Current Pollution Reports (2024) 10:430–442
https://doi.org/10.1007/s40726-024-00296-9

Air Pollution Interactions with Weather and Climate Extremes: Current Knowledge, Gaps, and Future Directions

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Accepted: 1 February 2024

Abstract

Purpose of Review During the past decade, weather and climate extremes, enhanced by climate change trends, have received tremendous attention because of their significant impacts on socio-economy, public health, and ecosystems. At the same time, many parts of the world still suffer from severe air pollution issues. However, whether and how air pollutants play a role in weather and climate systems through complex interactions and feedbacks with meteorology and ecosystems remains an open question. So far, only a relatively small number of studies have been conducted to understand and quantify air pollution interactions with weather and climate extremes. As a result, there is limited process-level knowledge of this topic and associated mechanisms. This review paper provides a concise synthesis of recent scientific advances, current knowledge gaps, and future directions on air pollution interactions with weather and climate extremes, such as extreme precipitation, floods, droughts, wildfires, and heat waves.

Recent Findings There is evidence (albeit limited) that air pollution can contribute to or interact with each of the aforementioned extremes, and several possible mechanisms (e.g., physical, thermodynamical, dynamical, chemical, and ecological processes) have been identified and proposed to explain their relationships. However, there are still substantial knowledge gaps that need to be addressed in future studies, which will benefit from enhanced observational and modeling capabilities as well as interdisciplinary collaborations.

Summary Overall, the air pollution interactions with weather and climate extremes are currently under-studied and less understood. More future research is needed for process-level investigations to improve the mechanistic understanding on this topic.

Keywords Air pollution · Climate and weather · Extremes · Interaction · Mechanism

Introduction

Air pollutants (including aerosols and trace gases) play a critical role in weather and climate systems through complex interactions and feedbacks with meteorology and ecosystems. In general, aerosols can affect atmospheric thermal structures and key meteorological fields (e.g., temperature profiles, radiation, clouds, precipitation, and snow albedo) through direct and indirect radiative effects [1, 2] as well as snow albedo radiative effects [3–5]. In turn, changes in meteorology modulate the life cycle (e.g., formation/emission, transport, and deposition) of aerosols [6–9]. Gaseous air pollutants (e.g., ozone and volatile organic compounds (VOCs)) can interact with vegetation and soil ecosystems through deposition [10, 11] and biogenic emissions [12], while weather and climate also exert important impacts on the lifecycle (e.g.,

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emission, chemical reaction, transport, and deposition) of trace gases [13, 14]. Moreover, some gaseous pollutants can be converted to particulate pollutants through chemical and thermodynamic processes (e.g., formation of secondary organic aerosol (SOA)) and further interact with weather and climate [15], which adds complexity to the climate-chemistry system.

In the past decade, multiple review articles have summarized the knowledge of air pollution from different aspects, including air pollution effects on the mean features of climate/weather [16–18], climate/weather impacts on air pollution [6, 7, 13], health impacts of air pollution [19–21], and air pollution-ecosystem interactions [11, 22, 23]. However, to the best of our knowledge, no review study specifically focused on two-way interactions between air pollution and weather/climate extremes at regional to global scales.

During recent years, weather and climate extremes (e.g., extreme precipitation, floods, droughts, wildfires, and heat waves) have received increasing attention due to their significant impacts on socio-economy, public health, and ecosystems [24–27]. For instance, storms in the North Atlantic in 2017 alone led to devastating flooding, which caused more than $170 billion in damages [28]. Droughts and floods over Asia substantially affect agriculture and food security, leading to ~ $49 billion loss in the economy during 2008–2018 [29]. Heat waves caused about 70,000 deaths in 2003 in Europe [26] and are projected to increase global mortality under future climate change [27]. The increasing wildfires in the U.S. alone lead to thousands of deaths due to smoke pollution and degradation in ecosystem functioning, which requires billions of dollars for suppression expenditures [30].

Majority of attribution studies on weather and climate extremes have focused on the role of long-term climate change mainly due to greenhouse gas build-up, year-to-year natural variability (e.g., ENSO), and to less extent the role of land use and land cover change. However, only rather limited studies have been done to understand and quantify the role of air pollution in influencing and feeding back on weather and climate extremes [31, 32, 33•]. As a result, there is very limited understanding of air pollution interactions with weather and climate extremes and associated process-level mechanisms, suggesting an imperative need for a synthesis of current knowledge gaps and potential future directions on this topic.

This paper therefore seeks to provide a concise review of recent scientific advances in understanding the two-way interactions and the associated feedback mechanisms between air pollution and weather/climate extremes that are socio-economically important, including extreme precipitation, floods, droughts, wildfires, and heat waves. Figure 1 summarizes a general framework to address this interdisciplinary problem. We specifically try to answer the following questions: (1) Is there strong evidence that air pollution is contributing to and/or interacting with weather and climate extremes? (2) If the answer to question (1) is yes, then what is the current understanding of the associated mechanisms and where are the knowledge gaps? (3) What future research directions and innovative approaches should we follow to reduce the knowledge gaps and enhance societal resilience

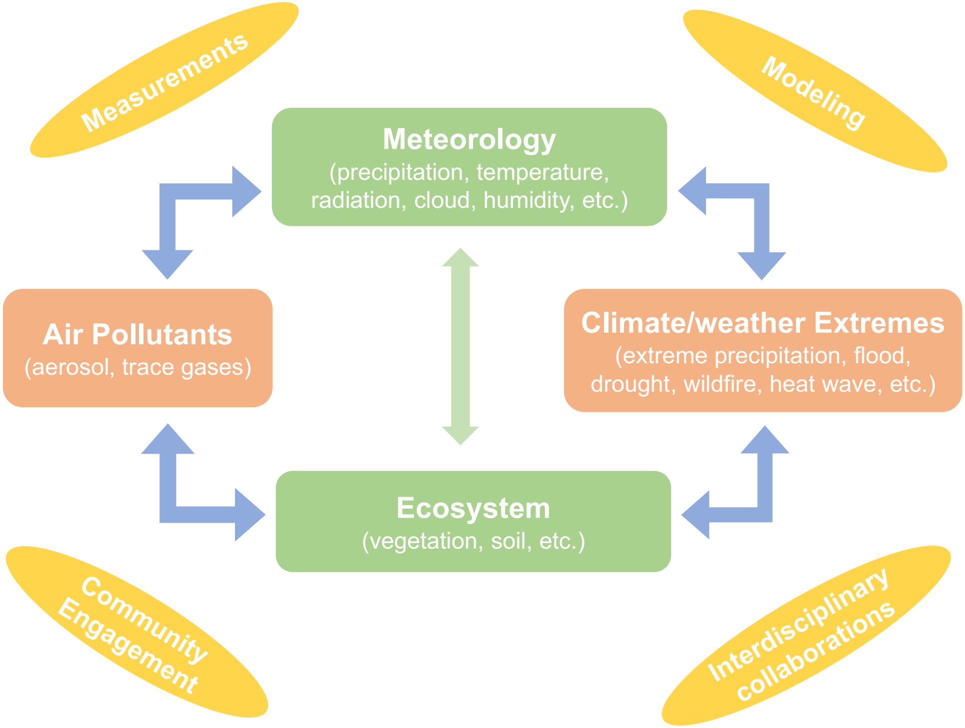

Fig. 1 Framework for addressing air pollution interactions with climate and weather extremes. Note that some of the mechanisms involved in the proposed interaction and feedback loops between air pollution and climate/weather extremes in this framework have not been understood yet, with the lack of direct evidence in literature

to both climate/weather extremes and air pollution in the future decades?

This short review is constructed to cover each type of weather and climate extremes in the following sections with a synthesis at the end. Note that we include those types of extremes due to relatively abundant literature covering at least one-way influence and a viable pathway to explore more explicitly the two-way interactions. The list of weather and climate extremes focused by this review should not be considered exhaustive.

Air Pollution and Extreme Precipitation

Extreme precipitation has received an increasing amount of attention in the past decade, because it can pose significant risks to ecosystems and human socio-economy, particularly over urban, coastal, and monsoon regions [7, 34, 35]. Extreme precipitation events are typically defined as instances with the amount of rain/snow during a certain period (e.g., hourly or daily) substantially exceeding the climatological values. Previous studies used different metrics (e.g., top 1% or 5% of precipitation probability distribution) to define extreme precipitation according to different scientific goals. Both observational and modeling evidence have suggested that in addition to global warming caused by greenhouse gases, air pollutants like aerosols also play a key role in altering and interacting with extreme precipitation [36–41].

Mechanisms of Interactions

Aerosols have long been studied and found to affect precipitation in several major ways. In terms of microphysical effects, aerosols can act as cloud condensation nuclei (CCN) through aerosol-cloud interactions, which facilitates the formation of cloud droplets, delays cloud-to-precipitation transformation, invigorates convection, and hence increase precipitation intensity at a later time [7, 34, 35, 42]. In terms of radiative effects, aerosols can scatter and absorb incoming solar radiation and hence alter atmospheric stability and the development of convective clouds and precipitation [7, 34, 42]. Additionally, some aerosols can directly interfere with the precipitation process by acting as ice nuclei [43, 44], leading to the formation of ice crystals and potentially changing the type, amount, and intensity of precipitation. Moreover, aerosols also impact precipitation via interacting with topography (e.g., mountain-valley), local thermodynamic conditions (e.g., urban heat island), and large-scale circulations (e.g., monsoon systems) [7, 45, 46, 47•], which adds complexity to understanding the full picture of the problem. In general, aerosol effects on precipitation can vary depending on aerosol properties, such as size, composition, and concentration, as well as on the background meteorological conditions at which aerosols operate on and interact with.

The aforementioned mechanisms of general aerosol effects on precipitation provide a basis for understanding and quantifying aerosol impacts on extreme precipitation. On local to regional scales, some studies found that aerosols can enhance extreme precipitation due to aerosol-induced invigoration via microphysical and/or thermodynamical effects [34, 40, 46, 48, 49], especially when interacting with topography [35] and even with ultrafine particles [50]. In contrast, many other studies pointed out that local aerosols can inhibit or weaken the convection and precipitation intensity via radiative effects (surface dimming and atmospheric heating) and/or thermodynamic effects (changing atmospheric thermal structures and the atmospheric stability) [7, 34, 51].

On continental to global scale, aerosols can affect extreme precipitation via interactions with background (global) warming and/or large-scale circulation. For example, aerosols have been found to enhance precipitation intensity and contribute to extreme rainfall in Asia through interaction with the Asian monsoon, Asian Westerly jet streams, or the Tibetan Plateau topography [41, 45], which however may also depend on aerosol types with enhanced intensity due to black carbon and reduced intensity due to sulfate [7, 52, 53]. Over West Africa, anthropogenic aerosols have been found to reduce extreme precipitation during the West African Monsoon by weakening westerlies, monsoon circulation, and moisture fluxes [54]. The cooling radiative effect of aerosols can also offset the effect of global warming, which tends to suppress extreme precipitation [38, 55], but to a less extent than the suppression of mean precipitation [56]. Similarly, future projections suggested that aerosol reductions due to air pollution regulation in future climate will magnify the global warming effect [57] and hence enhance extreme precipitation [58–61].

Extreme precipitation can also affect air pollutants through altered wet deposition and hence their concentrations. For example, the wet removal efficiency of aerosols can be weakened by the shift toward more frequent extreme precipitation in the future compared to that in the present climate, which could lead to increased aerosol concentrations in the future [62]. Extreme precipitation may also indirectly affect air pollutants' emissions by changing the transportation and traffic patterns, which however are seldom studied.

Gaps and Future Directions

Although the understanding and quantification of the relationship between air pollution and extreme precipitation have improved over the last decade, there are still gaps in the current understanding of this complex relationship. For instance, at smaller and shorter scale, whether aerosols enhance or weaken extreme precipitation relies on a number of microphysical factors, such as aerosol type, size, and concentration, as well as the background cloud type and synoptic pattern state. Due to the complex interactions among these factors, the involved mechanisms can vary case by case and are highly region-dependent. At the larger and longer scale, the extreme precipitation responses are more controlled by radiative effects; therefore, due to the different responses of extreme precipitation to absorbing and scattering aerosols, it is crucial to accurately determine aerosol optical properties and assess the associated radiative effects conditioned on the background thermodynamic state and large-scale circulation.

In addition, the relative importance of anthropogenic aerosols in altering extreme precipitation compared to other climate factors (e.g., greenhouse gas warming, natural variability, natural aerosols, and land use change) also remains unclear. A few gaps are highlighted here. (1) There is a lack of sustained and collocated monitoring of air pollutants including aerosol chemical composition, aerosol optical properties, and cloud optical and microphysical properties particularly in the developing countries (where pollution loading is high). This makes it very difficult to identify trends in this relationship and establish cause-effect relationships. (2) There is an inadequate representation of aerosol processes in chemistry-climate models, especially in the operational weather prediction models that are running on a daily basis as well as the IPCC-type of global climate models for long-term climate projection. This results in errors in the simulated aerosol physical, chemical, and optical properties, particularly in conjunction with clouds and precipitation. (3) There is a lack of cross-scale mechanistic understanding of the role of air pollutants in perturbing the synoptic-scale complex cloud-radiation-precipitation systems, which then is coupled with other larger-scale environments (e.g., urban–rural contrast, high mountains, monsoon, and jet streams).

Addressing these knowledge gaps will require targeted long-term multi-platform (in situ, spaceborne, balloon-borne, ship-borne, airborne, and spaceborne) monitoring of air pollutants and extreme precipitation features (e.g., onset, progression, and duration) in different parts of the world. Such monitoring efforts may be informed by long-term analysis of the current global weather monitoring networks from which observations are shared under the World Meteorological Organization (WMO), and/or the state-of-the-art reanalysis dataset in which the monitoring of precipitation and aerosol are assimilated into. Current Earth system models (ESMs), especially the ones with more advanced aerosol-cloud treatment and higher spatial resolution, need to be subjected to comprehensive process-based evaluations through international partnerships between model developers and end users to identify regions of the largest discrepancies between models and observations. Such regions, especially when leveraging unique opportunities such as COVID lockdown or volcanic eruptions, could be the focus of future intensive field campaigns, in order to improve parameterizations of aerosol-precipitation-relevant processes in current models. National meteorological agencies that are responsible for providing actionable information to the public about extreme precipitation events also need to be engaged in the process of establishing new observational sites/networks and improving models.

Air Pollution and Floods

Flood is one of the most devastating hazards that cause significant socio-economic damages, particularly in coastal regions and urban areas. Flood events are defined as instances with substantial overflow of water onto normally dry lands, which are typically caused by excessive rainfall, overflowing rivers, coastal storm surges, or the strong melting of snow/ice [63–65].

Mechanisms of Interactions

One possible mechanism through which air pollution can affect floods is by altering precipitation patterns, intensity, and duration via aerosol-cloud-radiation-precipitation interactions and feedbacks [1, 34, 35]. As discussed in Section "Air Pollution and Extreme Precipitation," several studies have been conducted to understand and quantify how air pollution affects precipitation (including extreme rainfall), but very few studies directly linked air pollution with floods quantitatively. For example, one study [35] found that the severe air pollution in Sichuan Basin (China) suppresses precipitation during daytime and hence substantially enhances the precipitation intensity during night via the aerosol-enhanced conditional instability, which contributed to the devastating flood in the region in 2013. Aerosols can also alter atmospheric thermodynamic states through aerosol radiative effects and interact with monsoon systems, which impacts precipitation intensity and pattern and potentially flood severity [7]. Aerosols have also been suggested to modify tropical cyclones [37] and mid-latitude storm tracks [36], which may further impact floods in coastal areas. One additional complexity during the process of evolving from heavy/extreme precipitation to flooding is the urbanization and infrastructure which typically have large areas of impervious surfaces and hence could enhance flooding [65].

In addition, light-absorbing aerosols can reduce snow albedo after deposition onto snowpack [66, 67] and hence substantially accelerate snow melting [3, 68], which may contribute to flooding. However, there is no study directly connecting aerosol-enhanced snow melting with flooding quantitatively, which needs more investigations in the future.

In turn, floods might indirectly impact air pollution through several potential mechanisms, which however requires more studies. For example, sediments and organic matter carried by floodwater may decompose and release gaseous pollutants to the atmosphere [69]. Floods can destroy infrastructures (e.g., power plants and industrial factories) and change human activities (e.g., transportation patterns and relocation of people to shelters), which further affects anthropogenic emissions of air pollutants. However, these mechanisms have not yet been explored or quantified.

Gaps and Future Directions

Overall, there is currently a lack of direct and effective evidence on the interaction between air pollution and floods, and very few studies have been conducted to directly quantify their relationships. Current knowledge of the mechanisms is still very limited, with many unresolved pieces as discussed above. Even for the aerosol-precipitation mechanism that has received relatively more attention and could be one major driver for floods, there are still large uncertainties as discussed in Section "Air Pollution and Extreme Precipitation." To address these knowledge gaps, more observational and modeling studies are needed, which should target on quantifying the interactions between air pollution and floods through process-level analyses to enhance the mechanistic understanding. Particularly, many confounding factors (e.g., unique urban environment, terrain, proximity to coasts, and storm formation) may also play a role, which add complexity to the problem. Case studies would be a good starting point, while analyses of long-term data record are necessary to obtain robust air pollution-flood relationships and the associated variability. Interdisciplinary collaborations across different groups (e.g., atmospheric chemistry, meteorology, land, and hydrology) will be very beneficial to achieving effective solutions.

Air Pollution and Droughts

Droughts are defined as periods with drier-than-normal conditions, which feature sustained low precipitation and high evapotranspiration leading to drop in soil moisture and surface water level. Drought is one of the most complex and damaging natural disasters, often leading to significant concerns and devastating consequences on water and food security and socio-economy [70]. Many regions (e.g., western U.S., Australia, South America, and part of Europe) have been experiencing severe droughts in the past decade [71, 72], and droughts are projected to occur more frequently over those areas under future climate change [71].

Mechanisms of Interactions

Observational and modeling studies, albeit limited, have shown evidence that droughts can affect air pollution through several complex mechanisms related to land–atmosphere interactions as summarized below.

(1) Droughts favor increased wildfire occurrences, severity, and extent [30, 73], which leads to elevated fire emissions of air pollutants and their precursors [74, 75•]. For instance, summertime surface $PM_{2.5}$ concentrations have been found to increase by 26% in the southern U.S. due to drought-driven wildfire emissions of organic carbon [76].

(2) Droughts favor more frequent and severe dust storms and increase dust and PM concentrations [77–79], which would become more impactful in the future [80] due to the projected increasing droughts in regions like the U.S. Southwest.

(3) Droughts can lead to either increased or decreased surface ozone concentrations [77, 81, 82, 83•] and $PM_{2.5}$ concentrations [14, 77] by altering biogenic emissions, dry deposition, and atmospheric chemistry. For example, biogenic VOC emissions such as isoprene have been found to decrease during long-term severe drought periods because of drought stress on plants, which further reduce ozone production [83•, 84, 85]. However, other studies [82, 86] found that the response of isoprene emissions to drought depends on the duration and severity of drought, where isoprene emissions may increase during short-term or mild droughts due to different plant responses to water stress. The change in isoprene emissions further affects ozone and SOA production (contributing to $PM_{2.5}$ changes). In addition, droughts have been found to change vegetation characteristics (e.g., leaf area index and stomatal functioning) and hence affect the stomatal and non-stomatal pathways for ozone dry deposition [81, 83•, 87].

(4) The meteorological conditions during droughts often favor high temperatures (affecting chemical production/loss) and lack of precipitation (reducing wet scavenging of pollutants) [88]. The elevated air temperature during drought events contributes to the accelerated photochemical process and ozone production [78, 83•]. In addition, little precipitation, surface high pressure system, and low boundary layer height during droughts can weaken the dispersion of air pollutants [89].

(5) Drought-induced changes in electricity generation sources from the use of hydropower to the use of coal and natural gas can lead to enhanced power sector emissions of air pollutants and their precursors [90].

(6) Drought impacts on air pollution can be further complicated by regional and long-range transport of air pollutants. For instance, drought-driven wildfire smoke has been found to transport to downwind regions and exacerbate the air pollution in those regions [91].

Compared to the investigation of drought impacts on air pollution, there are much fewer studies on how air pollution may affect drought development and intensity. An earlier study [34] proposed a conceptual framework showing aerosols can lead to either drought or flood through complex aerosol-cloud-radiation-precipitation interactions based on specific environmental conditions and pollutant levels. A recent study [92] pointed out that the high aerosol levels in north China can enhance drought conditions by suppressing convective precipitation.

Although there is rather limited evidence directly showing the feedback of air pollution to droughts, a few potential mechanisms have been suggested, which require more future investigations. First, aerosols can suppress precipitation via aerosol-cloud-radiation interactions under typical conditions [1, 6, 34, 93], which may further exacerbate drought conditions. For instance, aerosols can suppress convection by reducing solar radiation reaching the surface and increasing lower atmosphere stability as well as by serving as CCN thus delaying the cloud-to-precipitation conversion, which all favor a reduction of precipitation [34]. Second, aerosols can alter temperature gradient and atmospheric circulation through direct and indirect radiative effects [7], which can further affect moisture supply from adjacent oceans and thus precipitation over the dry regions [94]. For example, aerosol-induced regional circulation changes have been found to modify weather patterns and may impact drought conditions [95]. Third, it should be noted that drought is not simply a result of precipitation deficit but is also worsened by the high potential evapotranspiration. A series of analyses have emphasized the aerosol's role in affecting the latter [96], including the subtle competition with greenhouse gas [97] and among different aerosol species [98]. Fourth, related to the third point, air pollutants (e.g., ozone, but to less extent aerosols) may indirectly impact drought conditions by damaging vegetation growth and its physiological processes [99], and hence impacting evapotranspiration and soil moisture.

Gaps and Future Directions

Overall, due to the limited number of studies on the interaction between air pollution and droughts, there are still key knowledge gaps in this topic. (1) Although many studies have indicated that droughts can increase wildfire risks, the associated mechanisms via the complex land–atmosphere interactions are still not fully understood and quantified. This introduces additional uncertainties in the prediction of drought-induced wildfire emissions of air pollutants and associated precursors, where wildfire emission itself is already associated with large uncertainties (see Section "Air Pollution and Wildfires"). (2) Although there is some evidence that droughts can enhance dust storms, there is still a lack of sufficient quantitative knowledge of the relationship between droughts and dust emissions as well as dust transport under prolonged drought conditions, particularly under future climate change. (3) It is not fully understood how soil conditions, vegetation characteristics, and physiological functioning respond to droughts, which further introduces uncertainty to drought-induced changes in biogenic emissions, dry deposition, and chemical processes of air pollutants. (4) The impacts of meteorological conditions during droughts (potentially in conjunction with heat waves; see Section "Air Pollution and Heat Waves") on chemical production/loss, dispersion, and deposition of air pollutants have been under-studied. (5) It is also less well known how drought-induced local air pollution changes are coupled with regional and long-range transport and may impact downstream regions. (6) The effects and interactions of air pollution on droughts are very much under-studied, especially with natural sources of aerosols from wildfires and dust storms in the feedback loop. There is little knowledge on both the associated quantitative impacts and mechanisms, which may involve complicated chemistry-vegetation and aerosol-cloud-radiation interactions as well as some unidentified processes.

To address these knowledge gaps, we provide the following recommendations. (1) More process-level studies and observational data focusing on major drought events are needed. A synthesis of existing in situ and remote sensing observations of droughts, meteorology, and air pollution will provide a good starting point. More analyses of long-term regional air pollution data together with monitored droughts and relevant meteorological data are required to improve the quantification of impacts and interactions between air pollution and droughts. (2) Global/regional climate-chemistry modeling studies, such as process-level sensitivity tests, will be useful to explore and identify the key mechanisms of air pollution-drought interactions. Particularly, the chemistry-vegetation-hydrology interactions are key modeling processes to be enhanced in order to capture the two-way coupling of air pollution and droughts. (3) Collaborations among observational and modeling groups as well as scientists in atmospheric chemistry, meteorology, hydrology, and ecology are needed to facilitate the progress on this interdisciplinary but under-studied topic.

Air Pollution and Wildfires

Wildfires are a key component in our Earth system and have significant social impacts, including directly posing risks to public health and property as well as indirectly impacting the human and earth systems by affecting weather, climate, air quality, ecosystem health, and agriculture [100]. We include wildfire as one type of weather extremes in this study, since it is an unusual, severe weather event that often occurs under extremely dry and/or hot conditions together with droughts and/or heat waves. Previous studies suggest that global wildfire risk will likely increase in the future [101, 102].

Mechanisms of Interactions

Wildfires have long been recognized as one of the major sources of air pollution [74, 75•, 103]. During the combustion process, wildfires directly emit significant amounts of primary air pollutants and precursors of secondary air pollutants [104, 105]. Emissions of a chemical species from a wildfire event can be calculated as a product of fire burned area, fuel load, the fraction of fuel that is burned, and emission factor of the chemical species which varies with vegetation type. Several widely used global fire emission inventories use this approach [103, 105]. Uncertainties exist in all four variables mentioned above, while the uncertainty in fuel load is a major driver of uncertainty in fire emission estimates [105]. Emission factors vary with combustion efficiency, but quantifying combustion efficiency remains challenging. Fires in the wildland-urban interfaces (WUI) also need particular attention as WUI fires can involve structure burning leading to different emissions than wildfires. When trace gases and aerosols are emitted from fires to the atmosphere, they undergo transport and chemical processing. Therefore, understanding transport (e.g., fire plume rise) and atmospheric chemistry (e.g., ozone and SOA formation) are also critical to understanding wildfire impacts on air pollution.

Not only do wildfires impact air pollution but also air pollution can feed back on wildfires, which however is a much less understood process. In theory, there are a few possible pathways through which air pollution may impact wildfires. (1) Air pollutants (particularly aerosols) could change regional atmospheric states (cloud, precipitation, wind, and atmospheric stability) [106], which can affect wildfire occurrence, spread, and intensity. For example, a recent study [9] found that wildfires can be enhanced by the radiative effects of smoke aerosols in different coastal areas through modifying near-surface winds, air dryness, and rainfall patterns, which hence triggers positive smoke-weather-wildfire feedback. (2) Air pollutants can impact the climate by altering atmospheric composition and large-scale radiative balance [107, 108], and the changed climate can further impact wildfire activities. (3) Air pollution can also impact vegetation [99, 109], and vegetation density and distribution largely drive wildfire activities. (4) Under some circumstances, air pollution can impact human activities which are relevant to fire ignition. For example, as more people move to WUI due to urban expansion, the chances of fire ignition are also enhanced [110].

Gaps and Future Directions

Wildfire impacts on air pollution are an active research field. Several gaps need to be addressed. For example, it is crucial to (1) reduce uncertainties in fire emission estimates and (2) understand wildfire-related physical and chemical processes such as plume rise and interaction with meteorology, chemical processes like SOA formation, ozone chemistry, VOC-related processes, and aerosol-cloud interaction.

To address the aforementioned gaps and fully understand the wildfire emissions, subsequent processes, and impacts, it takes joint efforts from lab experiments, field measurements, satellite retrievals, and modeling communities. Lab experiments provide valuable data on emission factors and chemical processes [111]. Field campaigns focusing on fires such as FIREX-AQ (Fire Influence on Regional to Global Environments and Air Quality), WE-CAN (Western wildfire Experiment for Cloud chemistry, Aerosol absorption and Nitrogen), and BBOP (Biomass Burning Observation Project) can significantly push our understanding of wildfires forward [112–115]. Satellite products such as burned area, fire radiative power, atmospheric composition, aerosol optical depth, and plume height retrievals provide large-scale continuous measurements on multiple aspects of wildfires. Climate-chemistry models are very useful to assess wildfire impacts on air pollution at a regional to global scale [114]. It is important to integrate knowledge learned from different approaches together to understand wildfire impacts on air pollution and continue improving the representation of wildfires in climate-chemistry models.

In addition, more studies are needed to understand and quantify the impacts of air pollution on wildfires. At this point, it is unclear how and to what degree air pollution can impact wildfires, which needs to be addressed through interdisciplinary collaborations (e.g., atmospheric chemistry, meteorology, climate, and ecology).

Air Pollution and Heat Waves

Heat waves are typically defined as a period of consecutive days where conditions are excessively hotter than normal [116]. Heat waves have negative impacts on human health [117] and the environment [118]. Previous studies have found that in recent decades, the frequency and intensity of heat waves have increased globally [119], and in the future, more frequent and severe heat waves are expected to occur in many regions due to climate change [120, 121].

Mechanisms of Interactions

Heat waves can contribute to air pollution in multiple ways. Heat waves can directly enhance wildfires and hence fire emissions of air pollutants [122•]. Heat waves in general enhance emissions of biogenic VOCs [123, 124] which are the precursors of ozone and SOA. The higher air temperature during heat waves can increase chemical reaction rates [125].

As a result, previous studies have found that surface ozone and PM pollution are enhanced during heat waves [125–128].

In addition to the direct influences of heat waves, there are other indirect ways through which heat waves can affect air pollution. The broader definition of heat waves includes metrics beyond temperature, but also humidity and radiation. Humid conditions can affect PM formation via aqueous chemistry and wet growth of particle size. Enhanced solar radiation during cloud-free conditions also affects ozone chemistry. For example, the meteorological patterns contributing to heat waves often feature high pressure, low wind, and stagnation, which can impact the horizontal dispersion and vertical ventilation of air pollutants. In addition, droughts, often co-occurring with heat waves [129, 130], can further enhance wildfires and fire emissions as well as affect air pollution in multiple ways as laid out in Section "Air Pollution and Droughts."

Previous studies focused more on how heat waves impact air pollution as discussed above. However, air pollution, especially aerosols as scattering and absorbing agents of solar radiation, may also influence heat waves by altering thermodynamic conditions (generally surface cooling and atmospheric heating). For example, anthropogenic emissions of aerosols can enhance the urban heat island effect locally, which further exacerbates the heat stress resulting from heat waves [131]. Furthermore, aerosols can perturb the regional [7] to global dynamical climate conditions [57, 132, 133•] through aerosol-meteorology interaction, which however is a process that has not yet been explored much.

Gaps and Future Directions

The knowledge of the interactions between air pollution and heat waves is very limited currently. To understand how air pollution might interact or modulate heat waves, it would be beneficial to conduct dedicated model sensitivity studies using a coupled climate-chemistry model that is evaluated comprehensively with existing multi-platform observations of weather and atmospheric chemistry, for specific heat wave events in the recent past, especially those close to large population centers and that have led to major health outcomes.

In addition, via the ecological linkage (Fig. 1), a quantitative understanding of how heat waves (jointly or after drought conditions) impact wildfire occurrence and intensity and hence fire related emissions of air pollutants and precursors will be valuable, especially under the changing climate where heat waves and wildfire activities are both projected to increase in the future.

Conclusions

Air pollutants need to be considered as a key component of weather and climate systems, because they induce complex interactions via meteorological and ecological feedback pathways (Fig. 1). Several existing review articles have covered the state of knowledge of air pollution research from different aspects, such as how air pollution affects climate and weather, how meteorology affects air pollution, the interaction with ecosystems, and impacts on public health. However, to the best of our knowledge, no review article has jointly assessed the two-way interaction between air pollution and climate/weather phenomena, or specifically focused on extremes which have substantial social impacts. Considering the very limited process-level mechanistic understanding at event basis (weather) as well as the general under-appreciation of the role of air pollution for long-term (climate) characteristics of extremes so far, we therefore provided this concise review of the current knowledge and gaps on the role of air pollution in impacting and feeding back on weather and climate extremes. We also proposed some potential future directions to address the knowledge gaps.

We focused this review on the relationships between air pollution and a few representative types of climate and weather extremes, including extreme precipitation, floods, droughts, wildfires, and heat waves, because they are socioeconomically important and also there is relatively more abundant literature addressing at least one-way influence. We note that there are other extremes (e.g., tornado and hurricane) that might interact with air pollution but with very few studies so far. We found that existing literature provides evidence (albeit limited) that air pollution can contribute to and/or interact with each of those extremes focused by this review. Several possible mechanisms, especially via complex air pollution-meteorology and air pollution-ecosystem interactions, have been identified and proposed by previous studies to explain the connections between air pollution and those extremes. Some of these meteorological (e.g., aerosol-cloud interaction) and/or ecological (e.g., ozone-vegetation interaction) mechanisms similarly apply to those of interactions between air pollution and general (mean, non-extreme) climate, but some are unique to extremes (e.g., drought-induced vegetation change affects ozone deposition; unique meteorological conditions during droughts or heat waves affect atmospheric chemistry). Currently, there is still a lack of quantitative assessment of two-way interactions and mechanistic understanding of the feedbacks involved. Moreover, the weather and climate extremes are also often compounded spatiotemporally, such as extreme precipitation-flood and drought-wildfire-heat wave, adding complexity to the problem. Some mechanisms through which air pollution interacts with these extremes may be similar (e.g., aerosol-cloud interaction impacts extreme precipitation and floods; high temperature during droughts and heat waves favors wildfires and thus fire emissions of air pollutants), but there are interactions that are more unique to a specific extreme (e.g., vegetation response to droughts affects biogenic emissions; aerosol wet removal efficiency altered by increased extreme precipitation).

To address the knowledge gaps, there is an imperative need for (1) more process-level investigations focusing on representative weather events and climate conditions to improve the mechanistic and quantitative understanding; (2) synthesizing, enhancing, and sustaining multi-platform multi-scale observations of atmospheric chemistry, meteorology, and ecosystem; (3) multiple modeling analyses for climate and weather extremes contributing to or modulated by air pollution, especially with fully interactive gas-phase and aerosol chemistry as well as ecologically relevant biogeochemistry; and (4) facilitating greater interdisciplinary collaborations across fields (e.g., air quality, synoptic meteorology, climate change, and ecology) and groups (modeling and observation).

Funding C. He was partially supported by NOAA's Climate Program Office's Modeling, Analysis, Predictions, and Projections Program (MAPP) grant NA20OAR4310421. W. Tang was partially supported by NOAA Atmospheric Chemistry, Carbon Cycle and Climate (AC4) Program (Award Number: NA22OAR4310204). The NSF National Center for Atmospheric Research is sponsored by the National Science Foundation.

Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Disclaimer Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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