Cloud physics perspective on the mechanism of frequent wildfires in the context of climate change: a review of the coupling effect between cloud droplet nucleation and convective processes

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Abstract. Wildfires represent one of the most severe ecological disturbances in the Anthropocene, with their frequency and intensity strongly linked to climate change. From a cloud physics perspective, wildfire mechanisms are shaped by the coupling of aerosol–cloud interactions and convective processes. The Twomey and Albrecht effects alter cloud microphysical properties, reduce precipitation efficiency, and intensify drought conditions. Wildfire-emitted black carbon further modifies radiative forcing, prolongs cloud lifetime, and reinforces feedback loops within the climate system. Global warming enhances convective instability, facilitating aerosol uplift and amplifying the cycle of suppressed rainfall and increased wildfire risk. Recent empirical studies and modeling efforts reveal the multi-scale feedback between aerosols, clouds, and convection that underpin wildfire dynamics. Current monitoring frameworks and policy approaches remain limited, underscoring the urgent need for interdisciplinary strategies that strengthen prediction, prevention, and post-fire ecological recovery.

Keywords: Wildfires; Aerosols; Cloud Microphysics; Convection; Climate Feedbacks.

1. Introduction

Wildfires have emerged as one of the most critical ecological disturbances in recent decades, attracting increasing scientific and policy attention due to their complex links with climate variability and global environmental change [1]. The occurrence and intensity of wildfires are no longer viewed solely as local ecological events but as global and interdisciplinary challenges. Understanding the physical mechanisms that connect climate change with wildfire frequency is essential for advancing predictive capacity and developing effective mitigation strategies.

One of the key perspectives lies in cloud physics, particularly the interaction between aerosols, cloud droplet nucleation, and convective processes. As climate warming accelerates, enhanced emissions of natural and anthropogenic aerosols provide abundant cloud condensation nuclei (CCN). According to the Twomey effect, this results in increased droplet number concentration and reduced droplet size [2,3]. The Albrecht effect further suppresses coalescence, prolongs cloud lifetime, and reduces precipitation efficiency [4]. At the same time, stronger atmospheric convection—driven by uneven surface heating and amplified by global warming—facilitates aerosol transport to higher altitudes while promoting evaporation of raindrops before reaching the ground. These coupled processes intensify drought conditions and reduce effective precipitation.

Drought does not ignite wildfires directly but creates highly favorable conditions by drying vegetation fuels, lowering ignition thresholds, and accelerating combustion [5]. Moreover, wildfire emissions themselves, particularly black carbon aerosols, act as additional CCN, further perturbing cloud microphysics and strengthening climate–fire feedback loops [6]. This reciprocal relationship forms a vicious cycle: prolonged drought enhances wildfire risk, and the greenhouse gases and aerosols released by wildfires further amplify climate change. A comprehensive understanding of these coupled mechanisms is therefore crucial for improving wildfire prediction, strengthening prevention strategies, and informing policy responses under a warming climate.

2. Literature Review

The existing body of literature highlights several thematic areas that are central to understanding the relationship between climate change and wildfire dynamics. First, long-term monitoring and modeling studies have documented significant trends in wildfire frequency and burned area, revealing strong associations with rising temperature and increasing drought severity. Second, comparative analyses across different climatic zones emphasize that wildfire drivers are not uniform but are shaped by region-specific fuel characteristics, hydrological regimes, and vegetation responses. Third, substantial attention has been devoted to the microphysical mechanisms by which aerosols, acting as cloud condensation nuclei, modify droplet number concentration, cloud albedo, and precipitation efficiency. Fourth, studies have examined how aerosols emitted directly by wildfires, particularly black carbon, alter atmospheric radiative forcing, cloud lifetime, and feedback processes. Finally, research indicates that global warming enhances convective instability and modifies precipitation dynamics by increasing atmospheric moisture capacity and altering large-scale circulation patterns.

3. Results and Findings

3.1. Wildfire Trends and Climate Change

According to long-term monitoring data from the National Inter Agency Fire Control Center (NIFC) in the United States, the area burned by wildfires has shown a significant expansion trend since 1983 [7]. In 2020, wildfires in the United States burned approximately 10.1 million acres, compared with only 1.3 million acres in 1983, representing nearly an eightfold increase. Although it has decreased to nearly 7.1 million acres in 2021, it is still 5.5 times that of 1983. Between 2015 and 2024, several years—including 2015, 2017, and 2020—recorded burned areas exceeding 10 million acres, a threshold not reached in any year between 1983 and 2009 This accelerated expansion has been closely associated with climate change, particularly with rising temperatures and prolonged drought conditions that extend the fire season. For example, compared to the 1980s, the wildfire season in California in 2024 has been extended by 25 days, resulting in the state burning 4250 square kilometers, or approximately 1.05 million acres, annually, setting a record for the fifth highest wildfire season in history. Meanwhile, not only in the United States, according to data modeling, the scope and probability of global fire incidents are increasing year by year [8].

Climate change significantly increases the risk of wildfires by exacerbating drought, a mechanism that has been confirmed by multiple studies. According to data from the National Integrated Drought Information System (NIDIS) in the United States, the main reason for the rapid increase in wildfires is the rapid increase in surface vapor pressure deficit (VPD), which is an indicator of atmospheric thirst [9]. High VPD indicates hot and dry air, which extracts moisture from both soil and vegetation, thereby reducing plant water availability. This not only increases the combustibility of biofuels, but also reduces river flow and reservoir water levels.

3.2. Differences of Factors Influencing Wildfires in Different Climate Zones

In Westerling's 2003 paper, the author presented the influencing factors of drought conditions in different regions [10]. In arid shrubs such as Mojave, fire activity shows a slower response - rainfall 1-2 years ago had a greater impact on fires, while current drought conditions are less important. This pattern is typical of regions dominated by fine fuels, where vegetation responds rapidly to changes in moisture availability. In contrast, forested areas such as the Sierra Nevada exhibit a more direct response to summer drought - due to heavy fuels, the current drought makes vegetation more easily ignited.

The transitional areas, on the other hand, exhibit a more complex mixed situation, particularly evident on the Mogolon edge in southeastern Arizona [10]. There, the fire activity is associated with both the accumulation of fuel years ago and the combustibility of the current season. This biphasic

reaction reflects the combined effect of rapidly growing fine fuels and slowly growing heavy fuels in mixed vegetation in open forests to affect fire situations.

3.3. Empirical Study on the Mechanism of Aerosol Action

Based on the Twomey effect, also known as the "first indirect effect" in aerosol cloud interactions, if the total amount of liquid water in the atmosphere remains constant, an increase in aerosol concentration will significantly alter the microphysical properties of clouds [2,3]. During this process, aerosol particles in the atmosphere, such as sulfates and black charcoal, can act as cloud condensation nuclei (CCNs), reacting with water vapor in the clouds to accelerate the formation of cloud droplets. This process increases the concentration of cloud droplets. Meanwhile, when liquid water has the same content, the average effective radius of cloud droplets will become smaller than without aerosols. This change will enhance cloud albedo, the ability of clouds to reflect solar radiation, while suppressing cloud droplet collisions and hindering their growth into raindrops, which may delay or reduce precipitation and lead to land drought over time.

The Albrecht effect describes the climate mechanism by which aerosols extend cloud life by suppressing precipitation formation [4]. When the concentration of aerosols increases, the number of cloud droplets will significantly increase, because aerosols act as cloud condensation nuclei to promote the formation of water droplets. Meanwhile, the effective radius of a single cloud droplet typically decreases to 8 to 12 micrometers. This change leads to a decrease in the collision efficiency between cloud droplets, which may decrease by about 40% to 60%, and thereby will delay or suppress the precipitation process. For example, in layered clouds, observational data shows that an increase in aerosols can prolong cloud maintenance time by 30% to 50% and increase cloud cover by 15% to 25%. The extension of cloud lifespan further enhances the reflection ability of cloud layers towards solar radiation and affects the surface energy balance through continuous coverage. The Albrecht effect is particularly significant in low cloud systems, but its intensity is regulated by meteorological conditions such as vertical wind shear and atmospheric stability, as well as aerosol types such as absorptive black carbon.

3.4. Role and Feedback of Wildfire-Emitted Aerosols

The black carbon aerosols emitted by wildfires are an important component of atmospheric fine particulate matter, and their environmental behaviors are special [11]. Black carbon, types of particles generated by incomplete combustion of biomass, typically have a particle size of less than 2.5 microns and can exhibit strong light absorption capabilities in the visible light spectrum. Unlike organic carbon aerosols that mainly scatter sunlight, the complex fractal aggregation structure and high specific absorption cross-section of black carbon make it a key factor affecting radiation balance. Wildfire emissions are estimated to account for approximately 40% of the global black carbon burden, and their optical properties and environmental effects largely depend on combustion temperature and fuel type.

Black carbon (BC) affects the climate system through multiple pathways. For example, when BC deposit on the surface of ice and snow, they can cause a decrease in albedo of about 20-50%, leading to accelerated melting of ice and snow. Especially in the Arctic region, temperature warming of 1.5 degrees Celsius will be observed in some areas. In addition, according to cloud physics processes, black charcoal exhibits unique behavior as cloud condensation nuclei. It can reduce the effective radius of cloud droplets by 15-30% and decrease the precipitation efficiency of cloud layers by 20% -40%. According to the Albrecht effect [4], these effects significantly prolong the lifespan of clouds and increase cloud cover. Finally, the black carbon layer in the atmosphere also produces unique diurnal temperature effects, increasing the absorption of solar radiation by up to 50W/m ^{2} during the day while reducing the amount of solar radiation received by the surface. This change usually forms a temperature inversion layer, exacerbating drought conditions.

3.5. Research on Convection and Precipitation Mechanisms

Global warming significantly enhances convective activity by altering atmospheric thermal structure and dynamic conditions. For example, the increase in temperature enhances the atmospheric water holding capacity, about 7% increase in water vapor content for every 1 ℃ rise, and the warm and humid air in the lower layers releases more latent heat during the uplift process, resulting in a significant increase in convective effective potential energy (CAPE) and a 35-50% increase in the frequency of severe thunderstorms. At the same time, the amplification effect of the Arctic weakens the meridional temperature gradient, intensifying the fluctuations of the westerly jet stream, causing frequent blockage of high pressure in mid latitudes, prolonging high temperature and high humidity conditions, and further promoting the emergence of convection. Strong updrafts will not only transport surface aerosols, such as black carbon and sulfates, to high altitudes, but also promote the proliferation of aerosols as cloud condensation nuclei (CCNs) through cloud microphysical processes. These processes will form more small cloud droplets; inhibit precipitation formation; and extend the cloud lifespan [12-14].

Enhanced convective activity further alters precipitation efficiency through thermodynamic feedbacks. In high-temperature environments, aerosols carried by strong updrafts form a "core-shell structure" in clouds, doubling their light absorption capacity, intensifying atmospheric heating, and suppressing raindrop collisions. At the same time, the heat convection induced by surface heating causes raindrops to partially evaporate during the falling process, resulting in precipitation not effectively reaching the ground, but instead heating the lower atmosphere through latent heat of evaporation, forming creating a self-reinforcing cycle characterized by elevated temperature, intensified convection, and reduced precipitation". This mechanism is particularly significant in polluted areas, where the positive feedback between aerosols and convection can raise the cloud top height by 500-1000 meters, further expanding the climate impact.

4. Solution and discussion

4.1. Scientific research and modeling

In recent years, many countries and regions around the world have begun to establish intelligent wildfire prevention and management systems, among which the AEGIS system (Advanced, Efficient, and Green Intermodal Systems) developed in collaboration between the Aegean University in Greece and the Forest Service of the US Department of Agriculture is a typical representative [16]. This system combines multi-source data and advanced technology to enable integrated management from early warning to rapid response. This system provides a scientific basis for decision-making in wildfire prevention and control. The core functions of AEGIS system include multi-scale data integration, intelligent warning decision-making, and emergency linkage response. The system operates across three core functions: (i) multi-scale data integration, which combines satellite remote sensing, meteorological observations, terrain, and vegetation data to generate fire risk assessments; (ii) intelligent warning and decision-making, which employs artificial neural networks and minimum propagation time algorithms to simulate fire spread and adjust alert levels using real-time meteorological data; and (iii) coordinated emergency response, which facilitates interoperability with other management systems to enhance operational efficiency.. The system has been deployed in multiple high-risk areas in Greece, significantly improving response times and the effectiveness of fire suppression operations, providing important reference for the development of global wildfire management systems.

4.2. Management and Policy

According to research findings, current policies in various countries face common challenges: insufficient prevention funds (usually less than 1% of the budget), ineffective enforcement of regulations, inadequate adaptation to climate change, limited institutional coordination, and

insufficient community participation [17]. For example, although South Africa has established a fire protection association, rural resources are insufficient; The United States focuses on firefighting rather than prevention, and there are obvious conflicts of interest among stakeholders; Although EU countries have strengthened their monitoring systems, there are still frequent wildfires in the Mediterranean region; Model projections suggest a substantial increase in wildfire hotspots in South America by 2024, with some estimates indicating a several-fold rise compared to the historical baseline.

In order to better mitigate the damage caused by wildfires, we can formulate and implement policies from different perspectives: Adequate governmental funding represents a fundamental prerequisite for effective wildfire management. However, in many countries, prevention budgets remain below 1% of total allocations, limiting preparedness and rapid response capacity. Secondly, mobilizing community participation and strengthening international cooperation are also important aspects that need to be taken seriously. By raising community awareness of fire prevention and promoting international sharing of fire data, problems can be largely solved in the early stages of wildfires; Finally, the ecological restoration work after the end of wildfires also needs to be paid attention to by the government. Timely ecological restoration and post-fire management are critical to minimizing long-term environmental degradation and facilitating ecosystem recovery..

5. Conclusion

Wildfire occurrence is governed by complex and interacting mechanisms rather than a single causal factor. Key drivers include aerosol–cloud interactions, atmospheric convective activity, aerosol–climate feedback loops, and region-specific variations in fuel and climatic conditions. These processes operate across multiple spatial and temporal scales, jointly shaping wildfire frequency and intensity under a changing climate.

The increasing evidence of such interactions underscores the urgent need to view wildfires not merely as isolated ecological disturbances but as integral components of the climate system. Wildfire emissions, particularly greenhouse gases and black carbon, further reinforce climate feedbacks, thereby amplifying both regional drought and global warming. This dual role positions wildfires as both a consequence of and a contributor to climate change, creating self-reinforcing cycles with profound ecological, social, and economic implications.

Addressing these challenges requires a multi-pronged strategy. Advances in predictive modeling and monitoring systems, such as integrated early-warning platforms, are critical for enhancing preparedness. At the policy level, governments and institutions must strengthen prevention funding, improve interregional collaboration, and prioritize post-fire ecological restoration. Coordinated efforts across science, policy, and society are essential to mitigate wildfire risks and to build resilience against climate-driven disasters.

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