Analysis of Surface Level PM$_{2.5}$ Measured by Low-Cost Sensor and Satellite-Based Column Aerosol Optical Depth (AOD) over Kathmandu

Jeevan Regmi$^{1,2}$, Khem N Poudyal$^3$, Amod Pokhrel$^4$, Nabin Malakar$^5$, Madhu Gyawali$^6$, Lekhendra Tripathee$^7$, Mukesh Rai$^7$, Srikanthan Ramachandran$^8$ Katrina Wilson$^9$, and Rudra Aryal$^*$

$^1$ Prithvi Narayan Campus, Tribhuvan University (TU), Pokhara, Nepal
$^2$ Central Department of Physics Tribhuvan University, Kirtipur, Nepal
$^3$ Dept. of Applied Sciences, IOE Pulchowk Campus Tribhuvan University, Lalitpur, Nepal
$^4$ University of California Berkeley, California, USA
$^5$ Worcester State University, Massachusetts, USA
$^6$ Department of Physics, San Jacinto College, South Campus, 13735 Beamer Rd, Houston, TX 77089, USA
$^7$ State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
$^8$ Physical Research Laboratory, Ahmedabad, India
$^9$ Franklin Pierce University, 40 University Drive, Rindge, NH, USA

$^*$ Corresponding author. Tel: 1-305-519-9720
E-mail address: aryalr@franklinpierce.edu

Abstract

A low-cost PurpleAir PA-II sensor was installed, in 2020 at the Institute of Engineering (IOE) Pulchowk Campus, TU located in Kathmandu valley, Nepal, to measure particulate matter with an aerodynamic diameter equal to or smaller than 2.5 μm (PM$_{2.5}$). The observation shows that hourly averaged PM$_{2.5}$ fluctuates bimodally in four seasons (Winter: December, January, and February; Spring: March to May; Summer: June to Sep; and Autumn: October to November), with the highest levels occurring during morning and evening rush hours. PurpleAir records PM$_{2.5}$ with a maximum
average of 101± 26.31 μg m⁻³, in winter, 55.58± 11.42 μg m⁻³, in spring, 45.46± 12.16 μg m⁻³, in autumn, and a minimum of 22.78± 3.23 μg m⁻³, in the summer. Due to rain and diffusion in the vertical atmosphere, PM₂.₅ levels are lowest during the summer. The ± number for each season represents the standard deviation from the hourly average. AOD550nm data collected by MODIS (Moderate Resolution Imaging Spectroradiometer) onboard two NASA satellites, Terra and Aqua, are compared with simultaneously observed PM₂.₅. With humidity correction factor f(RH), R² increases from 0.413 to 0.608 (in winter), 0.426 to 0.508 (in spring), and 0.083 to 0.293 (in autumn). The summer AOD data PM₂.₅ are not compared due to a lack of AOD observations. By comparing the column-integrated aerosol data with the surface-level aerosol concentration, this study illustrates the relevance of atmospheric parameters while investigating the reliability of PurpleAir measurements. A cluster analysis of five-day back trajectories of air masses arriving at different altitudes in different seasons indicates that long-range transport of air pollution contributes to MODIS's column integrated AOD by adding aerosol population.

Keywords: Aerosol Optical Depth, MODIS, PM₂.₅, PurpleAir, Transboundary Aerosols

1. INTRODUCTION

The study of atmospheric aerosols, particulate matter, is important since they influence Earth's radiation budget by scattering and absorbing incoming solar radiation and altering cloud microphysical properties(Haywood & Boucher, 2000; Ramanathan et al., 2001). Their ability to affect Earth's radiation budget and their effects on health, air quality, and clouds are strongly related to their size (Dusek et al., 2006; Ruzer & Harley, 2005). A PM₂.₅ particle has an aerodynamic diameter of less than 2.5 micrometers. Particulates of this size can be either natural or anthropogenic, and their composition varies according to their sources (Devi et al., 2020).

Human-produced particles are generally smaller in size, while naturally produced particles are larger. PM₂.₅ is also one of the most common pollutants contributing to global health burdens.
(Lim et al., 2012). According to Shiraiwa et al., (2017), these particles penetrate deeply into the lungs of humans and cause adverse health effects depending on their chemical composition. Statistical analysis shows a strong correlation between hospitalizations, and deaths and exposure to high PM$_{2.5}$ concentrations (Di et al., 2017; Schwartz et al., 1996)(Klemm & Mason, 2000). As a result, a comprehensive measurement and analysis of particle concentration in the atmosphere are essential for protecting local health and studying atmospheric conditions. Several studies highlight the importance of low-cost air quality monitoring instruments, such as PurpleAir Monitors, for determining both spatial and temporal air quality, since traditional real-time air quality monitors lack this capability due to their high installation and maintenance costs (A. Kumar et al., 2018); Munir et al. 2019). Because of their availability, size, and price, PurpleAir monitors are being widely used in almost every continent to measure PM concentrations on surfaces, as well as for assessing air pollution (Ouimette et al., 2022).

These monitors work on the light scattering principle in which a fan draws air particles into the chamber and passes along the laser path. The sensor's photodiode detector converts scattered light into voltage pulses from light. These pulses use to count the number of particles of sizes 0.3, 0.5, 1, 2.5, 5, and 10 μm and determine mass concentrations of PM$_{1.0}$, PM$_{2.5}$, and PM$_{10}$ by using an algorithm for PM concentration (Ardon-dryer et al., 2019)(Sayhi & Kelly, 2018; Ardon-Dryer et al., 2020); https://www2.purpleair.com/community/faq). In a variety of environmental conditions,
PurpleAir monitors were evaluated for measuring atmospheric particle concentrations (Morawska et al., 2018; Stavroulas et al., 2020; Zhang et al., 2009) Peterson et al., 2017; White et al., 2012). Ardon-Dryer et al., (2020) showed that PurpleAir PM 2.5 data significantly correlated with PM$_{2.5}$ measured by AQMS (Air Quality Monitoring Stations) operated by the Environmental Protection Agency. This study will also aid in investigating the low-cost monitors for measuring air pollution by comparing them with other reliable reference data, such as satellite-based aerosol optical properties. The simultaneous measurements of aerosols at ground level and those based on remote sensing provide reliable information about air pollutant loading over the observation site (Baral & Thapa, 2021; Segura et al., 2017). Comparison of surface and atmospheric level aerosol data can also be used as a statistical basis to extrapolate regional aerosol data (R. P. Aryal et al., 2014; Moody et al., 2014).

In atmospheric column observations, satellites provide long-term data and global coverage, providing insights into regional air quality and climate variations through the precise timing and spatial resolution of PM$_{2.5}$ concentrations (Karagulian et al., 2015; Schwarze et al., 2006; Zhong et al., 2015). Satellites, however, view the entire atmosphere column, which makes it difficult to distinguish surface-level particle concentrations. Therefore, ground-based measurements and comparisons with satellite-based aerosol data can lower the uncertainty associated with local and external aerosols, and meteorological parameters (Kumar et al., 2007).
The use of low-cost sensors in surface measurements can alleviate the limitations of human resources and can enable setting up multiple ground-based measurement stations easier, regardless of a lack of funding and/or technical expertise. A correlative analysis based on satellite-based aerosol optical depth (AOD) data and ground-level particle concentration can be conducted to evaluate the proposed method for estimating PM$_{2.5}$ in areas that lack ground-level observations (van Donkelaar et al., 2015).

Several studies have examined the air quality and aerosol loading trend over the Kathmandu Valley (R. K. Aryal et al., 2009; Islam et al., 2020; Mahapatra et al., 2019). MODIS-equipped Earth observation satellites Terra and Aqua pass over the Kathmandu valley every morning and afternoon (at about 10:30 am and 1:00 pm local time, respectively), and MODIS' AOD data (3 km $\times$ 3 km) can be used to compare with surface level PM$_{2.5}$ (Ramachandran & Kedia, 2013).

This paper will present and analyze the hourly variability of PM$_{2.5}$ observed by PurpleAir monitor at the Pulchowk Engineering Campus (TU), located about a hundred meters from the bus station, for each season and compare surface-level particle concentrations with satellite-based AODs using relative humidity correction factor. Relative humidity influences aerosol particle growth and refractive index, affecting aerosol mass concentration (Altaratz et al., 2013; Hagan & Kroll, 2020; Malm et al., 2000). Kathmandu valley's bowl-shaped structure and surrounding mountains make it a unique case study for investigating air pollution (Kitada & Regmi, 2003; Panday &
This paper also presents the local and regional aspects of long-range air pollution transport over Kathmandu Valley using cluster analysis of back trajectory air masses arriving over the observation site.

2 MATERIALS AND METHODS

2.1 Site Description

A PurpleAir sensor was deployed in the Kathmandu valley (Pulchowk Engineering Campus, IOE, Lalitpur, Lat. 27.68° N, Long. 85.31° E, and Alt. 1350m Fig. 1) to measure real-time PM$_{2.5}$ concentration data. The city of Kathmandu is Nepal's largest metropolitan area and is highly polluted. Nepal is surrounded by the Indo-Gangetic Plain in the south and the large Himalayas in the north (Sarkar et al., 2017; Regmi et al., 2020). High mountains surround the Kathmandu valley, ranging from 2000 meters to 2800 meters, and the valley is shaped like a bowl, trapping pollution.
Fig. 1. As seen in the MODIS image (taken by NASA’s Terra satellite on February 9, 2020), there is a noticeable accumulation of haze on the foothills of the Himalayan range. The top right corner of the figure shows a purple air monitor located at Kathmandu Valley.

This city is experiencing rapid urbanization and population growth. The region is characterized by haphazard construction, unmanaged industries, brick and kiln production, and solid waste and biomass burning. Kathmandu also experiences significant amount of transboundary air pollution (Kitada & Regmi, 2003). Transported dust aerosols impact the cloud microphysical properties significantly. As a result of biomass burning and dust storms in the Indo-Gangetic Plain region, and long-range transportation, aerosols accumulate over Nepal, which, when combined with local pollution sources, contributes to high levels of pollution (Adhikari & Mejia, 2022; Becker et al., 2021a; Das et al., 2021; Jethva et al., 2019; Regmi et al., 2020)
2.2 PurpleAir, Sampling Methods and MODIS AOD

Purple Air's website (https://www2.purpleair.com/) provides real-time PM$_{2.5}$ (in $\mu$g m$^{-3}$) data. Microprocessor-based circuits are used to calculate equivalent particle diameters and the number of particles with different diameters per unit volume (Ouimette et al., 2022; Yong, 2016). The processing algorithms for the Plan-tower PMS5003 sensors (PA-PMS) used in the Purple Air (PA) monitor configuration are provided in He et al., (2020). The remainder of this paper uses the symbol PM$_{2.5}$(PA) for PM$_{2.5}$ observed by a purple air monitor. Additionally, we compare PM$_{2.5}$(PA) data with PM$_{2.5}$(US) data to indicate the reliability of purple air. PM$_{2.5}$(US) is monitored by the Ambient Air Quality Monitoring Station (Beta Attenuation Monitor, BAM) at the Phora Durbar Recreation Center, 3 km from the purple air monitoring site and supported by the United States Embassy (Edwards et al., 2021). The BAM 1022 measures and records airborne PM concentrations in $\mu$g m$^{-3}$ at local temperatures and atmospheric pressures by utilizing beta-ray attenuation (Magi et al., 2019). The manufacturer's website provides a complete description of the BAM 1022's operation (https://metone.com/air-quality-particulate-measurement/regulatory/bam-1022/)
A significant correlation exists between PM$_{2.5}$(PA) and PM$_{2.5}$(US) data sets with a coefficient of determination ($R^2$) of 0.98. The best fit line equation is $PM_{2.5}$(PA) = 0.93(± 0.04) $PM_{2.5}$(US) + 13.23 (± 2.40) as shown in Fig. 2.

However, the two sets are not validated individually against other nearby reference optical devices. In Fig. 2, the scatter plot shows that purple air data PM$_{2.5}$(PA) near the bus station is slightly above the 1:1 line compared to PM$_{2.5}$(US) at Phora Durbar and shows that PM$_{2.5}$(PA) provides usable data representing the atmosphere of Kathmandu valley.

![Scatter plot showing correlation between PM$_{2.5}$(PA) and PM$_{2.5}$(US). The best fit line equation is given as $PM_{2.5}$(PA) = 0.93(± 0.04) $PM_{2.5}$(US) + 13.23 (± 2.40).]

Figure 2. The scatter plot shows the monthly averages for PM$_{2.5}$(PA) and PM$_{2.5}$(US). Based on the legend in the figure, the symbols are ordered from higher to lower PM$_{2.5}$ for the different months. December month is discarded for comparison due to a lack of data availability.
In this study, PM$_{2.5}$(PA) is compared with NASA's MODIS column integrated Aerosol Optical Depth (AOD at 550nm) product, which is corrected for relative humidity. The rest of this paper uses AOD$_{550\text{nm}}$ to represent AOD retrieved from Satellite data. AOD$_{550\text{nm}}$ aerosol products collected from MODIS Aqua and Terra at 3×3 km is analyzed in this study. The 3km × 3km algorithm differs from the 10km × 10km algorithm simply in the way reflectance pixels are ingested, organized, and selected (Levy et al., 2013). Purple air provides optical data matching the products of aerosol optical devices such as cell reciprocal and TSI 3563 integrating nephelometers, according to Calvello et al., (2008); Ouimette et al., (2022).

2.4. Model Description

The relationship between PM and AOD is illustrated by a simplified linear equation with a relative humidity correction factor. To express a statistical model, we have written the particle concentration (PM) in general, observed at the ground level with the dry sample, which can be expressed quantitatively (Xu & Zhang, 2020a) as

\[ PM = \frac{4}{3} \pi \rho \int_{0}^{\infty} r^3 n_{dry}(r)dr \] (1)
\(n_{dry}(r)\) denotes the number of particles per unit volume in atmospheric space per unit particle radius and \(\rho\) is the aerosol particle density. Based on the hypothesis of spherical particles, the columnar AOD can be calculated using the Mie scattering theory with the equation (Calvello et al., 2008), and can be written as,

\[
AOD = \int_0^\infty dh \int_0^\infty \pi r^2 Q_{ext,amb}(r)n_{amb}(r,h)dr
\] (2)

where \(r\) is the radius of the assumed spherical particles, \(Q_{ext}\) is the extinction efficiency factor defined by van de Hulst H.C., (1981), and \(n_{amb}(r,h)\) represents the aerosol size distribution giving a concentration of particles per unit volume per particle radius at height \(h\), which is factorized in two parts based on height.

\[
(n_{amb}(r,h)) = n_{amb}(r)n(h) = n_0 n_{amb}(r) \exp(-h/H)
\] (3)

where \(n_0\) is the particle concentration at the surface level and \(H\) is the aerosol scale height, then the equation for AOD can be expressed as given by Calvello et al., (2008).
Several models explain the relationship between f(RH) and Relative humidity (RH) (Brock et al., 2016, 2021; Chen et al., 2016; Kasten, 1969; Kotchenruther & Hobbs, 1998; Zheng et al., 2017). This work utilizes the f(RH) expression (Brock et al., 2021; Zheng et al., 2017) to examine aerosol light extinction induced by hygroscopic growth.

\[
f(RH) = \frac{AOD}{AOD_{dry}} = \left(1 + \frac{RH}{100-RH}\right)
\]  

where AOD_{dry} represents the aerosol optical depth with dehydration adjustment. Then the expression for AOD in terms of the dry condition can be expressed as,

\[
AOD = n_0 H f(RH) \int_0^\infty \pi r^2 Q_{ext, dry}(r)n(r) dr
\]
To investigate the AOD vs PM relation, the size distribution and extinction efficiency $Q_{\text{ext}}$ and effective aerosol radius $r_{\text{eff}}$ are expressed (Xu & Zhang, 2020b) as,

$$Q_{\text{ext}} > = \frac{\int_0^\infty Q_{\text{ext}}(r)n(r)r^2dr}{\int_0^\infty n(r)r^2dr} \quad (7)$$

And, the effective radius of aerosol particles is given as,

$$r_{\text{eff}} = \frac{\int_0^\infty n(r)r^2dr}{\int_0^\infty n(r)r^3dr} \quad (8)$$

Based on the above Eqs. (2), (4), (7), and (8) a relation between AOD/$f($RH$)$ and PM can be obtained as

$$AOD = \frac{3}{4}n_0 \cdot H \cdot f(RH) \cdot PM \frac{<Q_{\text{ext,dry}}(r)>}{\rho_{\text{eff}}} \quad (9)$$
Thus Eq. (9) provides, assuming $H$ as a constant for all data for this study, $f(RH)$ as the correcting factor to study the correlation between $\frac{AOD}{f(RH)}$ vs. $PM$.

2.4. Statistical Analysis

$AOD_{550nm}$ obtained from two satellite measurements, Aqua and Terra, is compared with the hourly averaged purple air data $PM_{2.5(PA)}$. For comparison with ground based $PM_{2.5(PA)}$, the $AOD_{550nm}$ are corrected by dividing with $f(RH)$, where RH is ambient relative humidity. At different humidity levels, aerosol particles with different chemical compositions but the same mass concentration exhibit different aerosol optical properties (Jin et al., 2022). Accordingly, this correlation study investigates the correlation between aerosol extinction and mass concentration using relative humidity correction factor, $f(RH)$.

MOD04 and MYD04_3K data (MOD04 for Terra, MYD04 for Aqua), 3km x 3km $AOD_{550nm}$ data were extracted and correlated with a temporal variation of $PM_{2.5(PA)}$ from purple air sensors at ground level. $AOD_{550nm}$ measurements from two satellites, Aqua and Terra, were observed simultaneously with $PM_{2.5(PA)}$ measurements. We performed the graphical analysis using the Levenberg-Marquardt least orthogonal distance method implemented in IGOR (https://www.wavemetrics.com/). The data were then analyzed using linear regression analysis,
and a coefficient of determination ($R^2$) was obtained. A two-tailed $P$ statistic and a coefficient of correlation coefficient ($R$) was calculated to determine the significance of the correlation. Data with confidence levels (based on $P$ values) < 95% were disregarded for statistical significance.

2.5 Cluster Analysis

The aerosol particle trajectories arriving at Kathmandu at 500m, 1000m, and 1500m asl were analyzed using cluster analysis to understand the origin of aerosol particles over Kathmandu Valley's vertical column. For each season, seasonal clusters were generated by analyzing five days of air mass trajectories starting at 500 m, 1000 m, and 1500 m asl over Kathmandu (Lat. 27.68° N, Long. 85.31° E) at 0:00, 6:00, 12:00, and 18:00 UTC each day. In this study, the cluster calculations were conducted using the free software Traj-stat (Regmi et al., 2020; Wang Y.Q., 2014).

3. RESULTS AND DISCUSSION

3.1. The hourly variation of the seasonally averaged PM$_{2.5}$

Fig. 3 shows hourly variations of PM$_{2.5(PA)}$ concentrations (in $\mu$g m$^{-3}$) for each season in 2020. The average maximum PM$_{2.5(PA)}$ is observed to be $101 \pm 26.31$ $\mu$g m$^{-3}$ in the winter season, while the minimum is seen in summer ($22.78 \pm 3.23$ $\mu$g m$^{-3}$). Similarly, the average concentration of 55.58 $\pm$ 11.42 $\mu$g m$^{-3}$ is observed in the spring and 45.46 $\pm$ 12.16 $\mu$g m$^{-3}$ in the autumn. The $\pm 1\sigma$ standard deviation obtained from hourly averaged measurements for each season are given...
adjacent to the seasonal mean values. Kathmandu is a bowl-shaped urban basin in Nepal, and during winter, the planetary boundary layer is thinner due to the dense, cooler air near the surface. A layer of cooler air sits beneath the warm air above, forming a kind of lid in the atmosphere referred to as winter inversion. Only within this layer does vertical air mixing occur, so pollutants cannot disperse in the atmosphere. Kathmandu relies mainly on wood for heating in winter, and wood burning contributes significantly to air pollution. Kotchenruther, (2020) found elevated levels of PM$_{2.5}$ during the winter in the Northwest U.S. According to the study, residential wood combustion, motor vehicle emissions, gaseous NOx emissions, and particulate sulfate emissions are the primary sources of PM$_{2.5}$ during winter.

For all seasons, particle mass concentrations are bimodal, significantly higher in the mornings (around 8:00 am) and evenings (around 6:00 pm). Fig. 3 shows the seasonal variations of hourly averaged PM$_{2.5(\text{PA})}$, which are bimodal in all seasons. The amplitude and width of PM$_{2.5(\text{PA})}$ is maximum during the winter seasons, and the patterns are similar during spring, summer, and autumn. No significant variation in hourly averaged PM$_{2.5(\text{PA})}$ is seen during summer. A signature of local activity can be seen in PM$_{2.5(\text{PA})}$, such as during the household cooking and traffic emissions time. Many studies have shown that household and commercial cooking significantly contribute to PM$_{2.5}$ pollution in urban areas (Balasubramanian et al., 2021; Pervez et al., 2018; Robinson et al., 2018). Earlier studies have also shown that traffic and cooking contribute to air
pollution in Kathmandu valley during rush hours (morning and evening) and off hours in the afternoon (Kamruzzaman 2012).

PM$_{2.5(\text{PA})}$ increases gradually during rush hours in traffic. On a global scale, cooking and heating fuels contribute 20-55% to anthropogenic particle emissions (Balasubramanian et al., 2021; Pervez et al., 2018). The study concludes that domestic cooking and traffic are significant anthropogenic factors affecting the Kathmandu valley's surface-level PM$_{2.5(\text{PA})}$ concentrations.

Previously, it has been shown that traffic contributes significantly to air pollution in different urban areas, with coarse particles originating from non-exhaust sources like road abrasion, brake wear, and tire wear, while fine particles are emitted directly from fuel combustion (Kumar & Goel, 2016; Pant & Harrison, 2013). Low temperatures can lead to the formation of secondary aerosols during the winter months (Duan et al., 2020; Mues et al., 2018). Previous studies have shown the importance of secondary organic aerosols (SOA) in contributing to PM$_{2.5}$ (Bui et al., 2022; Mancilla et al., 2015).

Fig. 3 also shows that the average particle concentration at hourly averaged PM$_{2.5(\text{PA})}$ decreases from winter to summer, then increases again in autumn as the seasons change. A rise in temperature in the summer causes surface-level particles to diffuse rapidly in the vertical atmosphere, resulting in lower surface concentrations. PurpleAir record shows an average temperature of 17.77 ± 4.00 °C in winter, 24.08 ± 2.65 °C in summer, and 28.96 ± 1.65 °C in
autumn. The summer also brings significant amounts of rain, which helps removal of aerosol particles from the atmosphere (Becker et al., 2021b). June to September are rainy monsoon months in Kathmandu, which can significantly reduce air pollution. Thus, the monsoon rain also plays a crucial role in reducing the surface level air pollution in Kathmandu in the summer months from June to September. The COVID lockdown period from March to July also significantly reduced traffic flow, which might have affected particle concentrations in the atmosphere (Baral & Thapa, 2021).

Fig. 3. Hourly averaged (at local time) averaged particle concentration (PM$_{2.5}$PA) for each season by using the corresponding months' data for each season.

3.2. Comparison of MODIS AOD with PM$_{2.5}$PA
Fig. 4 illustrates the correlation between Aqua and Terra AOD$_{550\text{nm}}$ and reveals $R = 0.942$, $R^2 = 0.888$, and $P < 0.005$. The calibration of two satellite sensors and the retrieval algorithm for MODIS AOD$_{550\text{nm}}$ during spatial observations may cause some deviations in the AOD data collected by the two satellites (Green et al., 2009; Gupta et al., 2020; Ichoku, 2005; Koelemeijer et al., 2006). However, a significant high correlation indicates that AOD$_{550\text{nm}}$ by two satellite measurements can represent reliable and comparable aerosol optical depth, and it can be used for daily averages and combined to compare with other concurrently observed aerosol concentrations such as PM$_{2.5}$ (PA).

**Fig. 4.** Scatter plot of MODIS AOD$_{550\text{nm}}$ (Terra) vs. MODIS AOD$_{550\text{nm}}$ (Aqua) comparing the same day data observed from two satellites in the morning and afternoon.
Fig. 5 presents a comparison of the hourly average of PM$_{2.5}$(PA) with the AOD data observed by two satellites at 550 nm wavelength, AOD$_{550\text{nm}}$, without relative humidity correction factor. Fig. 5 also shows the standard deviation and linear best fit line. The best fit line provides an equation, AOD$_{550\text{nm}}$ = 0.038(±0.037) + (0.0068±.0006) PM$_{2.5}$(PA), and the correlation coefficient (R=0.638, R$^2=0.407$) and P-values (<<0.005) are also obtained from the plot. Based on the correlation between these two parameters, Fig. 5 indicates that surface air pollution, PM$_{2.5}$(PA), significantly influences aerosol optical depth (AOD$_{550\text{nm}}$).

**Fig. 5.** A comparison between Aqua and Terra Satellites' spatially averaged AOD at 550 nm (AOD$_{550\text{nm}}$) and Purple Air Monitor's hourly average PM$_{2.5}$(PA) around the satellite overpass.
According to Table 1, the correlation coefficients between AOD$_{550nm}$ and corresponding PM$_{2.5(PA)}$ are improved by dividing AOD$_{550nm}$ by f(RH). In seasons of low temperature, f(RH) has a greater effect on the $R^2$ than in seasons of higher temperatures. As a result of the temperature inversion at low temperatures, particle concentrations can remain close to the surface due to the significant effect of vertical column AOD correction with f(RH). In low-temperature months, aerosol particles will distribute uniformly near the surface. In summer, however, very few AOD$_{550nm}$ coincide with the corresponding hourly averaged PM$_{2.5(PA)}$ due to persistent monsoon clouds. Correlation results obtained in summer are also given in the table which, however, are less reliable owing to a smaller number of data points on account of monsoon clouds.

Based on the variations in correlation coefficients, meteorological parameters such as relative humidity should be considered when retrieving aerosol optical depths from satellite data (Zhang et al., 2009).

Table 1. The correlation coefficients for each seasons using the available one-year 2020 data without and with the f(RH) corrected AOD data vs PM$_{2.5(PA)}$

<table>
<thead>
<tr>
<th>Seasons/Combined</th>
<th>AOD$<em>{550nm}$ vs. PM$</em>{2.5(PA)}$</th>
<th>AOD$<em>{550nm}$/f(RH) vs. PM$</em>{2.5(PA)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Data (172)</td>
<td>R = 0.638; $R^2$ = 0.407</td>
<td>R = 0.703; $R^2$ = 0.495</td>
</tr>
<tr>
<td>Winter (Dec-Feb) (28)</td>
<td>R = 0.643; $R^2$ = 0.413</td>
<td>R = 0.780; $R^2$ = 0.608</td>
</tr>
<tr>
<td>Spring (March-May) (77)</td>
<td>R = 0.653; $R^2$ = 0.426</td>
<td>R = 0.713; $R^2$ = 0.508</td>
</tr>
<tr>
<td>Season</td>
<td>R</td>
<td>R²</td>
</tr>
<tr>
<td>---------------</td>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>Summer (June-Sep) (9)</td>
<td>0.134</td>
<td>0.018</td>
</tr>
<tr>
<td>Autumn (Oct-Nov) (58)</td>
<td>0.288</td>
<td>0.083</td>
</tr>
</tbody>
</table>

### 3.3 Seasonal Cluster Analysis

Fig. 6 and supplementary figures Fig. S1 and Fig. S2 show the seasonal clusters of five-day back trajectories over Kathmandu Valley during four seasons at 500 meters, 1000 meters and 1500 meters.

According to percentage contributions, three predominant air masses reach over the Kathmandu valley every season, with five clusters exhibiting the best representation. The cluster analysis shows that fast-moving air masses contribute less, ranging from 1 to 7 percent, to air pollution at the observation site.

At 500 meters, 44% of the winter air mass comes from the Indo-Gangetic plain (IGP), Nepal's south, 38% from the southwest, 16% from the west, and 2% from the west (Fig. 6). The IGP is densely populated, and its aerosol loading is high due to industrial and urban pollution, dust, biomass burning, and the flat land of southern Nepal that lines its northern edge (Regmi et al., 2020). Fig. 6 illustrates the dominance of southerly and southwesterly air masses in winter (December-February) and spring (March-May). The trajectory also indicates that south-easterly air masses from the Bay of Bengal contribute significantly and prominently in summer (June-August), whereas southerly air masses dominate in autumn (September-November). According to
supplementary figures, Fig. S1 and Fig. S2, the dominant clusters at 1000 meters and 1500 meters are not significantly different from those at 500 meters. Therefore, the air pollution at the observation site is transported vertically from a similar direction to that of 500 meters. At different altitudes, the air mass trajectory crosses the IGP region on its way to the observation site, Kathmandu Valley. As a result, air pollution over the IGP region mainly impacts the aerosol optical depth and the overall vertical air pollution concentration.

**Fig. 6.** An analysis of five-day air mass back trajectories computed with Analysis NOAA HYSPLITT and HYSPLIT model reaching Kathmandu at 500 m at different seasons. For each season’s cluster analysis, the percentage contribution is presented.
4. CONCLUSIONS

The PurpleAir sensor was installed in the Kathmandu Valley, a Himalayan foothill, to determine its capability to measure surface-level small-size particles whose aerodynamic diameter is equal to or smaller than 2.5 micrometers (PM$_{2.5}$). The observation shows that the bimodal particulate concentrations (PM$_{2.5}$) peak at about 8 am and 7 pm, coincident with the density of traffic and other anthropogenic pollutants events, such as cooking and heating, which indicates Kathmandu has significant local sources of outdoor air pollution. In winter, temperature inversion causes particles to remain close to the surface rather than disperse vertically, showing the highest concentrations. During the summer, which is monsoon season, PM$_{2.5}$ levels are low and bimodal variations are smaller. PurpleAir's surface-level PM$_{2.5}$ and MODIS's AOD measurements correlate better with the relative humidity correction factor. For further analyzing the comparison between PM$_{2.5}$ and AOD, boundary layer height (BLH) data can be used, but these data are not available for this study. An air mass cluster analysis shows that transboundary air pollution over different altitudes at Kathmandu valley is received from different directions and source regions. The contribution of directional airmass varies with the season. The Indo-Gangetic Plain pollutes the atmosphere over Kathmandu during winter, spring, and autumn. In addition to contributing to aerosols over the atmospheric column and, eventually, to column integrated AOD550nm,
transboundary air pollution might bias the comparison between PM$_{2.5}$(PA) and AOD$_{550\text{nm}}$.

Moreover, the study establishes that simultaneous measurements of particle concentration at the surface level and AOD over a vertical column allow for the extrapolation of surface-level concentrations using satellite-based AOD, thereby, calling for a more robust and comprehensive analysis of spatial and temporal distribution of PM$_{2.5}$ concentration characteristics and columnar aerosol optical depth.

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**DISCLOSURE**

Any reference to companies or specific commercial products does not constitute a recommendation, support, or endorsement and we have no conflict of interest to disclose.

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