THE EFFECT OF SEVERE SMOG POLLUTION ON TURBULENCE

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Abstract

This study examines the complex interaction between anthropogenic air pollution and atmospheric turbulence. Particular attention is given to the critical role of turbulence in dispersing harmful substances within the atmospheric boundary layer. It is shown that pollutants such as soot not only deteriorate air quality but also suppress turbulent transport, thereby creating a positive feedback loop. This process leads to atmospheric stabilization and the accumulation of hazardous concentrations of fine particulate matter with diameters smaller than 2.5 μm, ultimately forming persistent smog. Conversely, reducing soot emissions can enhance turbulence and improve ventilation. The study summarizes field observations and modeling results that demonstrate the influence of the turbulent barrier effect and meteorological factors on pollutant transport. The findings provide a foundation for developing effective strategies to improve air quality and protect public health.

Keywords: air pollution, turbulence, soot, feedback, smog

Atmospheric pollution intensifies the greenhouse effect, contributes to the formation of acid rain, reduces air quality, and leads to the accumulation of toxic substances in soil and water, resulting in ecosystem degradation and biodiversity loss. Human interaction with the environment has long been the subject of research, as anthropogenic activities significantly affect both biotic and abiotic components of ecosystems. Pollution is defined as the release of harmful substances into the environment in concentrations exceeding natural levels, which leads to the degradation of air, water, and soil, as well as to climate change. Since the Industrial Revolution, mass production and the increase in emissions have become key drivers of environmental deterioration and a major threat to public health [1].

CO_2 emissions and soot exert opposite effects on turbulence and the height of the planetary boundary layer. With increasing CO_2 concentrations and decreasing aerosol emissions, the number of severe air pollution episodes is expected to decline, further confirming the health benefits of reducing black carbon emissions [2].

Theoretical models of the atmosphere have traditionally relied on radiative transfer and the characteristics of the underlying surface, where solar heating and anthropogenic emissions serve as primary energy sources. However, at the local scale, a significant factor is the kinetic energy of motor vehicles, which generates turbulence and influences the vertical distribution of pollutants in the lower troposphere. The authors of [3] developed a parameterization of vertical pollutant transport induced by traffic-related turbulence, drawing an analogy with subgrid approaches for industrial plume dispersion. Turbulence is a key factor contributing to ground-level pollution, while also being affected by it. Within the boundary layer—the lowest part of the atmosphere—turbulence mixes pollutants and can facilitate their removal (far-left panel).

At high concentrations of absorbing aerosols, such as soot, heating of the upper boundary layer stabilizes the air, reduces turbulence, and promotes the accumulation of pollutants closer to the surface (middle panel). Pollution studies have also revealed a weaker turbulence-enhancing effect associated with surface warming caused by greenhouse gases such as CO_2 (far-right panel). Under weak wind conditions, intermittent turbulence frequently develops in the atmospheric boundary layer, substantially limiting the vertical diffusion of pollutants and contributing to the formation of dense haze. Turbulence can vanish at specific altitudes, leading to the formation of a barrier layer that prevents the vertical transport of contaminants. Based on turbulence data across five layers and concentrations of fine particulate matter with diameters smaller than 2.5 μm at two levels, it has been demonstrated that the vertical turbulence barrier is directly linked to the accumulation and vertical distribution of particles [4–5].

Atmospheric turbulence and the properties of the planetary boundary layer play a crucial role in modulating near-surface concentrations of fine particulate matter ($PM_{2.5}$); however, the mechanisms of their influence remain insufficiently understood. Using meteorological observations, $PM_{2.5}$ data, turbulence measurements, and high-resolution sounding, a regional transport episode was analyzed. During the growth stage, northerly winds (2–4 m/s) carried a polluted air mass, which was accompanied by an increase in $PM_{2.5}$ concentrations. During the pollution period, a decline in turbulent kinetic energy and heat fluxes correlated with rising $PM_{2.5}$ levels, with the nature of this relationship varying across different stages of the event: a negative correlation was observed during the initial and maintenance stages, while a positive correlation was found in the growth stage.

The absence of a pronounced inversion below 500 m and vertically uniform northerly winds facilitated the transboundary transport of pollutants, whereas wind shear limited their downward transport to the surface [6]. Turbulent diffusion is often considered a desirable phenomenon in many contexts, yet it also presents significant challenges, particularly in the domain of air pollution. Air pollution, a widely recognized and condemned problem, deteriorates air quality and poses serious long-term health risks. Turbulent flows, characterized by chaotic and random fluid motions, give rise to turbulent diffusion—a process that serves as a transport mechanism for dispersing pollutants in the atmosphere. Advances in research have deepened the understanding of turbulent diffusion and its broad applications, as new methods are continuously being employed to expand both the scope of studies and practical applications [7].

Turbulence poses not only potential hazards but also economic costs for aviation, accelerating aircraft wear and increasing fuel consumption as pilots attempt to avoid it. The intensification of chaotic atmospheric motions has stimulated efforts to develop methods for forecasting and mitigating its effects. Among promising approaches is the use of lidar systems for three-dimensional mapping of the air surrounding an aircraft, similar to point cloud technology employed in autonomous vehicles. A 2023 study proposed a "dual-wavelength" system capable of detecting light and moderate turbulence up to 7–10 km ahead. However, at higher altitudes, such devices remain too bulky, heavy, and energy-intensive for use on commercial aircraft.

Flying through vortices, eddies, and updrafts with minimal disturbances requires not only precise engineering but also a profound understanding of hydrodynamics, as air, like water, obeys the laws of fluid motion. The chaotic nature of turbulence makes flow behavior highly sensitive to even small perturbations, whether caused by wind deflection near a building or the jet stream of another aircraft. Surface air pollution remains a serious threat to human health, causing millions of premature deaths each year. One of the major pollutants is soot, generated from coal combustion and vehicle exhaust.

In study [8], researchers employed a combination of global climate models, specialized modeling experiments, and previous findings on the relationship between soot emissions and turbulence in the lower atmosphere. It was shown that high concentrations of soot contribute to a reduction in turbulence. Under low-turbulence conditions, the atmosphere becomes more stable, leading to the accumulation of pollutants near the surface and resulting in intense pollution episodes, typical of the winter season. Dark soot particles absorb solar radiation, locally heating the air, enhancing stagnation, reducing the efficiency of vertical pollutant dispersion, and increasing the frequency of such events.

The anticipated reduction in soot emissions in the future may enhance turbulence and mitigate the adverse effects of aerosol pollution on human health. However, the magnitude and patterns of future emissions remain uncertain, particularly in Asia, and the number of people affected by changes in turbulence depends on specific pollution dispersion scenarios. Despite ongoing efforts to reduce emissions, air pollution continues to cause millions of deaths annually, and the effectiveness of mitigation measures will depend not only on emission levels but also on demographic and socio-economic factors.

Conclusions. The study demonstrates that atmospheric turbulence plays a critical role in the formation and dispersion of pollutants; however, its characteristics are strongly influenced by aerosol concentrations and meteorological conditions.

1. High concentrations of soot and fine particulate matter lead to a reduction in turbulent kinetic energy and the formation of barrier layers, promoting the accumulation of pollutants in the near-surface atmosphere and the development of persistent smog.
2. Conversely, the reduction of aerosol emissions enhances turbulence and increases ventilation efficiency, highlighting the importance of emission reduction measures for improving air quality.
3. Human activities exert a dual effect: on one hand, pollutant emissions contribute to air stagnation, while on the other, mechanical and thermal turbulence generated by transportation and human movement can facilitate local dispersion of contaminants.
4. The obtained data can be used to improve predictive air quality models and to develop effective environmental policy strategies aimed at mitigating the adverse health impacts of aerosol pollutants.

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