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Research Paper

Spatio-temporal variations in air pollutants and their impact on wheat crop production in eastern Uttar Pradesh

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ABSTRACT

Recently, air pollutants have posed significant hazards to agricultural production, emerging as a critical risk to global food security. To address this issue, the study examines the spatio-temporal variability of air pollutants, specifically aerosol optical depth (AOD) and black carbon (BC). It investigates the impact of these pollutants on wheat production in eastern Uttar Pradesh, India. The study uses MODIS satellite observations and MERRA-2 reanalysis data, the study analyzes monthly and seasonal variations in AOD and BC from 2001 to 2023. The findings highlight a noticeable rise in AOD and BC due to biomass/residue burning, fossil fuel emissions and transported dust. Backward trajectory analysis, conducted using HYSPLIT modeling, traces pollutant origins and transport pathways from regions like the Thar Desert and the Arabian Sea. Wheat yield assessments in districts such as Varanasi, Gorakhpur, and Sonbhadra reveal spatially variable impacts of aerosols on crop productivity. Elevated AOD levels are linked to reduced wheat yields in some districts, while BC exhibits minimal influence. This study underscores the critical need for targeted regional policies to mitigate air pollution and minimize its adverse effects on agriculture in this high-yielding wheat-growing region.

Keywords: AOD, Black carbon, Wheat yield, HYSPLIT model.

Increasing levels of air pollutants in India such as particulate matter (PM), ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_X), black carbon (BC) and many more have raised concern about their potential impacts on the environment, human health and crop yields (Burney and Ramanathan, 2014; Guttikunda *et al.,* 2014; Diksha *et al.,* 2024). Air pollution has emerged as a significant environmental threat, particularly in the Indo-Gangetic Plain (IGP) of India, where intensive agriculture and industrialization co-exist with high population density (Kumar *et al.,* 2020; Sharma *et al.,* 2025). Several studies have highlighted the significant seasonal and spatial fluctuations in air pollutant concentrations due to vehicular emissions, industrial operations, agricultural activities and biomass burning (Ali *et al.,* 2024). Eastern Uttar Pradesh is an agriculturally important region primarily known for wheat production (Kumar *et al.,* 2022a). The main causes of Uttar Pradesh's high aerosol levels are anthropogenic emissions and desert dust. It was found that anthropogenic aerosols reduced maize yields in India by 8.8% annually (from 1998-2019) by affecting temperature and photosynthetically active radiation, compelling action on aerosol pollution for food security (Gupta *et al.,* 2022). Payra *et al.,* (2021) analyzed long-term trends (2007-2018) in Aerosol optical depth (AOD) across four major Indian cities - Delhi, Kolkata, Chennai and Jaipur using MODIS satellite data. Results show a significant increase in AOD, driven by anthropogenic emissions and meteorological factors. Delhi and Kolkata show the highest aerosol concentrations. Seasonal patterns highlight peak AOD during the monsoon season in Delhi and in winter for Kolkata. Awasthi *et al.,* (2023) reported that the weather variability affects rice and wheat yields in Haryana (from 1991-2020), with rainfall and humidity boosting yields, while high temperatures and wind reduce growth, highlighting the need for climate adaptation. However, the different crop yields analyses are carried out using a statistical model (Tripathi *et al.,* 2016; Bhatla *et al.,* 2018) studied the sugarcane yield prediction using a statistical model. Most global emissions are

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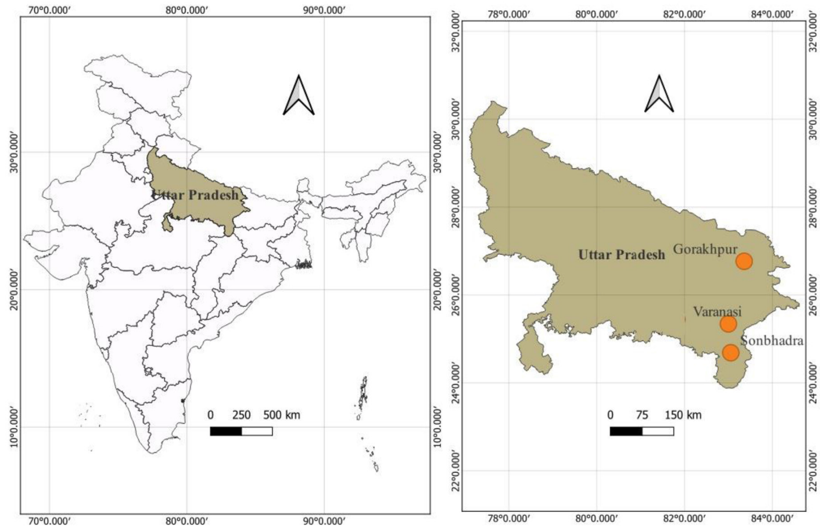

Fig. 1: Location map of study area.

caused by the burning of fossil fuels, especially coal and biomass (Alados-Arboledas *et al.,* 2011; Nasser *et al.,* 2024). Soni *et al.,* (2018) investigated the effects of an unusual dust storm event in March 2012, originating from the Arabian Peninsula and impacting northwestern India. AOD and radiative forcing were also examined, revealing reduced solar radiation at the surface and substantial atmospheric cooling and heating effects. The study highlights significant reductions in air quality (with PM10 concentrations exceeding 1800 $\mu g/m^3$) and changes in meteorological parameters such as visibility, temperature (declining by 2-10°C) and humidity.

Aerosols have an indirect impact on climate by changing the lifespan and optical properties of clouds, but when they come into direct contact with radiation, they absorb and scatter radiation. Direct and indirect interactions of aerosol with solar radiation result in the phenomenon known as radiative forcing (Lorente *et al.,* 1994; Krishna Moorthy *et al.,* 2013). BC aerosol is a result of incomplete combustion of biomass and fossil fuels and is believed to play a major role in the radiative forcing of the atmosphere due to its strong ability to absorb solar light (Bond *et al.,* 2004). After CO_2, BC may be the second-most important direct forcing factor contributing to global warming (Jacobson, 2000, 2001). As the main atmospheric absorber, BC aerosols have a beneficial effect on tropospheric radiative forcing (Jacobson, 2001; Ramanathan and Carmichael, 2008). Burney and Ramanathan (2014) reported that short-lived climate pollutants like BC and ozone caused up to 36% wheat and 20% rice yield losses in India during 1980-2010. Mehrotra *et al.,* (2024) examined the 13-year trend from 2009 to 2021 of BC mass concentration over Varanasi. Seasonal and annual variations show a significant decrease in BC levels (-0.47 $\mu g/m^3$ per year) due to factors like cleaner fuel adoption and reduced crop burning. Winter and post-monsoon months exhibit the highest concentrations, driven by local emissions and unfavorable meteorological conditions. Seasonal crop residue burning and meteorological conditions from regions like Punjab, Haryana and Delhi-NCR also contribute to elevated levels of PM10 and PM2.5 and greenhouse gases in the winter months, exacerbating air quality deterioration during critical stages of wheat crop growth (Sanyal *et al.,* 2023; Kumar *et al.,* 2024). PM10 and PM2.5 levels in Varanasi (winter of 2016-2017), driven by biomass burning, fossil fuels and long-range pollutant transport, highlight the need for emission controls in the Indo-Gangetic Basin (Pratap *et al.,* 2020). In another study high aerosol levels were observed over Kanpur and Varanasi during 2011-2015 resulting from industrial activities, biomass burning and dust, suggesting seasonal and meteorological influence on air quality and climate (Kumar *et al.,* 2022b).

In Eastern Uttar Pradesh, wheat is a primary winter crop, the combined effects of increasing pollution levels and changing climatic conditions pose a dual threat to crop health and productivity. Many studies have demonstrated that air pollutants not only reduce crop yields but also affect the quality of the grains produced (Bhattacharya *et al.,* 2023). Burney and Ramanathan (2014) highlighted how particulate matter from biomass burning and industrial sources affects both wheat yield and food security, as reduced photosynthetic activity lowers the carbohydrate content in grains, impacting their nutritional value. Given earlier mentioned emerging challenges and issues, the present study is organized and examines (i) the seasonal and yearly variations in AOD and BC. (ii) Air mass back trajectories analysis using the HYSPLIT model during the Pre-monsoon, Monsoon, Post-monsoon and Winter seasons. (iii) impact of AOD and BC on wheat crop production in Varanasi, Gorakhpur and Sonbhadra districts of Eastern Uttar Pradesh**.**

MATERIAL AND METHODS

Eastern Uttar Pradesh (23.51 ^{0}N to 28.31 ^{0}N latitutes 81.30 ^{0}E to 84.39 ^{0}E longitudes) covers an area of 85298.79 km^2 including several areas with industrial developments. Gorakhpur, Varanasi, and Sonbhadra are selected as study area (Fig. 1). We have used mean_MOD08_M3, Deep Blue AOD 550nm over eastern Uttar Pradesh. We have analyzed Level-3 MODIS monthly global product, MOD08_M3, http://modis-atmos.gsfc.nasa.gov/) containing data collected from the Terra platform to show spatial extent. MERRA-2 provides data at 0.5° × 0.625° resolution covering a period from 1

January 2001 to February 2023. Further, crop yield data is provided by Directorate of Economics & Statistics, India.

To understand the likely source regions and the transport pathways of the detected air pollutants, the air mass backward trajectories obtained from Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model were utilized over Gorakhpur, Varanasi, and Sonbhadra. HYSPLIT's back trajectories, when integrated with satellite imagery of NASA's satellites, offer insights into whether elevated air pollution levels stem from local sources or were transported from distant areas by wind. HYSPLIT has been widely used in simulations that show how pollutants and dangerous particles are transported, dispersed, and deposited in the atmosphere (Fleming *et al.,* 2012; Stein *et al.,* 2015). These applications include tracking and forecasting the spread of radioactive materials, smoke from wildfires, wind-borne dust, emissions from both mobile and stationary sources, allergies, and volcanic ash (Stunder *et al.,* 2007). Seven-days back trajectories were used to account for air masses to the study locations at the altitudes of 500, 1500, and 2500m.

RESULTS AND DISCUSSION

Trends of AOD in different months and seasons

Analysis has been done on the fluctuation in AOD across the eastern part of Uttar Pradesh from 2001 to 2023 throughout the winter (December–January–February), pre-monsoon (March–April–May–June), monsoon (July–August–September), and post-monsoon (October–November) seasons. It is found that the January month has higher AOD values i.e., 0.98 than December and February 0.85, and 0.58, respectively. Probably, the high AOD during the Pre- monsoon in June i.e., 0.82. It reveals that AOD is remarkably increased during the Pre- monsoon season followed by the winter, post-monsoon, and monsoon. In January, the maximum AOD was 0.98 and 0.85 while the minimum AOD recorded was 0.29 and 0.31 in 2001 and 2023, respectively. Kumar *et al.,* (2020) found comparative results for AOD in Varanasi. Aerosol levels have significantly escalated over the past 23 years primarily attributed to heightened energy consumption. In recent times, there has been a substantial rise in aerosol concentrations across eastern Uttar Pradesh, mainly due to biomass burning for domestic purposes and emissions from thermal plants (including gases and fly ash). Anthropogenic emissions are the main source of aerosol throughout the winter months (December to February), particularly from burning agricultural waste and urban/industrial emissions over eastern Uttar Pradesh. By burning fossil fuels like coal, oil, and gas, humans release a large number of aerosols into the atmosphere (Wolf and Hidy, 1997). Seasonal Variation of AOD from 2001 to 2023 is shown in Fig. 2.

Trends of black carbon in different months and seasons

The monthly average concentration of BC shows its lowest levels during July and peaks in November. BC concentrations are lowest during the monsoon season, followed by summer, winter, and post-monsoon periods. During winter, extremely high loading of BC aerosol i.e.,0.09 followed by post-monsoon i.e., 0.06-0.08. The low range of BC concentrations 0.0015- 0.035 mainly prevailed during the Pre-Monsoon and Monsoon season. During post-monsoon season, farmers burn their crop residue in the fields, and the emitted aerosols travel which increases the BC concentration over Eastern Uttar Pradesh. The rainfall and high wind speed during the monsoon season reduces the BC concentration. Additionally, during the non-polluted seasons (summer and monsoon), larger frequencies were only observed for small concentration bins while, in polluted seasons (post-monsoon and winter), larger frequencies were noted for high concentration bins. Monsoon and pre-monsoon seasons displayed a comparatively weak BC mass concentration. Comparable results were found in Varanasi (Mehrotra *et al.,* 2024). The seasonal Variation of BC from 2001 to 2023 is shown in Fig. 3.

Annual variation and trends of AOD and black carbon

Fig. 4 represents the AOD trend over time, showing a gradual increase. The regression equation ($y = 0.0069x - 13.395$) indicates a positive trend, suggesting rising aerosol levels. The R^2 value (0.6884) signifies a moderate correlation, meaning the trend explains a reasonable portion of the variability in AOD. The data points, plotted yearly, show fluctuations but maintain an overall upward trend. This analysis highlights potential changes in atmospheric aerosols, which could be influenced by environmental factors such as pollution, climate change, or land-use changes, making AOD monitoring essential for air quality and climate studies.

The graph illustrates the BC concentration trend over time. The regression equation suggests a very slight increasing trend, while the R^2 value (0.0228) indicates a weak correlation, meaning the trend does not strongly explain the variations in BC levels. The data points fluctuate but remain relatively stable, with minor variations over the years. BC, a key atmospheric pollutant, affects air quality and climate by absorbing solar radiation. Monitoring BC trends is crucial for understanding its environmental impact and implementing effective mitigation strategies to reduce pollution and improve air quality.

Monthly variation of AOD and BC

Fig. 5 represents the monthly mean AOD and BC variations with standard deviation with data points from January to December. The blue line with error bars indicates monthly AOD values, showing fluctuations and a general increasing trend. The slight upward trend, indicating increasing atmospheric aerosols, which may be influenced by seasonal changes, meteorological conditions, or pollution sources. Higher AOD concentrations were found during winter months due to anthropogenic activities and during pre-monsoon months due to transported pollution from different regions.

The BC concentration over the months' trend shows a decrease from January to July, followed by a gradual rise towards December. The higher BC concentrations during winter months may be due to lower dispersion of BC and shallow atmospheric boundary layers. The error bars indicate measurement uncertainties. The seasonal variation likely reflects changes in emissions, meteorological conditions, or environmental factors influencing BC levels throughout the year. The increasing trend in AOD and BC

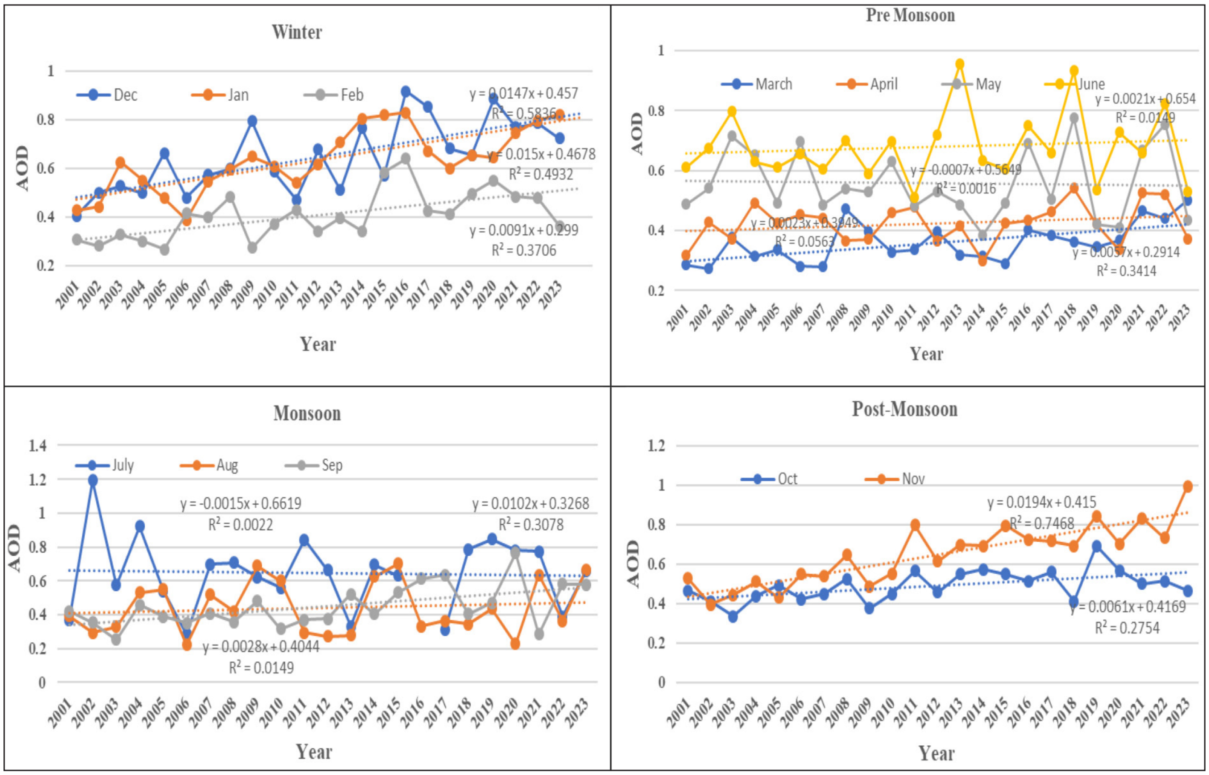

Fig. 2: Trend and variation of AOD in different months/seasons during 2001 to 2023

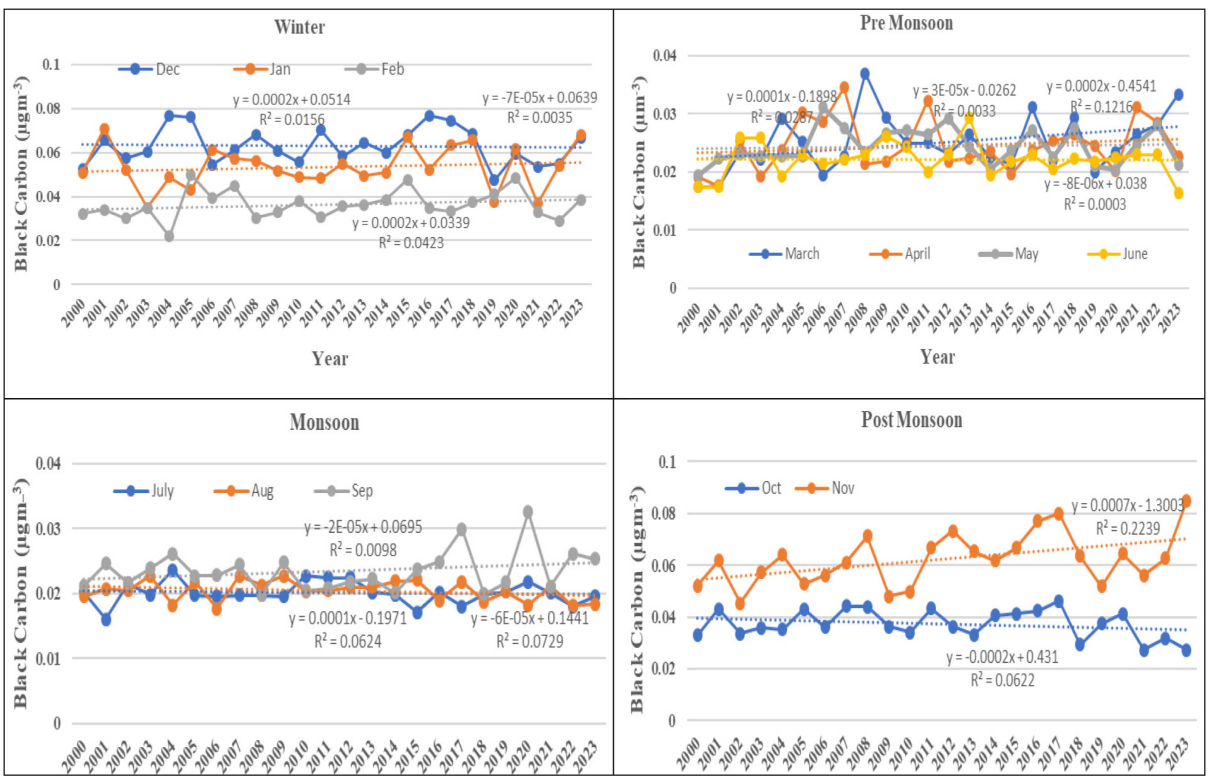

Fig. 3: Trend and variation of BC in different months/seasons during 2001 to 2023

concentrations during winter months may be attributed to regional anthropogenic activities, such as fossil fuel combustion and biomass burning.

Relation between AOD, BC and wheat crop yield

The scatter plots (Fig. 6) depict the relationship between AOD/BC and wheat crop yield in Varanasi. The regression

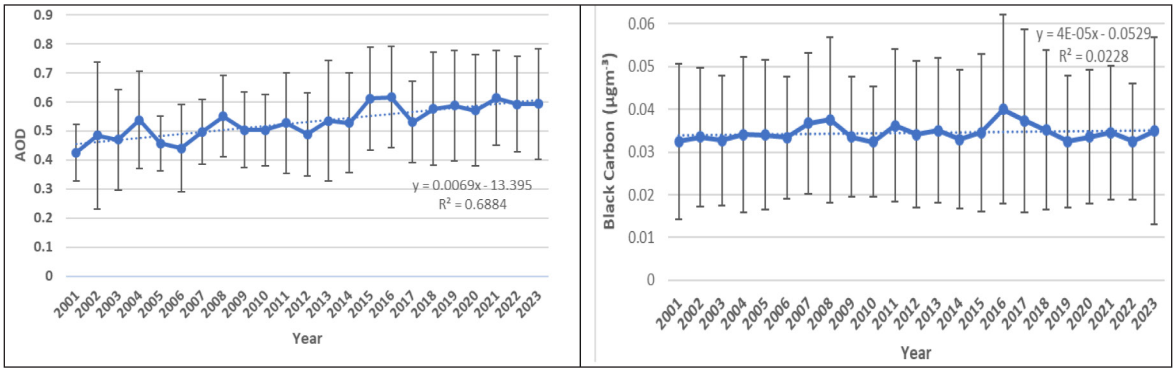

Fig. 4: Annual variation of AOD and BC during 2001 to 2023.

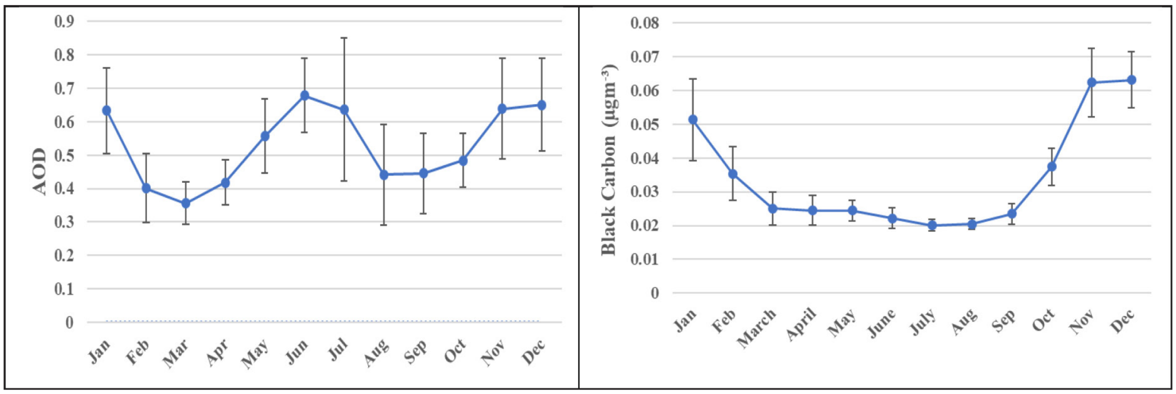

Fig. 5: Monthly variation of AOD and BC.

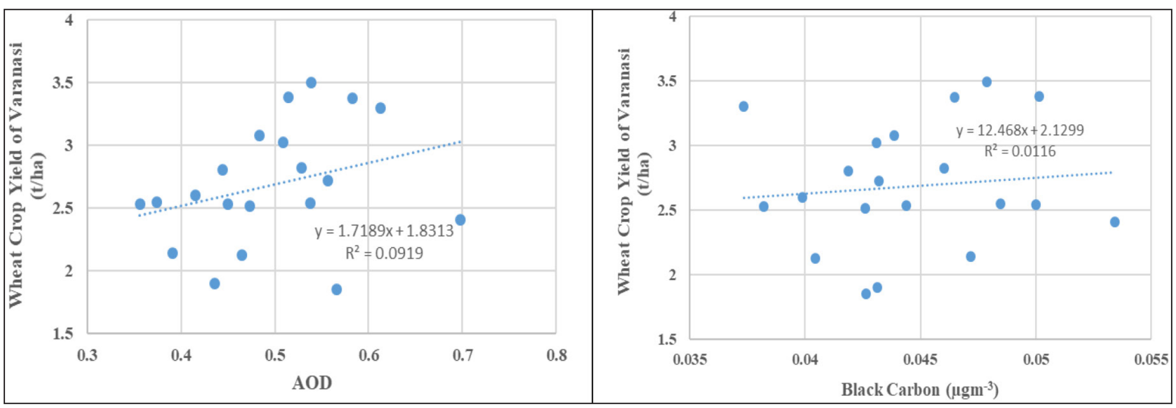

Fig. 6: Relation between wheat crop yield and AOD/BC during winter in Varanasi.

equation (y=1.7189x+1.8313) suggests a slight positive correlation, meaning higher AOD values may be linked to increased wheat yield. However, the R^2 value (0.0919) indicates a weak correlation, suggesting other factors significantly influence yield variations. Further research is needed to understand the impact of aerosols on agricultural productivity in the region.

The scatter plot illustrates the relationship between BC concentration (μg m^{-3}) and wheat crop yield (t ha^{-1}) in Varanasi. A trendline with the equation y=12.468x+2.1299 and an R^2 value of 0.0116 suggests a weak positive correlation. The dispersed data points indicate variability, implying that BC has minimal influence on wheat yield. Other environmental and agronomic factors likely play a more significant role in determining crop productivity in this region.

The scatter plot shows the relationship between AOD/BC and wheat crop yield (t ha^{-1}) in Gorakhpur (Fig. 7). The R^2 value of 0.0889 indicate a weak positive correlation. The scattered data points suggest significant variability, implying that AOD has a minor impact on wheat yield. Other environmental and agronomic factors likely have a more substantial role in influencing wheat productivity in this region.

The scatter plot represents the relationship between BC concentration (μg m^{-3}) and wheat crop yield (t ha^{-1}) in Gorakhpur. The R^2 value of 0.026 indicate a very weak positive correlation. The dispersed data points suggest that BC has minimal influence on wheat yield. Other environmental and agronomic factors likely contribute more significantly to wheat productivity in this region, necessitating further investigation.

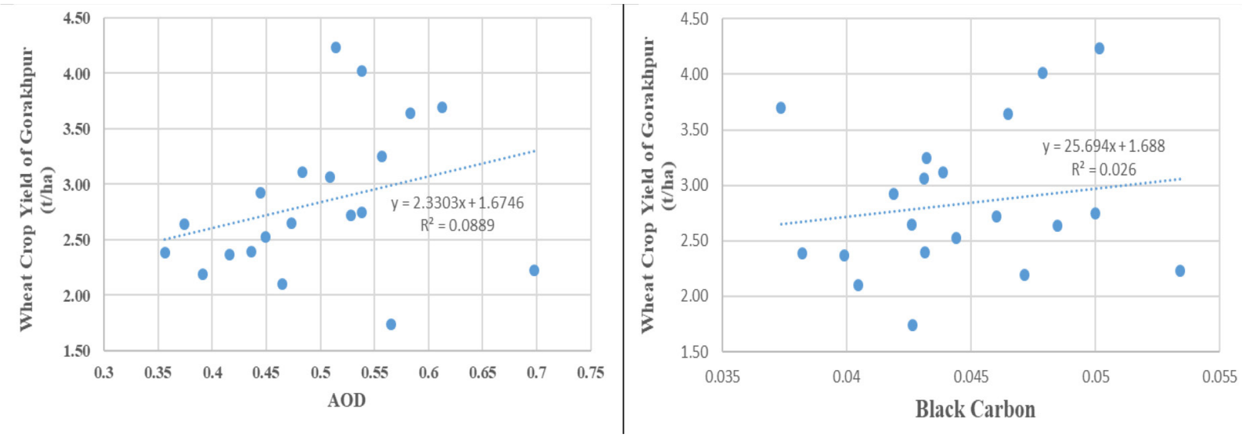

Fig. 7: Relation between wheat crop yield and AOD/BC during winter in Gorakhpur.

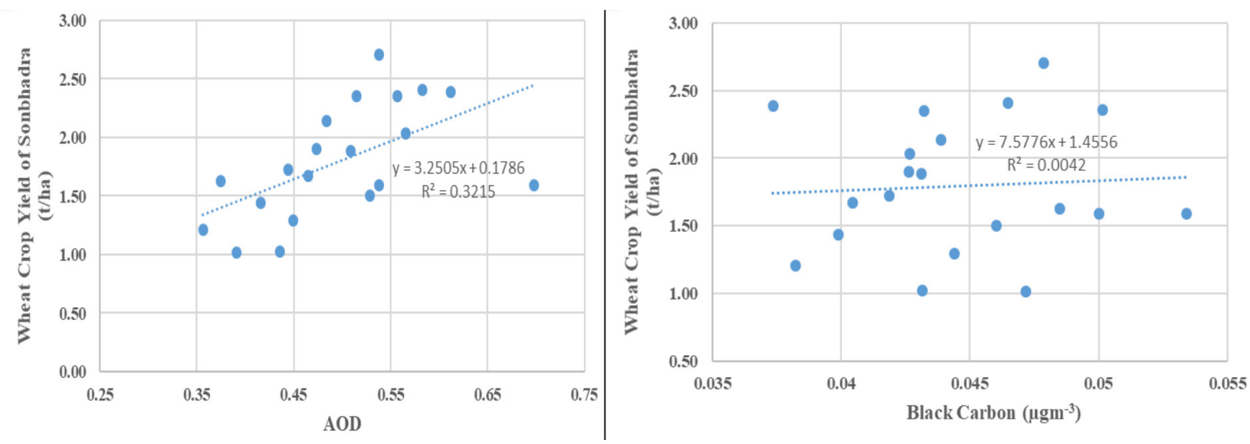

Fig. 8: Relation between wheat crop yield and AOD/BC during winter in Sonbhadra.

The scatter plot illustrates the relationship between AOD/BC and wheat crop yield (t ha^{-1}) in Sonbhadra (Fig. 8). The R^2 value of 0.3215 indicate a moderate positive correlation. This suggests that increasing AOD may have some influence on wheat yield. However, the scattered data points indicate variability, implying that additional environmental and agronomic factors also contribute significantly to crop productivity in this region.

The R^2 value of 0.0042 between BC and wheat crop yield indicate an extremely weak positive correlation. The widely scattered data points suggest minimal influence of BC on wheat yield. Other environmental and agronomic factors likely play a more significant role in determining wheat productivity in this region. This stability may suggest that, despite environmental stressors, wheat yield has remained relatively unaffected or resilient, possibly due to advancements in agricultural practices or crop tolerance (Patel *et al.,* 2023).

Backward trajectory analysis

In in the winter season values are higher indicating that aerosol particles are dominant due to anthropogenic activities (Fig. 9**)**. This image appears to depict, possibly showing the trajectory of air masses or pollutant dispersion over a region. Higher aerosols are transported from the Middle East countries on January 8, 2009 focused on a specific event occurring in early January. Such visualizations are crucial for studying air pollution, climate impacts, or transboundary pollution transport.

The paths suggest that air parcels at lower altitudes (red and blue) originated from areas to the west and southwest, moving across northern India (Fig. 10). The effect of air mass originating over the Bay of Bengal and Arabian sea has one of the effects is moisture content due to the warm and humid conditions over the ocean, increases the humidity level. Backward trajectories from Middle East, Thar Desert and the Arabian Sea, shows the transported aerosols, have regional influences. The altitude-based variation in origin highlights multiple transport pathways influencing air quality in northern India.

The trajectories in Fig. 11 indicate the origins of air masses reaching the specified location in northern India. The color-coded paths represent air movement from different regions, including areas to the west and southwest of India. Aerosols from crop biomass burning in Punjab, Haryana and Pakistan during the post-monsoon season reaches in Eastern Uttar Pradesh.

The trajectories primarily show air parcels originating from the Arabian Sea and Bay of Bengal suggesting influence from westward air flows (Fig. 12). The data shows that air parcels originate from various regions across the Arabian Sea, Indian Ocean, and nearby areas, potentially suggesting influences from regional

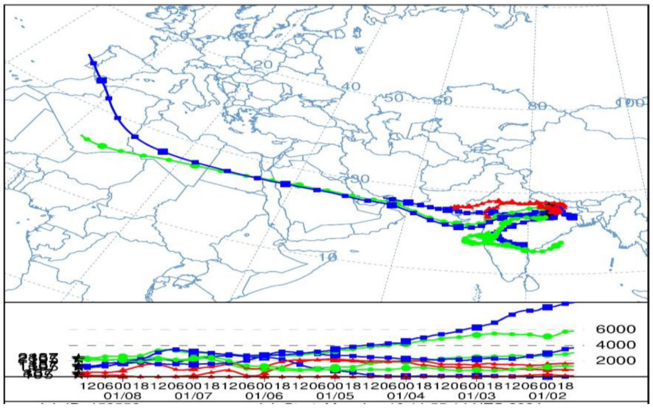

Fig. 9: The seven-day back trajectory analysis during winter (08/01/2009) at altitudes (500 m, 1500 m, and 2500 m) in Gorakhpur, Varanasi and Sonbhadra.

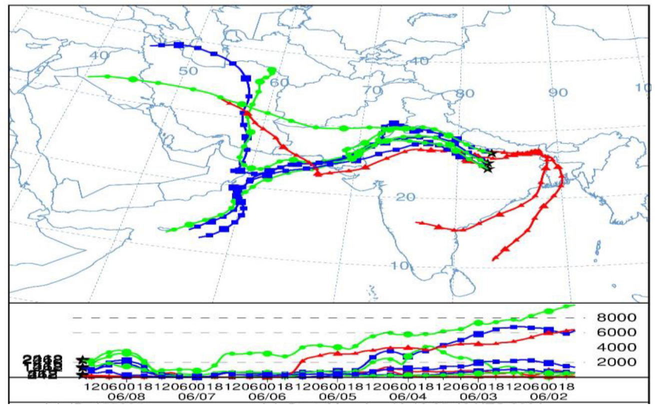

Fig. 10: The seven days' back trajectory analysis during pre-monsoon (08/06/2022) at altitudes (500, 1500, 2500m) in different districts.

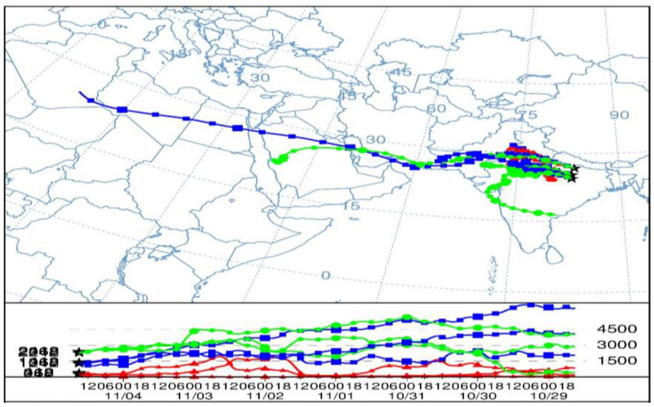

Fig. 11: The seven days' back trajectory analysis during post-monsoon (04/11/2019) at altitudes (500, 1500, 2500m) in different districts.

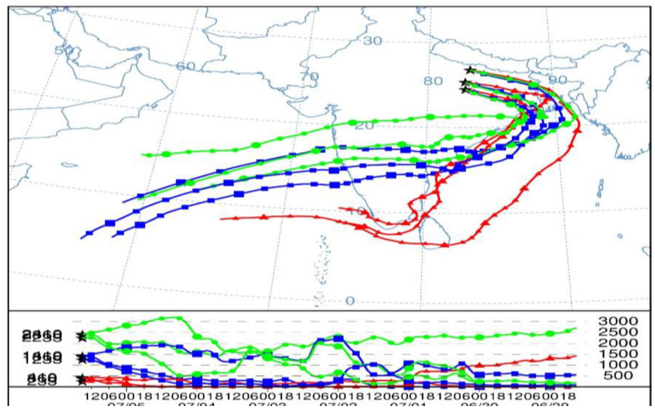

Fig. 12: The seven-day back trajectory analysis during monsoon (05/07/2011) at altitudes (500 m, 1500 m, and 2500 m) in different districts.

transport and monsoon circulation patterns over India (Kumar *et al.,* 2022b). During the monsoon season, moist air masses from the Arabian Sea and Bay of Bengal move towards Eastern Uttar Pradesh. This movement is driven by the seasonal reversal of winds.

CONCLUSIONS

The elevated values of AOD and BC originated from fossil fuel combustion, traffic, and biomass burning. Population growth, urbanization, economic expansion, and industrialization drive also responsible for rising aerosols level. HYSPLIT model indicate the higher AOD during winter are due to aerosols primarily from anthropogenic activities, while monsoon aerosols originated from the Arabian Sea and Bay of Bengal. In the post-monsoon biomass burning from Punjab, Haryana, and Pakistan reaches to the study locations, while in pre-monsoon season emissions stem from wheat stubble burning and some transported pollution from Thar and Sahara Desert. Post-monsoon AOD surpasses pre-monsoon due to intensified crop residue burning. Increased seasonal fuel use, home heating, and stagnant weather elevate BC concentrations in post-monsoon/winter. Poor correlations between AOD/BC and wheat crops yield indicates impact on production. Higher AOD levels reduce wheat yields by limiting sunlight and affecting photosynthesis, while BC has minimal direct impact due to its shorter atmospheric presence and lesser influence on sunlight scattering. This study will help the government and policymakers to identify pollution hotspots, understand the impact of air pollutants on wheat production, and develop targeted strategies to mitigate air pollution and safeguard agricultural productivity.

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Data availability: Data utilized in this study is accessible through open platforms.

Authors contribution: **R. Bhatla**: Conceptualization, Methodology, Supervision, Writing-review and editing; **Priya Raj:** Data Collection, Data Analysis, Visualization, Writing-original draft; **Pradeep Kumar:** Resources, Visualization, Writing-review

and editing; **Babita Dani**: Analysis, Visualization, Data Collection, Writing-review; **Akash Vishwakarma:** Analysis, Visualization and Data Collection.

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REFERENCES

Alados-Arboledas, L., Müller, D., Guerrero-Rascado, J. L., Navas-Guzmán, F., Pérez-Ramírez, D. and Olmo, F. J. (2011). Optical and microphysical properties of fresh biomass burning aerosol retrieved by Raman lidar, and star-and sun-photometry. *Geophys. Res. Lett.,* 38(1). https://doi.org/10.1029/2010GL045999

Ali, H. H., Wahab, B. I. and Al-Hmeed, H. M. A. (2024). Comprehensive air quality analysis in Karbala: Investigating the relationships between meteorological factors and pollutants across different landscapes. *J. Agrometeorol.,* 26(4): 401-410. https://doi.org/10.54386/jam.v26i4. 2665

Awasthi, N., Tripathi, J. N., Dakhore, K., Gupta, D. K. and Kadam, Y. E. (2023). Assessment of climatic impact on growth and production of rice (Kharif) and wheat (Rabi) using geospatial technology over Haryana. *Mausam,* 74(4): 911-920. https://doi.org/10.54302/mausam.v74i4.6194

Bhatla R., Dani Babita and Tripathi A. (2018). Impact of climate on sugarcane yield over Gorakhpur District, UP using statistical model, *Vayu Mandal,* 44 (1): 11-22

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J. H. and Klimont, Z. (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.: Atmos.,* 109(D14). https://doi.org/10.1029/2003JD003697

Burney, J. and Ramanathan, V. (2014). Recent climate and air pollution impacts on Indian agriculture. *PNAS, 111*(46): 16319-16324. https://doi.org/10.1073/pnas.1317275111

Diksha, Kumari, M., Mishra, V. N., Kumar, D., Kumar, P. and Abdo, H. G. (2024). Unveiling pollutants in Sonipat district, Haryana: Exploring seasonal, spatial and meteorological patterns. *Phys. Chem. Earth, Parts A/B/C,* 135:103678. https://doi.org/10.1016/ j.pce.2024.103678

Fleming, Z. L., Monks, P. S. and Manning, A. J. (2012). Untangling the influence of air-mass history in interpreting observed atmospheric composition. *Atmos. Res.,* 104-105, 1-39. https://doi.org/10.1016/j.atmosres.2011.09.009

Gupta, D. K., Pramanick, S. and Singh, A. K. (2022). Atmospheric Aerosol and weather vulnerability on Maize production in India. In 2022 URSI Regional Conference on Radio Science (USRI-RCRS) (pp. 1-4). IEEE. https://doi.org/10.23919/URSI-RCRS56822.2022.10118482

Guttikunda, S. K., Goel, R. and Pant, P. (2014). Nature of air pollution, emission sources and management in the Indian cities. *Atmos. Environ.,* 95: 501-510. https://doi.org/10.1016/j.atmosenv.2014.07.006

Jacobson, M. Z. (2000). A physically-based treatment of elemental carbon optics: Implications for global direct forcing of aerosols. *Geophys. Res. Lett., 27*(2): 217-220. https://doi.org/10.1029/1999GL010968

Jacobson, M. Z. (2001). Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature*, *409*(6821): 695-697. https://doi.org/10.1038/35055518

Krishna Moorthy, K., Suresh Babu, S., Manoj, M. R. and Satheesh, S. K. (2013). Buildup of aerosols over the Indian Region. *Geophys. Res. Lett.,* 40(5): 1011-1014. https://doi.org/10.1002/grl.50165

Kumar, P., Pratap, V., Kumar, A., Choudhary, A., Prasad, R., Shukla, A., Singh, R.P. and Singh, A. K. (2020). Assessment of atmospheric aerosols over Varanasi: Physical, optical and chemical properties and meteorological implications. *J. Atmos. Solar-Terrest. Phy.,* 209: 105424. https://doi.org/10.1016/j.jastp.2020.105424

Kumar, P., Choudhary, A., Joshi, P. K., Prasad, R. and Singh, S. K. (2022a). Multiple crop yield estimation and forecasting using MERRA-2 model, satellite-gauge and MODIS satellite data by time series and regression modelling approach. *Geocarto Intern.,* 37(27): 16590-16619. https://doi.org/10.1080/10106049.2022.2112301

Kumar, P., Kapur, S., Choudhary, A. and Singh, A. K. (2022b). Spatiotemporal variability of optical properties of aerosols over the Indo-Gangetic Plain during 2011–2015. *Ind. J. Phys.,* 1-13. https://doi.org/10.1007/s12648-020-01987-x

Kumar, R. P., Singh, R., Kumar, P., Kumar, R., Nahid, S., Singh, S. K. and Nijjar, C. S. (2024). Aerosol-PM2. 5 Dynamics: In-situ and satellite observations under the influence of regional crop residue burning in post-monsoon over Delhi-NCR, India. *Environ. Res.,* 255: 119141. https://doi.org/10.1016/j.envres.2024.119141

Lorente, J., Redan, A. and De Cabo, X. (1994). Influence of urban aerosol on spectral solar irradiance. *J. Appl. Meteorol. Climatol.,* 33(3): 406-415. https://doi.org/10.1175/1520-0450(1994)033<0406:IOUAOS>2.0.CO;2

Mehrotra, B.J., Srivastava, A.K., Singh, A., Parashar, D., Majumder, N., Singh, R.S., Choudhary, A. and Srivastava, M.K. (2024). Long-term trend in Black Carbon mass concentration over Central Indo-Gangetic Plain location: Understanding the implied change in radiative forcing. *J. Geophys. Res.: Atmos.,* 129. https://doi.org/10.1029/2024JD040754

Nasser, M.S., Al-Hassany, J.S. and Al-Jiboori, M.H. (2024). Assessment of air pollution dispersion during wet season: A case study of Rumaila Combined Cycle Power Plant, Basrah, Iraq. *J. Agrometeorol.,* 26(4): 411-418. https://doi.org/10.54386/jam.v26i4.2756

Payra, S., Gupta, P., Bhatla, R. Amraoui, L. and Verma, S. (2021). Temporal and spatial variability in aerosol optical depth (550 nm) over four major cities of India using data from MODIS onboard the Terra and Aqua satellites. *Arab. J. Geosci.,* 14: 1256. https://doi.org/10.1007/s12517-021-07455-y

Patel, N.R., Pokhariyal, S. and Singh, R.P. (2023). Advancements in remote sensing-based crop yield modelling in India. *J. Agrometeorol.,* 25(3): 343-351. https://doi.org/10.54386/jam.v25i3.2316

Pratap, V., Kumar, A., Tiwari, S., Kumar, P., Tripathi, A.K. and Singh, A.K. (2020). Chemical characteristics of particulate matters and their emission sources over Varanasi during winter season. *J. Atmos. Chem.,* 77: 83-99. https://doi.org/10.1007/s10874-020-09405-6

Bhattacharya, P., Bandyopadhyay, K.K., Krishnan, P., Maity, P.P., Purakayastha, T.J., Bhatia, A., Chakraborty, B., Kumar, S., Adak, S., Tomer, R. and Meenakshi (2023). Impact of tillage and residue management on greenhouse gases emissions and global warming potential of winter wheat in a semi-arid climate. *J. Agrometeorol.,* 25(4): 503-509. https://doi.org/10.54386/jam.v25i4.2337

Ramanathan, V. and Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nat. Geosci.,* 1(4): 221-227. https://doi.org/10.1038/ngeo156

Sanyal, S., Chakrabarti, B., Bhatia, A., Kumar, S. N., Purakayastha, T. J., Kumar, D., Pramanik, P., Kannojiya, S., Sharma, A. and Kumar, V. (2023). Response of aestivum and durum wheat varieties to elevated CO_2 and temperature under OTC condition. *J. Agrometeorol.,* 25(4): 498-502. https://doi.org/10.54386/jam.v25i4.2366

Soni, V.K., Bist, S., Bhatla, R., Bhan, S.C., Kumar, G., Sateesh, M., Singh, S. and Pattanaik, D.R. (2018). Effect of unusual dust event on meteorological parameters & aerosol optical and radiative properties. *Mausam,* 69(2): 227-242. https://doi.org/10.54302/mausam.v69i2.290

Sharma, V., Ghosh, S., Mishra, V.N. and Kumar, P. (2025). Spatio-temporal Variations and Forecast of PM2.5 concentration around selected Satellite Cities of Delhi, India using ARIMA model. *Phys. Chem. Earth, Parts A/B/C, Parts A/B/C*, 138: 103849. https://doi.org/10.1016/j.pce.2024.103849

Stein, A. F., Ngan, F., Draxler, R. R. and Chai, T. (2015). Potential use of transport and dispersion model ensembles for forecasting applications. *Weather Forecast.,* 30(3): 639-655. https://doi.org/10.1175/WAF-D-14-00153.1

Stunder, B.J., Heffter, J.L. and Draxler, R.R. (2007). Airborne volcanic ash forecast area reliability. *Weather Forecast,* 22(5): 1132-1139. https://doi.org/10.1175/WAF1042.1

Tripathi, A., Singh, R.S., Bhatla, R. and Kumar, A. (2016). Maize yield estimation using agro-meteorological variables in Jaunpur district of Eastern Uttar Pradesh. *J. Agrometeorol.,* 18(1): 153-154. https://doi.org/10.54386/jam.v18i1.923

Wolf, M.E. and Hidy, G.M. (1997). Aerosols and climate: Anthropogenic emissions and trends for 50 years. *J. Geophys. Res.: Atmos.,* 102(D10): 11113-11121. https://doi.org/10.1029/97JD00199