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Observations of aerosol-induced fog thickening over North India

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Abstract

Wintertime widespread fog events form in a heavy aerosol-laden environment over the Indo-Gangetic Plains, one of the major global hotspots of aerosol pollution. Although previous studies have indicated the discernible role of aerosols on the fog evolution, intensity and lifetime by using idealized numerical simulations, observational evidence of fog-aerosol interaction are rare and difficult. Unlike passive sensors (like MODIS) that cannot retrieve cloud and aerosol information simultaneously, lidar observations from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) provide better capability in detecting layers of cloud and aerosols. Using long term (2006-2021) vertically resolved observations, we develop a novel algorithm that detect fog layers whose base is still coupled with ground (base height < 75m above ground). Further we also find the presence of aerosol loading above fog. We analyze the isolated fog's top height and thickness variability due to aerosol-above-fog. We find a ~42% thickening of fog associated with an aerosol-above-fog increase from 0.02 to 0.2. The thickening of fog can prolong its lifetime causing disruption in the day-to-day chores of millions of people and incur substantial losses in transportation sector of the country. Although regional meteorology can play confounding role in thickening the fog layer, we argue that the observed fog-aerosol relationship is robust regardless of any meteorological regimes. However further modeling studies are required to warrant the micro-scale changes to fog under high aerosol loading.

1. Introduction

Fog formation and its persistence over the IGP are prime examples of radiation fog, where low-level moisture, calm winds, temperature inversion, and night-time radiative cooling are the main prerequisites for its development [1]. The characterization of a 'moderate fog' or 'dense fog' is directly inferred from the horizontal visibility parameter [2] rather than the vertical extent of the fog (such as geometrical thickness). Hence, the estimates of fog macro properties, such as the fog's top and its thickness, including their variations and the processes involved, are not well understood. The IGP also experiences high aerosol loading in the winter months [3-5]. These aerosols can impact the growth and dissipation of fog via competitive radiative and microphysical pathways [6-9]. In this study, we have used long-term simultaneous aerosols and fog observations from spaceborne Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) to understand the potential physical associations between the aerosol loading and fog macrophysics.

2. Methodology

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite payload carry an active lidar instrument Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) with passive infrared and visible imagers to probe the vertical structure and microphysical properties of clouds and aerosols over the globe [10]. The daytime winter months (December through February) for the last 15 years (2006-2021), exclusively over the IGP, have been chosen in this study. The CALIOP lidar observations can effectively differentiate cloud and aerosol layers at a vertical resolution of 60 m and horizontal resolution of 5 km during the day using the backscatter intensity measurements; hence can be utilized to constrain the base and top height of the cloud samples to identify the fog layer. The cloud top and base height estimates enable us to calculate the fog thickness, which can be used to infer the persistence of a fog event as the thicker fog can prolong the dissipation phase. Figure 1a depicts the top height-base height distribution of cloud samples from CALIPSO overpasses. The presence of fog is identified by the presence of highest number of cloud samples lying below base heights 0.075 km and top height less than 0.8 km. Simultaneous to the identified fog layer, we also found the co-existence of aerosol loading above the fog (hereafter AOD_{FOG}). Thus, for any corresponding fog layer AOD_{FOG} is calculated by vertically integrating the extinction coefficient above the identified fog layer from its top height to (top height + 1) km.

3. Results

A total of 1501 fog profiles were obtained over the entire IGP domain from 15 years (2006 - 2021) of CALIPSO data and out of these, 671 profiles found AOD_{FOG}. We separate the co-located the extinction coefficient and fog samples at each altitude according to according to low (<0.02) and high AOD_{FOG} (>0.06) bins. This segregation reveals that the aerosol extinction profiles for the high AOD_{FOG} bin are 2-3 times greater than the profile for the low AOD_{FOG} bin near the fog's top, and this difference, however, reduces with the altitude. Subsequently, this high aerosol loading is characterized by increased fog layers with fog tops between 0.4 – 0.8 km. However, in the low AOD_{FOG} scenario, the fog samples increased only near the ground (~0 km). These results suggest a relative vertical growth of the fog layer under a high aerosol loading regime.

To substantiate the fog occurrence changes in co-located fog top height–base height distribution between low and high AOD_{FOG} bins is obtained. Figure 1b shows a 6-10% increase in fog occurrences with fog top height greater than 0.4 km and fog base height less than 0.04 km at higher AOD_{FOG} scenario. Intuitively, the highest fog occurrences at tops less than 0.4 km for every fog base height in the low AOD_{FOG} scenario led to negative percentage changes. In general, a low aerosol-above-fog often promotes the growth of fog top height up to only 0.4 km, while on the other hand, the fog can grow/mature further above 4 km and up to 8 km under more significant aerosol loading above. We find that the top height increases by ~42% from 0.32 km to 0.49 km as the AOD_{FOG} increases from ~ 0.02 to 0.2. As a result of the observed increase in fog top height there is an unequivocal ~41% fog thickening from ~0.31 km at ~ 0.02 AOD_{FOG} to 0.46 km at ~ 0.2 high AOD_{FOG} (statistically significant correlation, r = 0.76). Hence these differences underscore a clear regime shift in the fog top height leading to the aerosol-associated fog thickening.

The observed aerosol-induced fog thickening could be driven by the local changes in meteorology, as coincidental moistening and turbulent mixing can dynamically drive the fog thickening independent of the background aerosol loading. Therefore, we further explore the causality of the regional meteorology on the observed relationship. We decompose these inherent effects by dividing the co-located fog top height-AOD_{FOG} sample according to anomalously low and high RH, windspeeds, and temperature. The linear regression fits for six subsets are shown in figure 2. We find a relatively higher slope for samples co-located with anomalously high RH (figure 2b), high windspeed (figure 2c), and low temperature (figure 2e) indicating a substantial increase in the fog top height per AOD_{FOG}. These results do not indicate any distinct inherent role of meteorological co-variabilities, at least from MERRA-2 reanalysis, but instead establish the robustness of the observed aerosol-fog relationship regardless of the background environmental conditions.

4. Figures

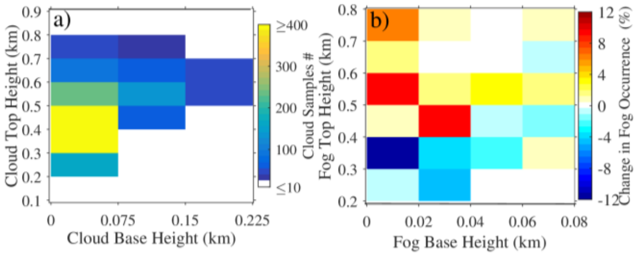

Figure 1: (a) The cloud top height – cloud base height (in kilometers above ground) distribution between 2006 – 2021 with color bar indicating the number of cloud samples (total number of profiles = 2201). (b) The percentage occurrence changes in the fog top height-base height distribution (high AOD_{FOG} minus low AOD_{FOG}). low AOD_{FOG} (0 – 0.02; 110 profiles) and high AOD_{FOG} (0.06 – 0.28; 109 profiles) scenarios. The bounds in figure 2a represent the 25th and 75th percentile values.

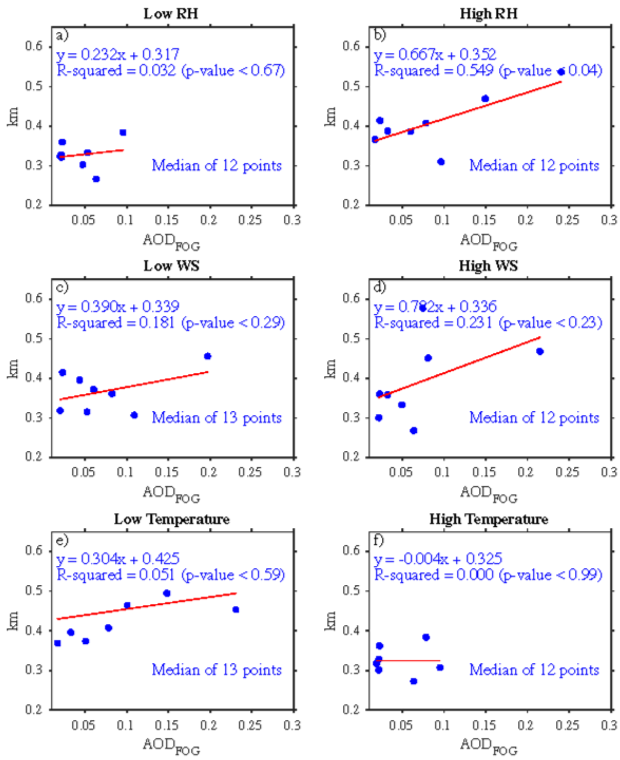

Figure 2: The 8-binned daytime fog top height-AOD_{FOG} relationship at anomalously (a and b) low and high RH, (c and d) low and high windspeed and, (e and f) low and high temperature. Each point is binned median of 'X' points.

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6. References

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