Review Article

Radiative and boundary-layer controls of smog on surface heat flux variability - A review

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Abstract

Smog is one of the most persistent and widespread forms of air pollution in rapidly developing regions, especially over South and East Asia. While its impacts on human health and visibility have been documented quite well, its role regarding the modification of the land-atmosphere energy exchange has received relatively less attention. This review synthesizes current understanding of how smog-related aerosols modify surface heat flux variability by altering radiative transfer, boundary-layer structure, and near-surface thermodynamic conditions. Smog-associated aerosols cause surface dimming by reducing incoming shortwave radiation through scattering and absorption processes. The reduction in available energy suppresses surface heating and, consequently, the turbulent exchanges in the lower atmosphere. Under heavy aerosol loading, latent heat flux and sensible heat flux are found to be reduced in several observational and modeling studies from South Asia, East Asia, and many polluted regions. In addition, enhanced atmospheric stability and a shallower planetary boundary layer further reduce vertical mixing, reinforcing reductions in evaporation and heat transfer. Aerosol–humidity interactions might further introduce feedbacks related to cloud formation and moisture retention and are responsible for reduced diurnal and seasonal variability in surface fluxes. This paper highlights the key physical pathways through which smog influences surface energy balance by reviewing evidence from satellite observations, reanalysis products, and regional modeling studies. Understanding these mechanisms is of paramount importance in view of improving the representation of aerosol–boundary-layer interactions in regional climate models and assessing the longer-term climatic implications of sustained air pollution. The findings underline that smog is not merely a pollutant causing deterioration of air quality but also an active player in modulating the exchange of heat and moisture at the Earth's surface, impacting local temperature variability and hydrological processes.

Keywords: Smog, Aerosols, Surface Energy Balance, Latent and Sensible Heat Fluxes, Boundary-Layer Stability.

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Introduction

Smog is not just a dirty fog over cities; it is a sign of fast industrial growth, too many vehicles, and weather conditions that trap polluted air close to the ground. In developing regions, as emissions from vehicles, coal burning, crop residue burning, and industrial activities increase, so too does the accumulation in the atmosphere of a dense mixture of aerosols, including dust, soot, or black carbon, sulphates, nitrates, and organic compounds. These particles do more than pollute air; they act to modify the Earth's surface energy budget [1 - 4].

When the sun's rays pass through such an atmosphere, a significant amount of the shortwave radiation gets either scattered back into space or absorbed before it even touches the ground. This surface dimming effect reduces the energy available at the surface to warm the land and drive turbulent processes. In parallel, aerosol absorption of solar radiation can heat the near-surface layer of the atmosphere, altering vertical temperature gradients and thus the stability of the boundary layer. The combination of reduced surface heating and enhanced atmospheric warming tends to suppress vertical mixing [5 - 7].

Because LHF and SHF depend on both the energy input at the surface and the capacity of the atmosphere to transport heat and moisture upward, they become sensitive to aerosol loading. In polluted conditions, the temperature difference between the surface and air reduces, and turbulence weakens, leading to diminished flux magnitudes and lowered variability [4, 6 - 7].

Moreover, long-term studies of South Asia's haze dynamics highlight the role of aerosol–water vapor interactions, wherein increased humidity amplifies aerosol optical depth and deepens surface dimming by 10–20 W m^{-2} over the Indo-Gangetic Plain [8]. Also, in a global context, scattering and absorption effects of aerosols change surface albedo and decrease net shortwave fluxes, thereby cooling the surface [9].

In short, smog and aerosol pollution should not be considered in terms of air quality and public health alone; they are active agents in changing the fluxes of heat and moisture between land and atmosphere. In atmosphere laden with heavy aerosol loading, the interaction between surface and atmosphere is weakened, and the natural diurnal and seasonal cycles of the heat fluxes are damped. The next sections will discuss mechanisms through which smog affects surface fluxes, review observational evidence, and discuss implications for climate modeling and regional impacts.

Radiative forcing and surface dimming

Figure 1 presents a conceptual overview of smog-induced suppression of LHF and SHF.

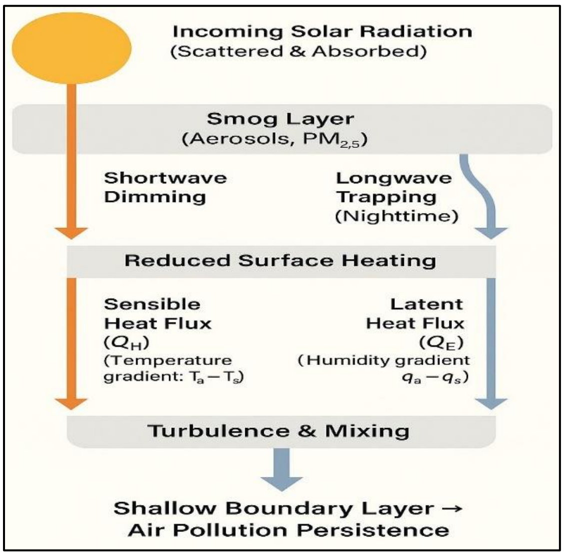

Figure 1. Conceptual schematic showing how smog modifies surface turbulent heat fluxes. Aerosol scattering and absorption reduce shortwave radiation ("solar dimming") and enhance longwave trapping at night, leading to reduced surface heating and weaker latent (Q_e) and sensible (Q_h) fluxes.

The most direct pathway between smog and flux variability is radiative forcing. Aerosols reduce shortwave radiation at the surface, a process referred to as solar dimming. Field studies in northern India and eastern China demonstrate that daytime net radiation can decrease by 30–60 W m^{-2} on days with severe haze events [10 - 11]. Evaporation decreases with reduced incoming energy. The reduced surface–air temperature difference lowers SHFs.

The polluted layer traps outgoing infrared radiation at night and produces mild nocturnal warming. This longwave retention flattens the daily temperature cycle and further dampens flux variability.

Boundary-layer stability

Smog stabilizes the lower atmosphere. In clear skies, solar heating produces turbulent eddies that mix sensible heat and water vapor vertically. In reduced sunlight, buoyancy becomes weak, giving rise to a shallow boundary layer. A shallow layer inhibits vertical mixing, allowing only a little upward transportation of warm and moist air. Observations over Beijing and Lahore suggest almost 40 % smaller daytime SHF under dense haze compared with clean conditions [12 - 13].

Moisture feedbacks and latent flux response

Under humid conditions, aerosols act as cloud condensation nuclei (CCN), which modify cloud microphysics and influence regional humidity. Under humid conditions, it may further enhance cloud brightness and reinforce surface dimming due to the increased reflection of sunlight. At the same time, stagnant polluted air traps water vapor in layers close to the surface and creates a paradox of humid but energetically starved conditions. In such conditions, the evaporation rate remains low under high relative humidity conditions due to reduced LHF. Thus, smog reduces both the magnitude and variability of LHF, especially in winter and pre-monsoon seasons when the radiation is already limited [14 - 15].

Regional evidence

Smog–flux interactions are most prominent over densely populated basins where emissions and stagnant meteorological conditions frequently coincide.

South Asia

Indeed, satellite and surface energy balance observations all indicate a consistent decline in LHF and SHF during post-monsoon haze episodes, particularly across the Indo-Gangetic Plain [10, 14].

East Asia

Long-term aerosol loading since the early 2000s has decreased the interannual variability of LHF by about 25 %, illustrating how long-term degradation of air quality moderates the surface energy exchange [11].

Urban clusters

The Megacities, which include Delhi, Lahore, and Beijing, show increased nocturnal heat island intensity because of longwave trapping, shallow boundary layers, and weak turbulent ventilation [13].

Taken altogether, these regional patterns confirm that smog acts as a flux suppressor in that it damps the natural diurnal and seasonal variability in surface heat exchange. A summary of key observational studies documenting the influence of smog on surface turbulent heat fluxes across different Asian regions is provided in Table 1.

Implications for climate modelling

Many global and regional climate models

Table 1: Summary of reported smog impacts on surface turbulent heat fluxes across major Asian regions.

Region / Study Area	Dominant Smog Sources	Observed Impact on Heat Fluxes	Key References
Indo-Gangetic Plain (South Asia)	Biomass burning, vehicular emissions, post-monsoon haze	↓ LHF and SHF by 30–60 W m^{-2} during heavy aerosol loading	[10, 14]
Eastern China	Industrial emissions, coal combustion, secondary aerosols	↓ Interannual LHF variance (~25 %) since 2000	[11]
Yangtze River Delta	Urban-industrial aerosols, stagnant winds	↓ Daytime SHF by 30–40 %; reduced turbulence	[13]
Lahore–Delhi Urban Corridor	Mixed urban/traffic emissions, boundary-layer trapping	Enhanced nocturnal heat island; weaker mixing and ventilation	[12]
South Asia (Regional Composite)	Mixed anthropogenic aerosols, high humidity feedback	Suppressed LHF variability during winter and pre-monsoon	[15]

Still underestimate how much aerosols affect the way energy is split at the Earth's surface. Most radiative transfer approaches do account for direct scattering and absorption, but they often oversimplify or overlook how aerosols impact turbulence and stability in the boundary layer. Because of these simplifications, model outputs for temperature, humidity, and energy fluxes can end up biased or less realistic [16]. Bringing together real-world data on aerosol optical depth (AOD) and particulate matter ($PM_{2.5}$) with flux reanalysis products like OAFlux, ERA5, or MERRA-2 can make these surface energy simulations much more accurate. Including these factors is particularly important when forecasting how pollution events change local convection, push back the start of the monsoon, or make the surface drier in areas with high aerosol concentrations [5, 12].

Broader consequences

When smog acts to disturb the normal energy exchange between the surface and atmosphere, a few clear consequences arise. The reduced daytime heating suppresses the growth of the boundary layer, with less vertical mixing. This in turn keeps the pollutants closer to the ground and lengthens the periods of poor air quality [6].

The result of this reduced LHF in agriculture regions is less evaporative cooling, and thus crops are much more sensitive to heat stress during dry periods. Cities tend to experience warmer nights and also smaller swings in temperature from day to night, which may make things less comfortable and increase health risks [17 - 18].

These constant fluctuations in energy exchange, over long periods, can affect the weather of a region. They are able to subtly shift high-pressure systems in the subtropics and alter rainfall over various seasons [12].

Future directions

Future research on smog–energy exchange linkages need to move towards higher spatial and temporal resolution. Current models often lack the resolution needed to represent shallow boundary layers, localized haze events, and rapid transitions between clean and polluted conditions. Such improvements will require tighter coupling of aerosol processes and land-surface schemes, especially those related to evapotranspiration and soil moisture feedbacks. In South Asia, where observational gaps are still considerable, long-term measurements from flux towers and vertically resolved aerosol profiles are needed to better quantify aerosol–flux responses across seasons. Continued development of satellite–model data fusion techniques offer promise for more accurate retrievals of LHF, SHF, and radiative fluxes during high-pollution episodes. Taken together, such advances will strengthen regional climate predictions and improve assessments of how persistent smog will shape future surface energy exchange [19 - 20].

Conclusion

Smog alters the surface energy exchange between land and atmosphere by scattering sunlight and heat, which in turn stabilizes the atmosphere. In this case, latent and sensible heat transfers become weakened. Consequently, the lower atmosphere is characterized as being much calmer, less ventilated, with cooler days and warmer nights, and often lesser daily temperature fluctuations. Given the trend of increasing air pollution over many developing countries, its space-time influence on surface energy exchange warrants the same level of importance now accorded to its effects on health and visibility. In fact, climate predictions will remain incomplete unless aerosol–energy flux interactions are properly considered as an integral aspect of the Earth's energy balance [5 - 6, 12, 15].

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Conflict of interest

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this manuscript.

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