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PERSPECTIVES

Advancing high-resolution modeling to unravel the interplay between extreme weather events and air pollution under global warming

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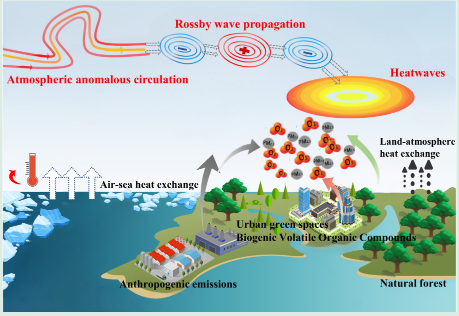
HIGHLIGHTS

- Understanding the interaction between extreme weather and air pollution is essential.
- High-resolution Earth system models are key to capturing multi-sphere interactions.
- There is a growing need to develop and apply high-resolution Earth system models.



ABSTRACT: Under global warming, extreme weather events and air pollution are becoming increasingly critical challenges. Both pose serious risks to human health, economies, and societal stability, and their complex interactions can further amplify these impacts. Numerical models are essential tools for studying these phenomena; however, traditional low-resolution Earth system models often fail to accurately capture the dynamics of extreme weather and air pollution. This limitation hinders our mechanistic understanding, reduces the reliability of future projections, and constrains the development of effective adaptation strategies. Dynamical downscaling—an approach that uses high-resolution regional models nested within global models—offers a partial solution. However, this method inherits biases from the parent global models and often fails to adequately represent multi-scale and cross-sphere interactions involving the atmosphere, land, and oceans. These shortcomings underscore the growing need for developing and applying high-resolution Earth system models that can more

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comprehensively and accurately depict land–sea–atmosphere interactions, including heat and material exchanges and their spatial heterogeneity. This article explores the current challenges, recent advances, and future opportunities in understanding the interplay between extreme weather events and air pollution, with a focus on the critical role of high-resolution modeling.

KEYWORDS: High-resolution Modeling, Extreme weather events, Air pollution, Multiscale and multi-sphere interactions

1 Recent progress in climate change and air pollution research

The number of publications on climate change in the Web of Science Core Collection increased from 3753 in 2000 to 63535 in 2023—A 17-fold rise. Publications addressing both climate change and air pollution followed a similar trend, accounting for approximately 18% of all climate change publications. Research at the intersection of climate extremes and air pollution has grown even more rapidly. Publications on climate extremes rose from 10% (380) of total climate change papers in 2000 to 13% (8477) in 2023, marking a 21-fold increase. Notably, studies that simultaneously address climate extremes and air pollution surged from 22 in 2000 to 594 in 2023—A 26-fold increase—highlighting the growing importance of this interdisciplinary field.

1.1 Extreme weather: from downscaling to high-resolution earth system models

Numerical models are indispensable for studying extreme weather and climate events, particularly under global warming. The spatial resolution of these models determines their ability to represent fine-scale physical, chemical, and biological processes, with at least four grid cells typically required to resolve such features (Salvador et al., 1999). Historically, global models operated at coarse resolutions of 100–200 km or more (Boville and Gent, 1998; Chen et al., 2021). Historically, global models operated at coarse resolutions of 100–200 km or more (Rummukainen et al., 2001; Qian et al., 2010).

Since the 1990s, regional climate models have advanced from resolutions of ~50 km (Dickinson et al., 1989; Giorgi, 1990; Leung et al., 1996) to kilometer-scale resolutions in recent studies (Gao et al., 2012; Walton et al., 2015; Chen et al., 2023; Ou et al., 2023). Initially, the Coordinated Regional Climate Downscaling Experiment (CORDEX) developed ensembles at ~50 km resolution (Giorgi et al., 2009; Giorgi and Gutowski, 2015), and its follow-up CORE initiative achieved finer resolutions of ~25 km (Gutowski et al., 2016; Giorgi et al., 2022), advancing the understanding of regional extremes under future climate scenarios (Rai et al., 2024).

Global models have also improved spatially. In the Coupled Model Intercomparison Project Phase 6 (CMIP6), the High Resolution Model Intercomparison Project (HighResMIP) includes models with ~25 km resolution, reaching scales comparable to regional weather-resolving models (Haarsma et al., 2016; Eyring et al., 2019). These advancements have significantly enhanced the simulation of extreme events (Kim et al., 2020). Tapiador et al. (2020) outlined the evolution of dynamical downscaling, identifying the 1990s as a development phase, the 2000s as a maturity phase, and the 2010s as transitional. Despite advancements, regional models remain valuable for policy-related studies (Coppola et al., 2020). Post-2020, the development of high-resolution Earth system models has accelerated, with models now targeting kilometer-scale resolutions, although long-term simulations remain a challenge. Examples include the ICOsahedral Nonhydrostatic (ICON) model (ICON-Sapphire) (Hohenegger et al., 2023), the Energy Exascale Earth System Model (E3SM) (Rasch et al., 2019; Reed et al., 2023), and the high-resolution coupled Earth system models at 'Sunway' heterogeneous-architecture supercomputer (SW-HRESMs; Zhang et al., 2023), leveraging supercomputing resources to achieve breakthroughs in resolution and accuracy.

1.2 Extreme weathers and air pollution: high-resolution simulations

Progress in high-resolution simulations of interactions between climate extremes and air pollution has lagged behind that in standalone climate modeling. However, the coupling of climate and air quality models has improved significantly (He et al., 2024). These coupled systems capture interactions between climate variables (e.g., temperature, wind, and precipitation) and pollutants (e.g., ozone and particulate matter), revealing how heatwaves can exacerbate air pollution and vice versa.

A major challenge is the high computational cost of simulating numerous pollutant tracers, which often exceeds that of meteorological simulations (Gao et al., 2025b). For instance, simulations at higher atmospheric resolution (e.g., 25 km) can be over ten times more expensive than those at lower resolutions such as 100 km (Gao et al., 2025b). In heterogeneous architecture supercomputing systems, improving the efficiency of slave core utilization can greatly enhance computational performance. Moreover, as cloud computing evolves toward increasingly heterogeneous structures, optimizing resource scheduling becomes critical for the development of kilometer-scale Earth System Models (ESMs) (Zhuang et al., 2020; Kathole et al., 2025).

Atmospheric chemistry models like GEOS-Chem (Bey et al., 2001) and fully coupled systems such as WRF/Chem (Grell et al., 2005) are widely used. While climate-focused multi-model intercomparison projects (e.g., CMIP1 (Lambert and Boer, 2001)) began in the early 2000s, similar efforts integrating atmospheric chemistry, like the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), started later and typically ran at resolutions of ~2° (Lamarque et al., 2013). Since simulating extreme weather and ocean-atmosphere interactions requires finer resolutions—such as 25 km for resolving weather phenomena (Eyring et al., 2019), high-resolution ocean models capable of capturing mesoscale eddies have also become important. These ocean models significantly influence atmospheric circulation patterns (Ma et al., 2024).

Recent computational advances have enabled simulations with ~25 km atmospheric and ~10 km oceanic resolution, as demonstrated by research led by Ocean University of China (Chang et al., 2020; Zhang et al., 2020). These simulations have been applied to study extreme events including marine and atmospheric heatwaves (Guo et al., 2022; Gao et al., 2023; Guo et al., 2024a), atmospheric rivers and extreme precipitation (Wang et al., 2023; Guo et al., 2024b), and atmospheric blocking (Gao et al., 2025a).

For air pollution, coarse resolution has long impeded accurate ozone simulations, primarily due to the inability to resolve precursor emissions from anthropogenic and biogenic sources. This issue, which contributes to ozone overestimation, was emphasized in the latest IPCC report (Liao et al., 2021; Szopa et al., 2021). Recent high-resolution Earth system models such as SW-HRESM, which use improved parameterizations for ozone dry deposition, have significantly enhanced ozone simulations (Gao et al., 2025b).

To address ozone biases, Gao et al. (2025b) increased spatial resolution to better represent urban–rural emission contrasts and identified ozone production regimes sensitive to VOCs or NO_x. They also incorporated leaf area index (LAI) to refine stomatal conductance and adjusted cuticular conductance under varying meteorological conditions (e.g., rainy vs. sunny days). These refinements improved the simulation of ozone dry deposition velocity and substantially reduced the overestimation of ozone concentrations in heavily polluted regions such as eastern China and the south-eastern USA. For example, the high summer ozone bias seen in low-resolution simulations from 2015 to 2019 was reduced by an average of 62%.

2 Challenges and future directions in modeling climate extremes and air pollution

The development of high-resolution Earth system models has created new opportunities to study the interactions between extreme climate events and air pollution across multiple Earth system components. Improving the simulation of historical periods and increasing the reliability of future projections are essential for developing effective mitigation and adaptation strategies—especially in urban areas where air pollution and climate risks converge. Key challenges and future directions are outlined below.

2.1 Compound climate extremes

Research on compound extreme events has gained increasing attention due to their potentially severe societal and environmental impacts (Zscheischler et al., 2018). These events often involve multiple extremes occurring simultaneously or sequentially, linked through complex mechanisms. Understanding these interconnections can greatly improve our ability to predict and respond to high-impact events (Aghakouchak et al., 2020).

A striking example is the interaction between the 2022 Pakistan floods and the East Asian heatwave, which occurred on opposite sides of the Tibetan Plateau. Convective heating in Pakistan acted as a wave source, triggering upper-level divergent winds that interacted with the subtropical jet stream, ultimately inducing the East Asian heatwave (Fu et al., 2024).

Capturing such dynamics requires high spatial and temporal resolution (Fig. 1). Traditional models with resolutions of hundreds of kilometers, such as those in CMIP5, often struggle to resolve fine-scale phenomena like cyclones and convection, undermining the credibility of future projections (Zscheischler and Seneviratne, 2017).

Compound extreme events also produce nonlinear impacts on air pollution, often exceeding the sum of individual events' effects (Gao et al., 2020). However, research into how these compound events interact with atmospheric pollutants—such as aerosols—remains limited, particularly at high resolution.

To address these gaps, it is essential to assess and project compound extreme events and their air pollution responses using high-resolution Earth system models. This will help uncover nonlinear relationships and improve our understanding of how multiple extremes and pollution interact under future climate scenarios.

Another key challenge lies in defining thresholds for future extreme events. Traditionally, fixed historical thresholds have been applied to identify both past and future extremes. However, recent studies highlight that this approach overlooks the adaptability of human and natural systems, as well as the influence of higher-order statistical properties such as variability (Jacox, 2019; Gao et al., 2023). Advancing research that incorporates dynamic thresholds is therefore critical for capturing the evolving characteristics of extreme events in a changing climate.

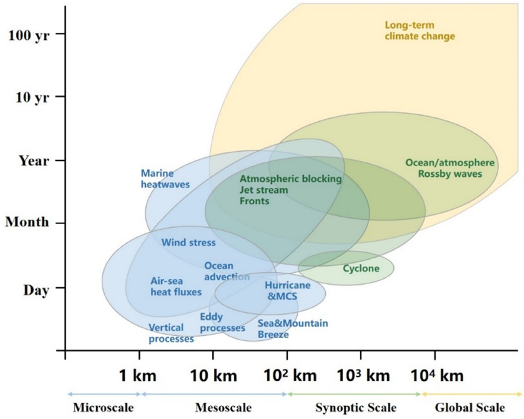

Fig. 1 Spatial and temporal scales of physical processes associated with extreme weather events. This schematic illustrates characteristic physical processes across scales ranging from the microscale (1 km, seconds to hours) to the global scale (10000 km, years to centuries). Different font colors represent various spatial scales, emphasizing the interconnectedness and complexity of these processes within the Earth system. The overlapping spatial and temporal dimensions highlight the need for high-resolution Earth system models to effectively capture and represent processes across multiple scales (Adapted from Tavakolifar et al. (2017); Holbrook et al. (2019)).

2.2 Climate extremes in areas of particular interest

Coastal cities are key population centers, with approximately 38% of the global population living within 100 km of the coast and 45% within 150 km (Luijendijk et al., 2018; Cosby et al., 2024). Offshore, large marine ecosystems cover 22% of the global ocean area and contribute to 95% of the world's fish harvest, highlighting their vital role in global food security and economic stability (Stock et al., 2017). These coastal regions are highly vulnerable to extreme climate events, including tropical cyclones, storm surges, sea-level rise, heatwaves (both terrestrial and marine), extreme precipitation, flooding, droughts, and their interactions with land-sea breeze systems (Huang et al., 2025). Understanding how these events evolve under global warming is both a scientific and societal priority, particularly in light of the increasing exposure and sensitivity of coastal populations and ecosystems.

2.3 Integration of artificial intelligence and high-resolution earth system models

Despite their advantages in simulating extreme climate events, high-resolution models face significant challenges, especially in terms of computational cost and time requirements, particularly for long-term simulations. In addition, small-scale physical processes—such as convection—still require accurate parameterizations.

Recent studies have demonstrated that machine learning (ML) techniques can help learn and emulate these parameterizations. For example, in the case of heavy precipitation, random forest algorithms trained on high-resolution simulation output (e.g., 12 km resolution) have been used to develop convective parameterizations. These can then be applied to coarser-resolution simulations (4–16 times lower) with comparable accuracy, while improving computational efficiency by 1–2 orders of magnitude (O'Gorman and Dwyer, 2018; Yuval and O'Gorman, 2020). This presents a promising path for improving parameterizations in high-resolution models.

However, kilometer-scale simulations that fully resolve these processes are still computationally prohibitive for routine use. As a result, limitations in parameterizations remain a key challenge. Furthermore, high-resolution models can produce divergent outcomes, increasing uncertainty and highlighting the need for multi-model ensemble analyses. Comprehensive inter-model comparisons are essential to improve the robustness and credibility of projections. Where feasible, emergent constraints can be employed to further narrow uncertainties and identify the most plausible future scenarios (Klein and Hall, 2015; Gao et al., 2016). Yet, running such ensembles is computationally intensive.

Integrating artificial intelligence (AI) and ML—especially explainable AI—into Earth system modeling provides a promising solution to these challenges (Chen et al., 2024). First, it can serve as a surrogate for computationally expensive modules, such as gaseous atmospheric chemistry, which would significantly reduce the computational burden. Second, AI can also be used for bias adjustment (Hess et al., 2023), improving model accuracy without increasing complexity. These technologies can enhance model efficiency, deepen our understanding of complex processes, and help identify key mechanisms governing the interactions between extreme climate events and air pollution.

3 Conclusions

In a warming world, extreme weather events are becoming more frequent and impactful. These events influence atmospheric composition by altering emissions, deposition, and chemical reactions. In turn, atmospheric constituents—such as aerosols and greenhouse gases—affect climate through direct and indirect processes. Land and oceans also play central roles, each interacting with the atmosphere in distinct ways: land through varying land cover and land-use changes, and oceans through the exchange of heat and moisture, contributing to complex, multi-layered interactions.

Advances in Earth system models, especially those with higher spatial resolution and improved physical representations, are crucial to understanding these dynamics. High-resolution models offer the ability to capture a broader spectrum of weather and climate phenomena at finer scales. However, realizing their full potential requires continued progress in model development, physical parameterizations, and rigorous evaluation.

This emerging "golden era" of high-resolution modeling calls for interdisciplinary collaboration to further develop and apply these tools. The insights they provide extend beyond climate science—contributing to public health, food security, and disaster risk reduction—and will play an important role in achieving the United Nations Sustainable Development Goals.

Conflict of Interests The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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