Altitude-Dependent Decline in Sulfate Aerosol Optical Depth and Its Role in Warming Across the Northwestern Himalaya

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Abstract:

Significant warming has been observed in the Northwestern Himalaya (NWH) in recent decades, but little is known about how sulphate aerosols, a key cooling agent, affect regional climate. This work uses sulphate aerosol optical depth (SO_4 AOD) MERRA-2 reanalysis data from 1980 to 2023 to investigate altitude-dependent patterns and their relationships to regional warming. Trend analysis reveals a clear SO_4 AOD decline at high elevations ($-0.002\ yr^{-1}$) and a modest increase in the foothills ($+0.013\ yr^{-1}$). Spatial mapping shows the strongest negative trends along the mountain front, with weaker or positive trends in lower valleys.

We attribute the high-altitude decline to the absence of local sulphate sources and inefficient vertical transport of hygroscopic sulphate particles. Under humid boundary-layer conditions, these aerosols absorb water, increasing mass and settling velocity; this growth hinders ascent across steep Himalayan terrain. Moreover, lower relative humidity at higher altitudes decreases aerosol growth and scattering.

To assess more radiative impacts, we also study trends in black carbon and dust AOD. The decrease in sulphate cooling, combined with stable or increasing warming agents, likely contributes to accelerated warming in the region. These data-driven insights clarify how aerosol distribution and mountain meteorology together influence climate change in the region.