from falling early and lets droplets rise to higher altitudes. This lets more latent heat out at higher altitudes and makes convective buoyancy stronger. However, when there are enough aerosols in the air, radiative cooling and freezing suppression can weaken clouds and lower lightning.

Convective Invigoration by Pollution: The WRF-ELEC model shows that polluted conditions make updrafts stronger (for example, > 50 m/s at 12 km altitude), release more latent heat, and have more ice crystals. All of these things make charge separation stronger and lightning more likely (~50% increase).

How charge separation and lightning start in polluted areas:

Charge Generation Mechanisms: The electrical structure of contaminated clouds is affected by microphysical interactions between graupel, ice crystals, and supercooled droplets. When droplet sizes change, the results of collisions change, and the main polarity of charge separation may also change. This could affect the ratio of positive to negative lightning that strikes the earth.

Threshold Effects and Nonlinear Behavior: When AOD was less than 1.0, observational study in Central East China from 2001 to 2014 indicated a positive linear association ($r = 0.64$) between the rate of lightning flashes and aerosol optical depth (AOD). This means that AOD was higher. But when AOD went above about 1.0, the link become weaker or even inverted, showing that aerosols had nonlinear effects on electrification.

Evidence from Observation:

Urban and Regional Studies: In megacities, pollution and urban heat islands make lightning more likely. A thorough study indicated that some studies show more lightning activity over polluted metropolitan areas, while others show less, presumably because of stability and radiative effects. For instance, long-term in situ analysis of the Pearl River Delta indicated that there were more lightning strikes when visibility was lower (a sign of pollution).

Shipping Lanes: Aerosols over the Ocean: Studies in the shipping lanes of the South China Sea and the Indian Ocean found that lightning strikes happen twice as often over shipping channels than they do in nearby clean areas. Aerosol emissions that fertilize cloud droplets are thought to be responsible for this impact. This makes clouds taller and lightning more powerful through convective invigoration.

Seasonal Pre-Monsoon Correlations: In the Indo-Gangetic Plain, the months before the monsoon (when there is a lot of aerosols) show a substantial positive correlation (r = 0.63) between the number of lightning flashes and the amount of NO_2 in the troposphere. This link gets weaker during the monsoon months when aerosol levels drop.

Local Surface-Air Pollution and Lightning: In Tehran, the amount of PM_{10} was positively connected with the number of lightning flashes and the amount of NO_2 and ozone that went up after lightning strikes. This suggests that pollution and electricity interact directly at the level of cities.

Studies of Modeling

WRF-ELEC is a sophisticated variant of the standard WRF model that adds physical schemes to simulate how electrification and lightning occur within storms. Instead of relying on proxy indicators (like graupel mass or ice content), it directly computes charge separation and lightning discharge based on microphysical processes.

Simulations that break up clouds: High-resolution models like WRF-CHEM with electrical modules (WRF-ELEC) show that when aerosols make droplets bigger, it makes convection stronger, which makes more ice and graupel, which makes charge separation stronger and lightning more likely. In the same way, additional convective simulations show that how cloud microphysical parameters are set has a big impact on anticipated lightning trends.

How sensitive are you to the type and amount of aerosol? Simulations of different types of aerosols (sulfate vs. smoke) show that sulfate aerosols usually make convection and lightning stronger, whereas smoky aerosols that absorb or are very dense can stop storms from forming by cooling and stabilizing the atmosphere.

A study on WRF-ELEC model over northeast India during the pre-monsoon season found that lightning data assimilation dramatically improves forecast skill. Without assimilation, the model underpredicts events, but with assimilation, it achieved over 91% prediction rate and a 0.78 success ratio for 1-hour lead time. The skill remains “acceptable” up to 3–4 hours, beyond which accuracy drops. Notably, the model can show location bias, sometimes displacing storms as they evolve.

Ways that things work in short:

Microphysical effect: More CCN means smaller droplets, which means deeper convection, which means more ice processes and lightning.

Radiative effect: aerosols absorb heat in the middle of the atmosphere and cool the surface. If there are too many of them, they stop convection.

Effects of charge polarity: changes in droplet size caused by aerosols may change the way graupel charges, which would change the distribution of CG flash polarity.

Effects on the Environment and the Atmosphere:

NO_x and Ozone from Lightning: When lightning strikes, it makes nitrogen oxides (NO and NO_2) because it creates a lot of heat. These oxides are very important for managing mid- and upper-Tropospheric hydroxyl radical (OH), which cleans up a lot of pollutants, including methane, a greenhouse gas, and ozone, a greenhouse gas and pollutant. The yearly contribution is small compared to what people put out, but the chemistry in certain areas and the high levels are important.

Feedback Loops: Lightning that is stronger in polluted places could start wildfires, which would contribute more aerosols and create a feedback loop between pollution and lightning.

Discussion and Next Steps:

There is strong evidence for relationships between aerosols and lightning in many different settings, yet there are still problems:

a) Separating the effects of pollution from the effects of weather.
b) Better defining threshold regimes when aerosol stops or boosts lightning.
c) Including the sort of aerosol, how it spreads vertically, and how long it has been around.
d) Making high-resolution observations better and using new sensors to record changes in polarity, spectrum emissions, and high-altitude electrification.
e) Linking mesoscale models with lightning parameterization to predict changes in the future based on urban and emission scenarios.

Conclusion:

When lightning strikes in dirty air, it shows how fragile the balance is between microphysical invigoration and radiative repression. Evidence from observations and models, from city centers to outlying shipping lanes, shows that moderate pollution makes lightning stronger, whereas extreme aerosol conditions may make storms less electrifying. These changes have effects on climate feedback systems, air quality, and atmospheric chemistry. To predict how lightning will behave in our changing, polluted environment, we need to better understand how it works and how to combine observations with models.

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