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RESEARCH ARTICLE - ATMOSPHERIC & SPACE SCIENCES

Spatial variation, sources, and trajectory of black carbon in the South Sumatra Region of Indonesia using MERRA-2 reanalysis data

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Abstract
A high temperature and lack of rainfall in the South Sumatra Region during the dry season of 2019 led to an increase in intense land fires that were attributed to biomass burning and the pyrogenic combustion process. This study tried to analyze the spatiotemporal distributions of atmospheric BC (black carbon) over the South Sumatra Region during 2016–2019 land fire events using the MERRA-2 satellite images. The spatial analysis was applied to estimate the increment in black carbon concentrations during land fire episodes. Some meteorological conditions that affect black carbon diffusion and transport over the study area are explained using a backward trajectory analysis. The results exhibited that the black carbon masses mostly came from local and long-range transports (from eastern to western) over the study area. A significant percentage increment of black carbon concentration during 2016–2019 was observed at around 139%. The highest black carbon concentration recorded in October 2019 was 3.96×10^{-6} kg/m^2, as hotspots were still abundant, especially on the eastern side of the study area. The black carbon trend was strongly related to total hotspots and burned areas. As a whole, this finding could be beneficial for mitigating black carbon pollution due to land fires by implementing geospatial technology for rapid monitoring of air pollution in vast areas.

Keywords Air mass transport · Black carbon · Merra-2 · Peatland fires · South Sumatra

Introduction

Black carbon is a component of very fine particles in the atmosphere that permeate ultraviolet and visible wavelength ranges (Takemura and Suzuki 2019). Black carbon is typically dispersed into the atmosphere as soot from biomass burning, industry, diesel machine, and factory sites (Rendana et al. 2016; Xu et al. 2020). The increment in black carbon concentration generally leads to an increase in air temperature (Yamineva and Liu 2019). Thus, black carbon emissions become one of the most prominent contributors to global warming. According to a previous study by Ramanathan and Carmichael (2008), the climate effect of black carbon is considered an agent for the increase in global surface temperature reaching 1 degree Celsius. Furthermore, the impact of black carbon can affect thermal balance and meteorological patterns, specifically in the troposphere layer. According to related research on the radiation impact of black carbon, it can also influence regional climate regimes and the monsoon cycle (Xie et al. 2020). In the air, black carbon may be transferred and accumulated on ice or snow surfaces. The lifetime of black carbon in the air is around 4–12 days (Guo et al. 2020); thus, the effect of black carbon can affect regional climate scales. As a result, most researchers agreed that reducing black carbon emissions could significantly reduce global warming (Brewer 2019). In a primary process for diminishing black carbon from the air through

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dry and wet depositions, more comprehensive analyses are needed to understand this mechanism (Sitnov et al. 2020).

Black carbon has a severe effect on human health and the environment due to its carcinogenic character (Kirrane et al. 2019). It enters the respiratory path, and particles accumulate in the alveoli, which then block gas circulation between the blood and lung, resulting in cardiovascular system sickness (Rendana et al. 2022a). The greatest source of black carbon in Indonesia is from biomass burning sites (around 60%) (Santoso et al. 2008). The average concentration of black carbon in many urban areas in Indonesia ranges from 2.6 to 3.8 μg/m^2 (Sattar et al. 2014).

The major source of black carbon emission in the South Sumatra Region comes from peatland fires. In aprevious report from the Indonesian Disaster Management Agency, the South Sumatra Region has sustained the biggest fire areas in Indonesia that increased from 8,505 ha to 144,410 ha during 2014–2015. To date, there were unsufficient data regarding black carbon concentration in the South Sumatra Region. Hence, if we compared to another adjacent province (Riau province), a study by Sari et al. (2022) obtained the black carbon concentration of 5.5×10^{-9} kg/m^3 during the severe forest fire event of 2019. In general, there are three main methods to estimate atmospheric black carbon emission: ground monitoring instruments, numerical analysis, and satellite acqusition. Notwithstanding, ground monitoring cannot investigate the large-scale black carbon emission and time consuming. Meanwhile, satellite data often occur miss, errors, over and under estimations of the data due to clouds, and other disturbances on the air (Li et al. 2020). Therefore, to overcome the weakness of ground observation and satellite data, a data reanalysis was applied. The Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) satellite has adopted this innovation. It useful to diffuse data from various types and sources with a specific model to obtain an optimal combination. Then, the MERRA-2 with reanalysis data gives a better data with high spatiotemporal resolution to analyze deeply the black carbon emission.

Peatland fires in the South Sumatra Region are common incidents especially they mostly occur during the dry season. Yin et al. (2020) reported that there was an increase of total hotspot and fire radiative value in the region with values of 78,055 and 4.05 × 106 MW, respectively, which aggravated to climate change phenomenon. Unfortunately, after knowing that the black carbon has a crucial role in climate change, its variation over the South Sumatra Region is less monitored. Because of that, the assesment of black carbon emission from peatland fires in the South Sumatra Region are uncertainty. Furthermore, the analysis of long-range transport of black carbon from fire areas over the South Sumatra Region has also been insufficiently investigated. The application of MERRA-2 reanalysis data may examine the spatial and temporal variation of black carbon during severe peatland fires incidents. Therefore, the objective of this study was to analyze a regional scale of black carbon pollution over the South Sumatra Region during 2016–2019 using the integration of MERRA-2 satellite data and backward trajectory analysis.

Materials and methods

Study area

This research was conducted in the Indonesian province of South Sumatra, at longitudes 101 0′0″E–106 0′0″E and latitudes 1 0′0″S–5 0′0″S (Fig. 1). According to a report from the Ministry of Environment and Forestry, this province is one of the major contributors to land fire events in the Indonesian region. While most land fires in Indonesia occurred in mineral soils, land fires in South Sumatra were more often attributed to organic soils, also known as peatlands (Lestari et al. 2021). This condition has made the area more vulnerable to wildfires. In 2019, around 11,826 hectares of land in South Sumatra have been burned (Sarmiasih and Pratama 2019). This region has also been home to many industries in the area, such as fertilizer, oil and gas, coal, and pulp and paper companies. The primary commodity in this area is the agricultural sector, such as oil palm plantations, and the remaining areas are developed as fish farms and horticultural activities (Rospiani and Lifianthi 2022).

Data sources

Monthly black carbon column mass density (M2TMNXAER v5.12.4) from the MERRA-2 satellite data with a spatial resolution of 0.5° × 0.6° was applied in this study. The data in geotiff format were acquired from the NASA Giovanni website (https://giovanni.gsfc.nasa.gov/giovanni/) and correspond to the border of the study area. Hotspot data with coordinates were obtained from the Indonesian Ministry of Environmental and Forestry and used to assess the fire events within the South Sumatra Region during 2016–2019. Meteorological data in Microsoft Excel format containing daily temperature, rainfall, and wind speed during 2016–2019 over the study area were collected from the Indonesian Meteorological, Climatological, and Geophysical Agency. In order to enhance the accuracy of the study, we selected some months in the dry season period (October–December) in each year of the study.

Methods

IDW (Inverse distance weighted)

Inverse distance weighted (IDW) is a prevalent technique of interpolation in geospatial analysis. It applies a linear weight

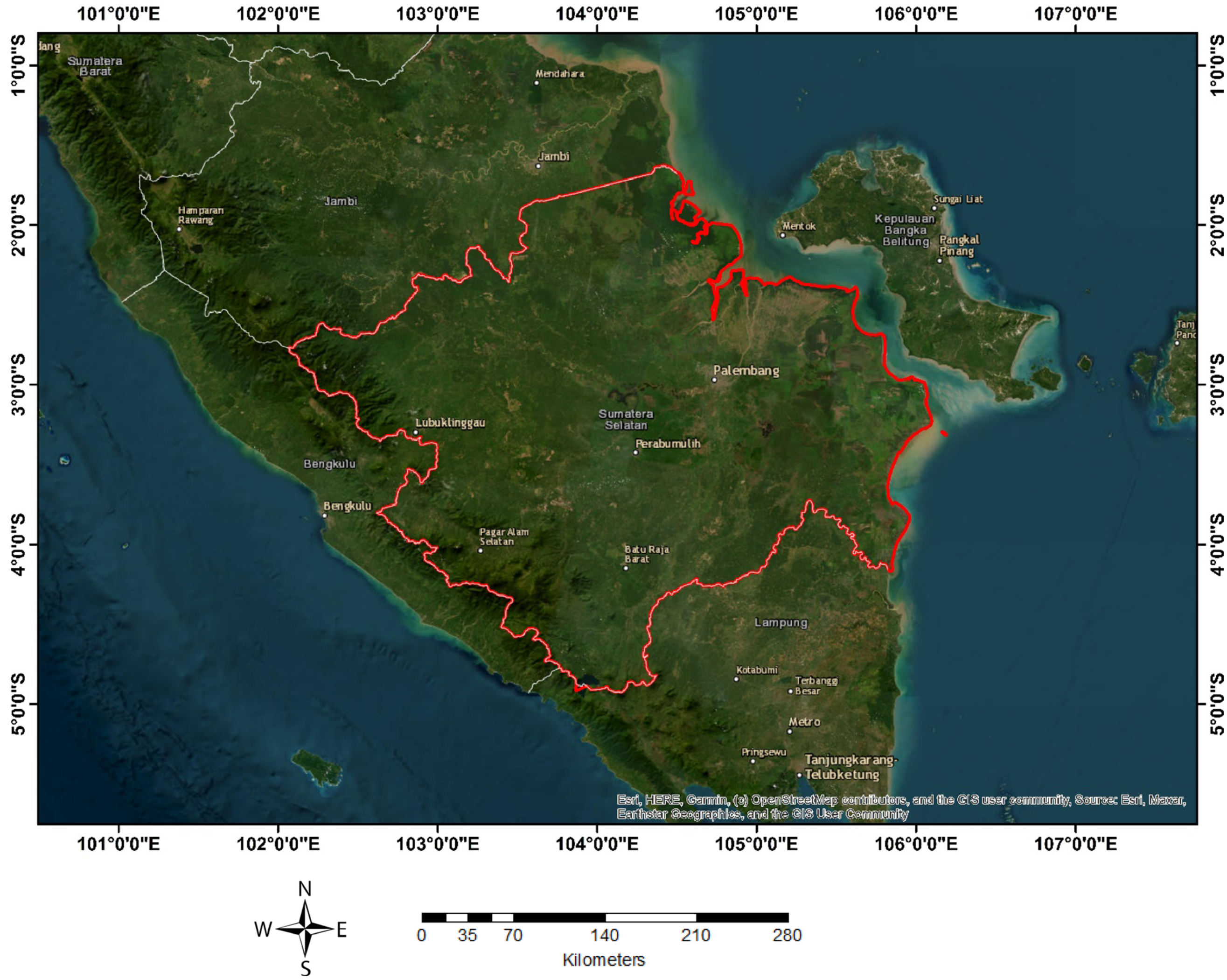

Fig. 1 Location of the study area. South Sumatra Province (red polygon) located in the southern part of Sumatra Island with total area around 91,592.43 km^2

integration from various sample points in order to estimate cell values (Masroor et al. 2020; Rendana et al. 2022b). Greater weight values indicate the nearest to target point. $Z(S_o)$ or the unknown value, S_o is computed using a formula as specified below:

$$Z(S_o) = \sum_{i=1}^{n} W_{\mathrm{i}} Z(S_{\mathrm{i}}), \tag{1}$$

where n is the observation station, $Z(S_{\mathrm{i}})$ means values at the sampled point S_{i}, while W_{i} indicates S_{i} weight:

$$W_{\mathrm{i}} = \frac{\frac{1}{d_i^k}}{\left(\sum_{i=1}^{n} \frac{1}{d_i^k}\right)} \quad i = 1, 2, \ldots, n, \tag{2}$$

where d_i means a horizontal gap between interpolation points and points studied, and k means a distance power. All interpolation analysis were conducted using the ArcGIS 10.2 software (Esri, USA). The geotiff format of spatial black carbon column mass density was processed using the ArcGIS. In order to create a fine spatial resolution, we converted a raster layer to vector point data and then applied an IDW technique for each black carbon column mass.

HYSPLIT model

Hybrid single particle Lagrangian integrated trajectory (HYSPLIT) is a model that created by NOAA and the Australian Weather Bureau. It is useful to estimate real time and reasonable assessment of air pollutants transport from sources (Ma et al. 2021). It can also predict air pollutants trajectory through diffusion, transport, and transport air masses. It provides various parameters that can be used in the transport model such as various meteorological input and emission sources from distinct clusters. Because of the accuracy and real-time data production, the HYSPLIT has been used to many studies regarding settlement, transport, and diffusion of air pollutants (Kim et al. 2020). The HYSPLIT data are extracted from NCEP global data assimilation system (GDAS) using $0.5° \times 0.5°$ spatial resolution and 1–6 temporal resolution to determine the air masses transport from biomass burning. The black carbon is presumed to be carried with the air mass trajectory without including the impact of deposition, particle size, and emission rate. In this study, 72 and 120 h back trajectory analyses were conducted at 250, 500, and 750 mdpl to predict local and regional air pollutant transport according to prior studies (Sumaryati et al. 2022).

Pearson's correlation

Pearson's correlation coefficients are generally applied to determine the statistic of a linear correlation between two parameters. In order to analyze the association between the black carbon and several meteorological parameters (rainfall, temperature, wind speed, and humidity), the Pearson's correlation was carried out during the study period using IBM SPSS statistics software (version 20). Additionally, the association between the concentration of the black carbon and its corresponding fire events was deeply examined. The Pearson's correlation formula is shown in the following equation:

$$r = \frac{\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}, \quad (3)$$

where r is Pearson's correlation coefficient, n is total number of values, x is values in the first set of data, and y is values in the second set of data. This study used remote sensing and supporting data to produce spatiotemporal black carbon concentration in the study area. Those data then were integrated using the pearson correlation anaylsis to check the accuracy of study. Hysplit model and GIS technique were applied to assess black carbon distribution comprehensively. The details of flowchart of this study are shown in Fig. 2.

Results and discussion

Yearly distributions of black carbon pollution in South Sumatra related to land fires

Figure 3 depicted the annual mean concentration of black carbon in South Sumatra from 2016 to 2019, as well as the annual total hotspots in South Sumatra. The figure showed that high fire events in the study site were recorded in 2019, while 2016, 2017, and 2018 were distinguished by low fire events. It was obviously found that the variation in black carbon concentration in this area corresponded to the hotspot variation. A correlation analysis obtained a positive association between black carbon concentrations and fire events in South Sumatra with an r value of 0.80 ($p < 0.05$) (Table 1). Based on the trend in Fig. 3, we could calculate the rate of black carbon concentration change corresponding to fire event changes, so we obtained 0.63×10^{-6} kg/m^2 per 1,000 fire events.

Figure 4 depicts the spatial variations of black carbon concentrations during a severe haze event (October–December 2019). High concentrations ($> 4 \times 10^{-6}$ kg/m^2) were mostly observed in the north-west part of the study area and spread toward the center, while low concentrations were found in the southern side, where human activity origins of black carbon were less. This result was much higher than a previous study by Mulyana (2017) who found the black carbon concentration ranged from 2 to 3×10^{-6} kg/m^2. Furthermore, this study also showed that the high black carbon concentration was more observed in the center and north part of the South Sumatra Region as we found in our study. If we compared to a study in New Delhi, India, the black carbon concentration in the South Sumatra also showed a notable higher concentration than that city which obtained the black carbon value around 1.5×10^{-6} kg/m^2 (Chauhan et al. 2023).

According to Fig. 4, the black carbon became more concentrated in the center of South Sumatra, causing Palembang, the capital city, to experience a severe haze event during November 2019. This black carbon anomaly dispersed to other nearby areas with lower concentrations, with areas on the outskirts of the South Sumatra Region having the lowest concentration. Finally, because this area had begun to receive a lot of rainfall, black carbon concentrations significantly decreased in December 2019. We conducted a correlation analysis between black carbon concentration and wind speed because this dynamic variation was closely related to wind condition. The obtained correlation coefficient value was $r = -0.85$, $p < 0.01$ (Table 1), indicating that lower wind speed contributes to higher accumulated black carbon concentration in the area.

We assumed there were anthropogenic sources of black carbon in the western part of the study area because biomass burning was the main source of black carbon in the northern and eastern parts of the study area, which came from peatland (Fig. 4). So, not all black carbon emissions came from biomass burning activities; some could also originate from other anthropogenic sources around the study area. As a whole, the spatial variation of black carbon over the study area was dynamic because it quickly shifted from one area to other areas in a 1-month interval (Fig. 4). Although it was

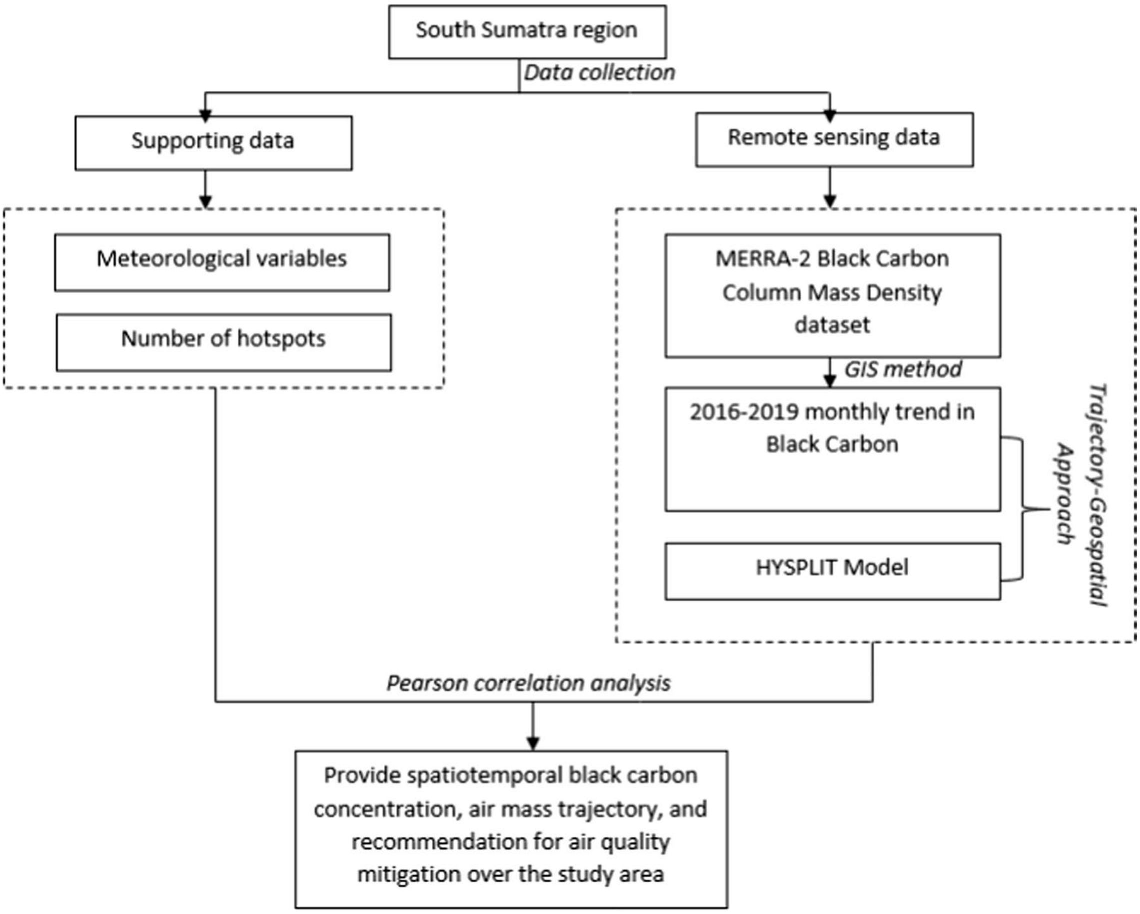

Fig. 2 Flowchart of the study

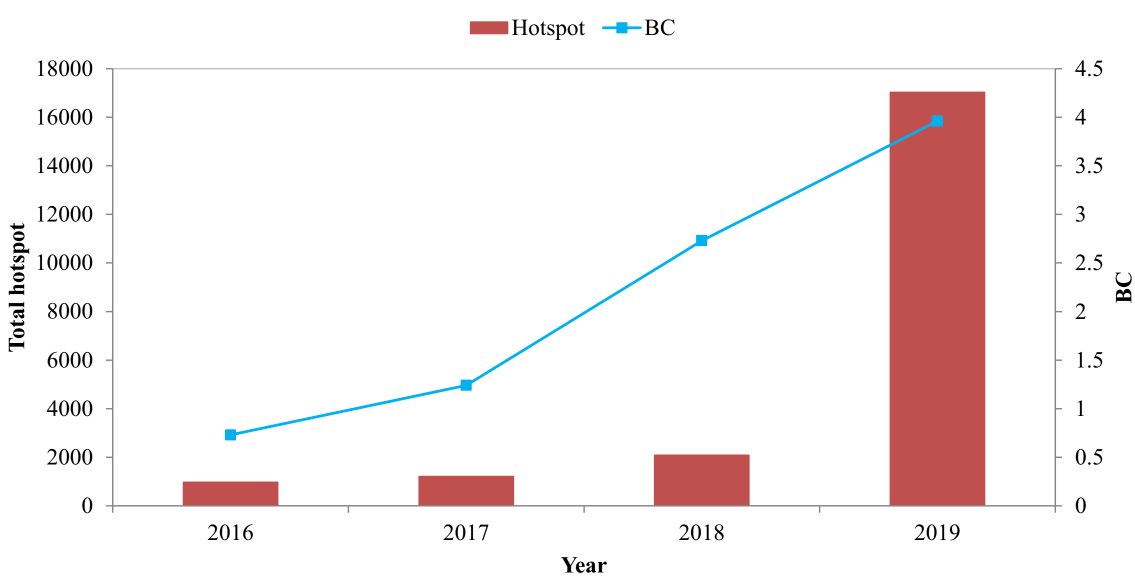

Fig. 3 Totals of hotspot and mean BC (black carbon) concentration in the study area during 2016–2019. (black carbon unit: $\times 10^{-6}$ kg/m^2)

Table 1 Pearson's correlation coefficient between black carbon concentration and meteorological variables

	Black carbon ($\times 10^{-6}$ kg/m^2)
Temperature (°C)	−0.15
Rainfall (mm)	0.18
Relative humidity (%)	−0.25
Wind speed (m/s)	−0.85*
Total fire events	0.80*

*Correlation is significant at 5%

dynamic, the mean concentration continuously decreased from October through December 2019. The enhanced black carbon concentration in South Sumatra during 2019 could be related to the increasing number of hotspots and total burned areas in South Sumatra (Fig. 3). These occasions have contributed to a higher black carbon level through regional land fire events and long-range transport pollutants from black carbon sources. The percentage changes in black carbon concentration from 2016 to 2019 increased around 139% (Table 2). In comparison, when we look at data from 2019, the percentage changes in black carbon concentration decreased by around 72%. This result was consistent with the total hotspots in the study area from 2016 to 2019 (Fig. 5).

The long-distance transport of black carbon amounts in the air over South Sumatra during the 2019 severe haze event

The backward trajectory of air masses reached in Palembang, the capital city, on October 14, 2019, revealed that three trajectories traversed in the midst of severe land fires in the eastern part of South Sumatra (Fig. 6). As a result, the increase in black carbon in Palembang on October 14, 2019, could be attributed to local transport of black carbon from eastern peatland fires. Further, the backward trajectory showed that the air masses arrived in Palembang city from areas distinguished by a high level of human air pollution by black carbon, which are situated in other long-range regions such as east Java, east Nusa Tenggara, and other eastern regions of Indonesia. As a result, the highest levels of black carbon concentration on October 14 may be related to air masses that arrived in Palembang City from those areas. Three types of trajectories in Fig. 6 were indicated by distinct colors. The red line represented most of the air masses traversed at 250 m, the blue line at 500 m, and the green line at 750 m. But basically, these three trajectories showed the same direction. In addition, for long-range transport, the blue trajectory first came from a higher altitude around 1,500–2,000 m, which it observed on October 10, 2019, and then, it started to move at a lower altitude (500 m) on October 11, 2019 (Fig. 6). Other trajectories revealed more of the typical way air masses transport. Because air masses at higher altitudes are more stable, they may be capable of long-distance transport to other regions (Kang et al. 2019). Based on the comparison of local and long-range transport of air masses, it could be assumed that the accumulative black carbon concentration traversed over peatland forest fires in South Sumatra exceeded the trajectory from the eastern region of Indonesia.

Spatial and temporal variations of hotspots in the South Sumatra Region in the dry season of 2019 (Fig. 7) showed the existence of two groups of land fires: the first on the eastern side and the second on the northern side, which were based on the peatland distribution in the South Sumatra Region. The data report from the Ministry of Environment and Forestry on October 14, 2019, noted that the total number of hotspots on the eastern side was 2–3 times greater than hotspots on the northern side (Fig. 7). This was due to the fact that the majority of peatland in the country's east has been converted into agricultural land (i.e., oil palm), which is frequently intentionally burned by humans to reduce the cost of replanting. While, in the northern region, the peatland areas are threatened by opening land activities for the agricultural sector, The highest black carbon concentration in the dry season was recorded in October 2019 (3.96×10^{-6} kg/m^2). This value was much exceeded (3 times greater) as compared with the previous years, which only recorded 1.24×10^{-6} kg/m^2 during 2016–2018 (Table 2). The increment in local black carbon amounts during 2019 was more substantial. This result was much higher than the black carbon concentration in Northern Eurasia that was induced by Sirebian forest wildfires, with an average value of 1×10^{-6} kg/m^2 (Sitnov et al. 2020). But, if we compared our result to other regional studies, we found almost the same result where the black carbon level in adjacent provinces exceeded 2×10^{-6} kg/m^2.

The northern and eastern parts of the study area, toward the center, had the highest concentration of black carbon, according to spatial analysis. Based on the trajectory analysis, the air masses first originated in the eastern areas, where they might be dispersed by the wind to the northern side. The prolonged dry season increased air temperature in South Sumatra from 2016 to 2019 (Fig. 8). Lack of rainfall contributed to a severe drought condition and then raised the risk of intense land fire occurrences. Several studies have shown that atmospheric blocking can affect long-distance transport of air masses such as biomass burning particulates (Steinfeld and Pfahl 2019). The air pollutants could be transported in a zonal or southerly direction (Lawrence and Lelieveld 2010). The wind direction and speed affected the long-range transport of pollutants in the air of South Sumatra in October 2019. The east wind dominated the entire

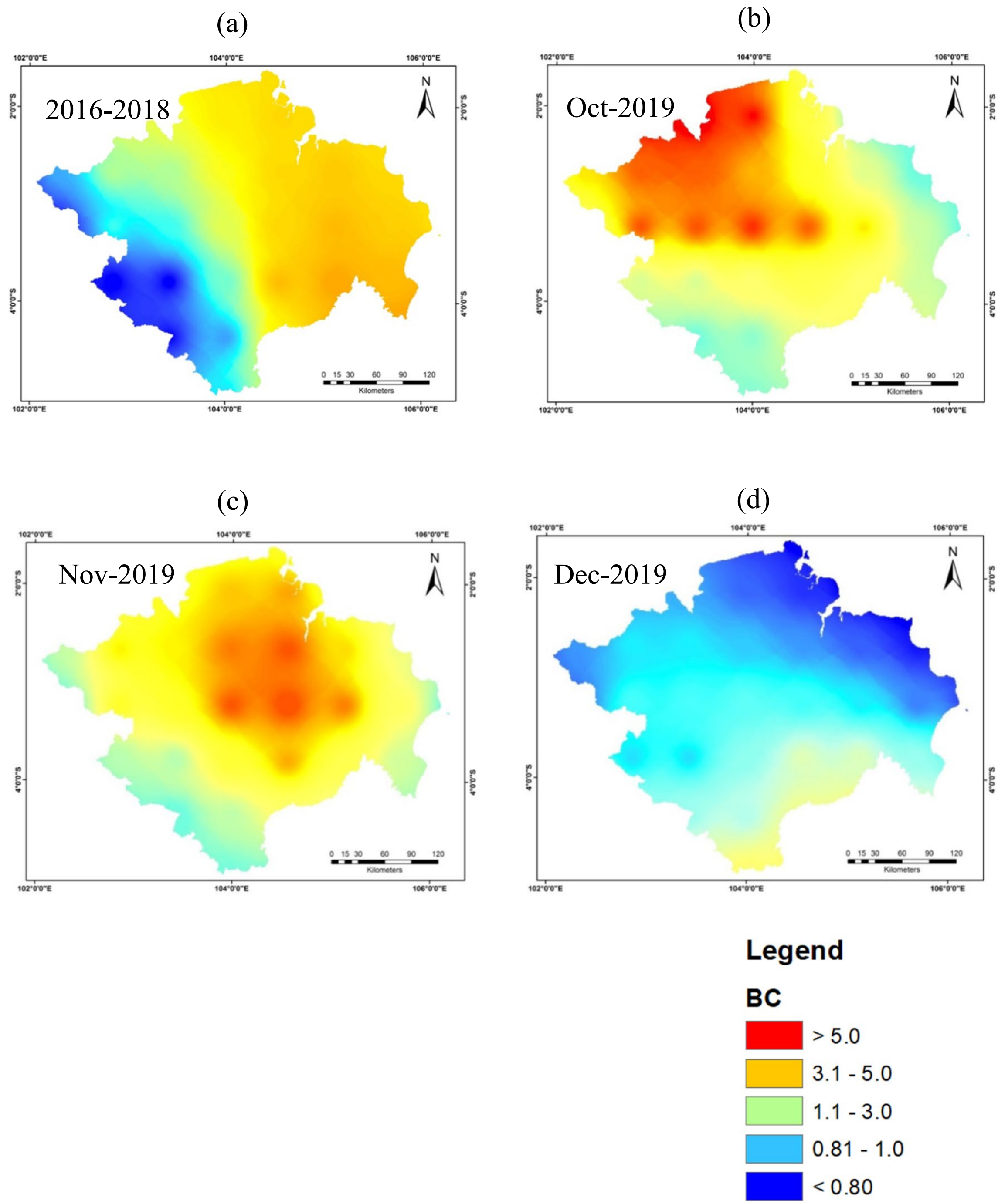

Fig. 4 Spatial variation of the BC (black carbon) column mass density (unit: $\times 10^{-6}$ kg/m.^{2}) in South Sumatra Region during the study period: **a** during 2016–2018, **b** October 2019, **c** November 2019, and **d** December 2019

Table 2 Percentage changes of the mean black carbon concentration during the study period

	2016–2018	Oct0ber 2019	November 2019	December 2019	Changes% (2016–2019)	Changes% (October–December 2019)
Black carbon ($\times 10^{-6}$ kg/m^{2})	1.24	3.96	3.84	1.12	+ 139	− 72

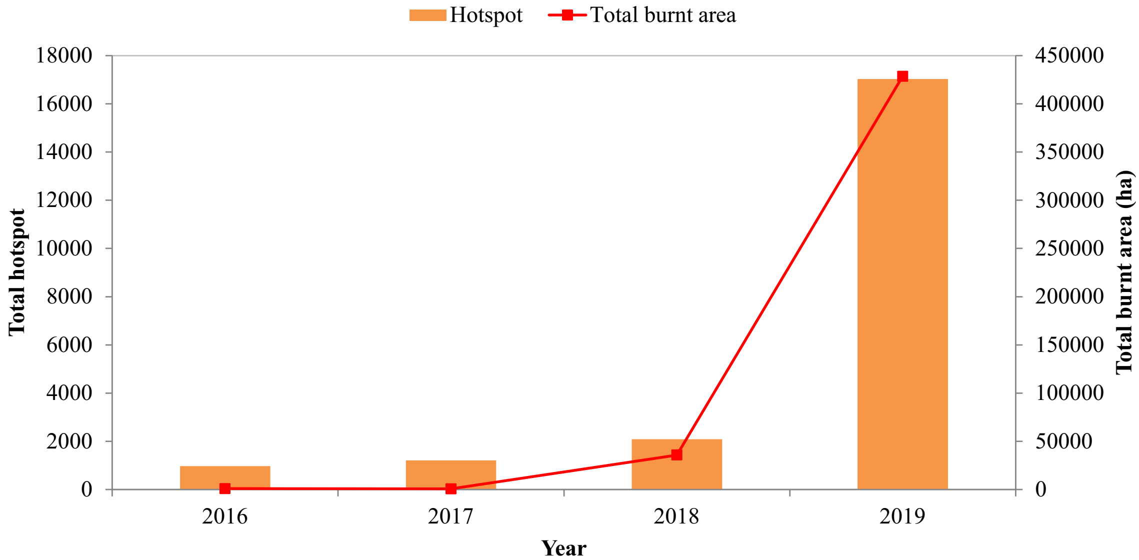

Fig. 5 Totals of hotspot and burnt areas over the study site during 2016–2019

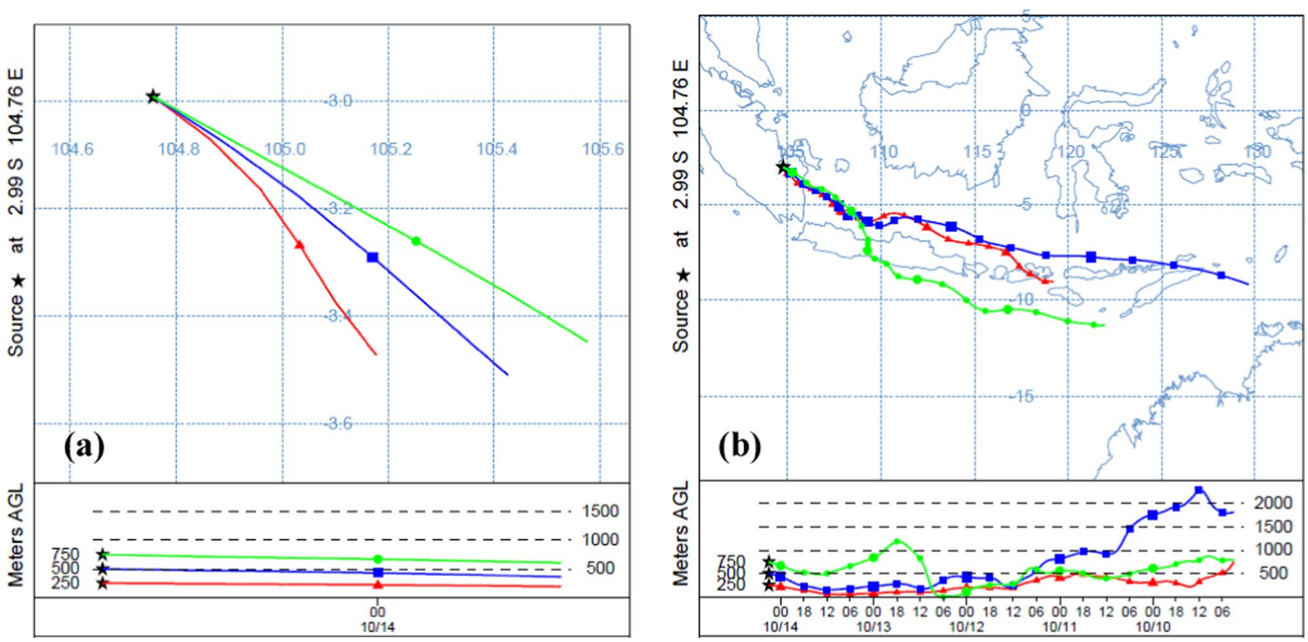

Fig. 6 Backward trajectories analysis in the study area on October 14, 2019, at various height of 250, 500, and 750 mdpl: **a** a local trajectory arriving and **b** a regional trajectory arriving

troposphere layer, according to trajectory analysis. It showed that black carbon transfer from east to west in South Sumatra during the 2019 dry season occurred frequently in the lower troposphere zone.

The black carbon obtained a negative relationship with all the meteorological variables, except for the atmospheric temperature (Table 1). Sahin et al. (2020) assessed the relationship between black carbon and the similar meteorological variables and found same outputs. The rainfall had a prominent effect of diminishing the particles of black carbon, while an increase in wind speed assisted in the black carbon dispersion. Based on a study by Kumar et al. (2023), the black carbon and wind speed were very anti-associated, regardless the various time (by day or seasonal). In addition, the black carbon showed a negative association with temperature in an urban area studies (Ambade et al.

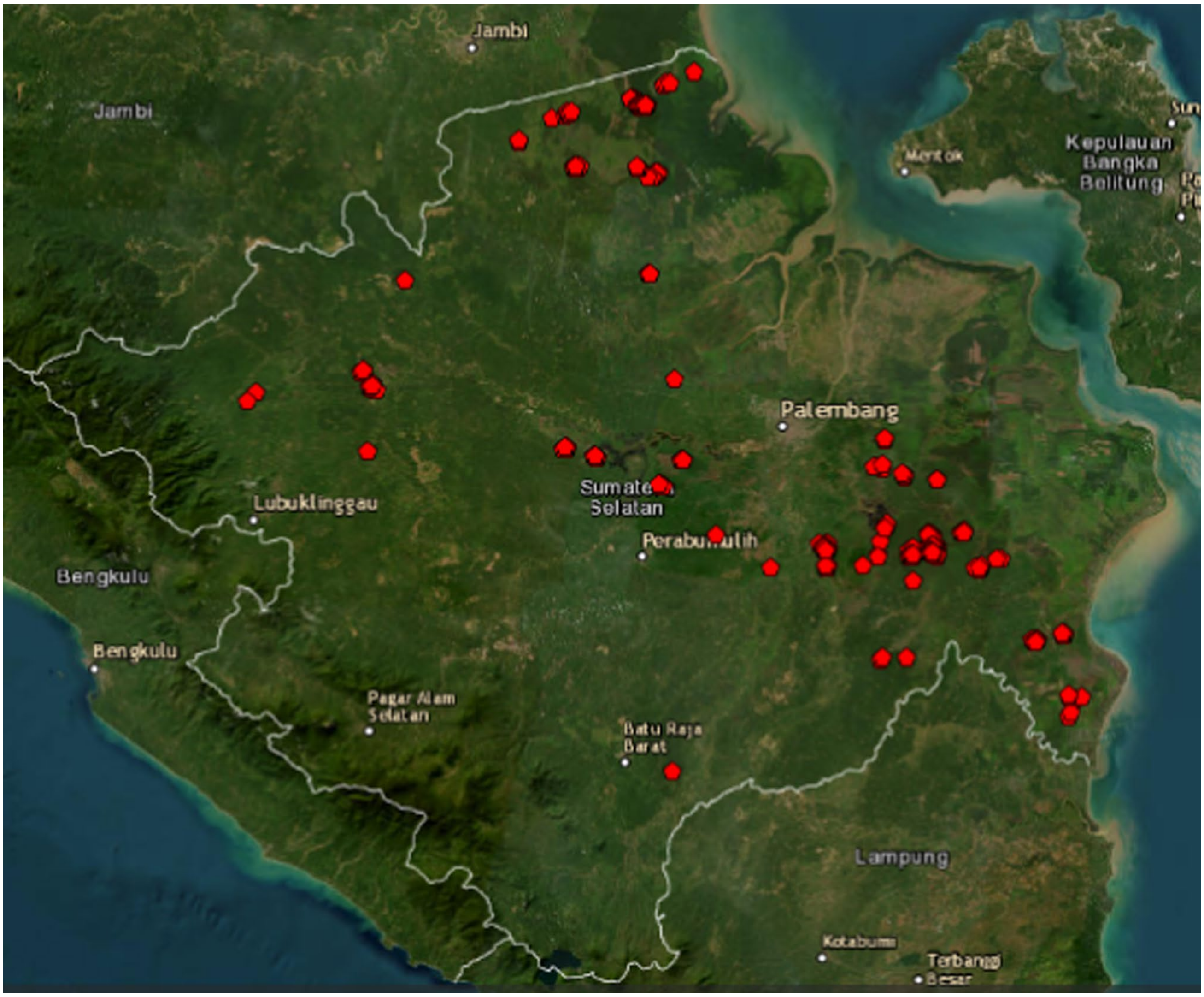

Fig. 7 Active fires distributions in the study area. Red dot indicates active fire events on the date of October 14, 2019, during severe haze event period. Source from Indonesian Ministry of Environment and Forestry

2021; Liakakou et al. 2020), but a low positive association was reported in this current study.

Conclusions

An assessment of the spatial and temporal patterns has obtained a high level of black carbon pollution within South Sumatra in October 2019, which was caused by black carbon emissions associated with peatland fire events in the eastern part of Sumatra and contributed to local transport of black carbon from the eastern region toward the center and northern parts. The analysis of air masses' trajectories obtained the black carbon transport in the study area on October 14, 2019. This first came from local air transport and long-range air transport with various altitudes (250–750 m). On October 10, 2019, the black carbon concentration from other sources in the eastern regions of Indonesia was distributed westward into the Sumatra Region. From 2016 to 2019, the increase in the black carbon plume over South Sumatra Region corresponded to higher temperatures and an increase in the total number of hotspots and burned area around this region. Because of the limitation of study area and monitoring techniques, there is a lack of black carbon ground monitoring dataset. Therefore, the evaluation of MERRA-2 black carbon was validated by the ground black carbon monitoring acquired from the published literatures. For future studies, we suggest to use hyperspectral satellite images or active sensors to compare with MERRA-2 black carbon concentration; thus, it can produce a new notion regarding the accuracy of the black carbon studies over a certain area.

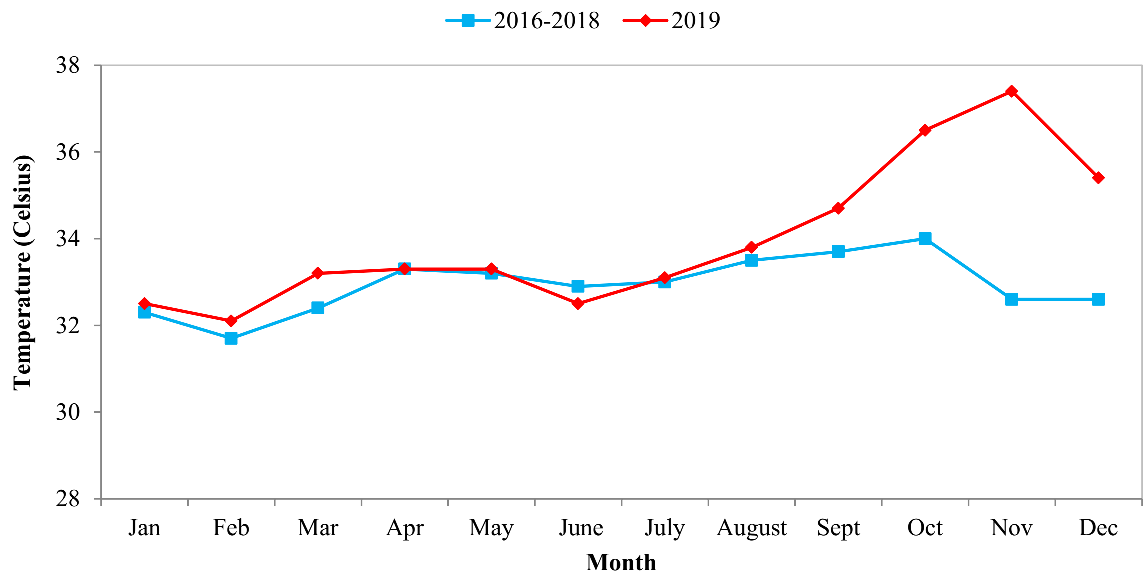

Fig. 8 Temperature variaton over the study area during **a** 2016–2018 and **b** 2019

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no confict of interest.

References

Ambade B, Sankar TK, Panicker AS, Gautam AS, Gautam S (2021) Characterization, seasonal variation, source apportionment and health risk assessment of black carbon over an urban region of East India. Urban Climate 38:100896

Brewer TL (2019) Black carbon emissions and regulatory policies in transportation. Energy Policy 129:1047–1055

Chauhan A, Gupta SK, Liou YA (2023) Rising surface ozone due to anthropogenic activities and its impact on COVID-19 related deaths in Delhi, India. Heliyon 9(4):e14975

Guo B, Wang Y, Zhang X, Che H, Ming J, Yi Z (2020) Long-Term variation of black carbon aerosol in China based on revised aethalometer monitoring data. Atmosphere 11(7):684

Kang H, Zhu B, Gao J, He Y, Wang H, Su J, Yu B (2019) Potential impacts of cold frontal passage on air quality over the Yangtze River Delta, China. Atmos Chem Phys 19(6):3673–3685

Kim HC, Chai T, Stein A, Kondragunta S (2020) Inverse modeling of fire emissions constrained by smoke plume transport using HYSPLIT dispersion model and geostationary satellite observations. Atmos Chem Phys 20(17):10259–10277

Kirrane EF, Luben TJ, Benson A, Owens EO, Sacks JD, Dutton SJ, Nichols JL (2019) A systematic review of cardiovascular responses associated with ambient black carbon and fine particulate matter. Environ International 127:305–316

Kumar P, Beig G, Singh V, Sahu SK, Siingh D, Bamniya BR (2023) Model simulation of carbonaceous fine particulate matter using SAFAR emission inventory and comparison with EDGAR-HTAP simulations. Atmos Environ 315:120147

Lawrence MG, Lelieveld J (2010) Atmospheric pollutant outflow from southern Asia: a review. Atmos Chem Phys 10(22):11017–11096

Lestari, S., Winarno, B., Premono, B. T., Syabana, T. A. A., Azwar, F., Sakuntaladewi, N., Jalilov, S. (2021, November). Opportunities and challenges for land use-based peatland restoration in Kayu Labu Village, South Sumatra, Indonesia. In IOP Conference Series: Earth and Environmental Science (Vol. 917, No. 1, p. 012021). IOP Publishing.

Li Y, Chen W, Zhang Y, Tao C, Xiao R, Tan Y (2020) Accurate cloud detection in high-resolution remote sensing imagery by weakly supervised deep learning. Remote Sens Environ 250:112045

Liakakou E, Stavroulas I, Kaskaoutis DG, Grivas G, Paraskevopoulou D, Dumka UC, Mihalopoulos N (2020) Long-term variability, source apportionment and spectral properties of black carbon at an urban background site in Athens Greece. Atmos Environ 222:117137

Ma Y, Wang M, Wang S, Wang Y, Feng L, Wu K (2021) Air pollutant emission characteristics and HYSPLIT model analysis during heating period in Shenyang, China. Environ Monit Assess 193:1–14

Masroor K, Fanaei F, Yousefi S, Raeesi M, Abbaslou H, Shahsavani A, Hadei M (2020) Spatial modelling of PM2. 5 concentrations in Tehran using Kriging and inverse distance weighting (IDW) methods. J Air Pollu Health 5(2):89–96

Mulyana E (2017) Penyebaran polutan dalam kasus kebakaran hutan dan lahan di sumatera selatan tahun 2015. J Sains Teknologi Modifikasi Cuaca 18(2):61–67

Ramanathan V, Carmichael G (2008) Global and regional climate changes due to black carbon. Nat Geosci 1(4):221–227

Rendana M, Rahim SA, Idris WMR, Lihan T, Rahman ZA (2016) Mapping nutrient status in oil palm plantation using geographic information system. Asian J Agric Res 10(3):144–153

Rendana M, Idris WMR, Rahim SA (2022a) Changes in air quality during and after large-scale social restriction periods in Jakarta city. Indonesia Acta Geophysica 70(5):2161–2169

Rendana, M., Razi Idris, W. M., & Rahim, S. A. (2022b). Effect of COVID-19 movement control order policy on water quality changes in Sungai Langat, Selangor, Malaysia within distinct land use areas.

Rospiani D, Lifianthi DWS (2022) Analysis of the sustainability of oil palm farming on plasma farmers in sungai lilin district Musi

Banyuasin Regency South Sumatra Province Indonesia. J Positive School Psychol 6(3):3503–3512
Şahin ÜA, Onat B, Akın Ö, Ayvaz C, Uzun B, Mangır N, Harrison RM (2020) Temporal variations of atmospheric black carbon and its relation to other pollutants and meteorological factors at an urban traffic site in Istanbul. Atmos Pollu Res 11(7):1051–1062
Santoso M, Hopke PK, Hidayat A (2008) Sources identification of the atmospheric aerosol at urban and suburban sites in Indonesia by positive matrix factorization. Sci Total Environ 397(1–3):229–237
Sarmiasih M, Pratama PY (2019) The problematics mitigation of forest and land fire district (Kerhutla) in policy perspective (a case study: Kalimantan and Sumatra in Period 2015–2019). J Governance Public Policy 6(3):270–292
Sattar, Y., Rashid, M., Ramli, M., & Sabariah, B. (2014, February). Black carbon and elemental concentration of ambient particulate matter in Makassar Indonesia. In IOP Conference Series: Earth and Environmental Science (Vol. 18, No. 1, p. 012099). IOP Publishing.
Sitnov SA, Mokhov II, Likhosherstova AA (2020) Exploring large-scale black-carbon air pollution over Northern Eurasia in summer 2016 using MERRA-2 reanalysis data. Atmos Res 235:104763
Steinfeld D, Pfahl S (2019) The role of latent heating in atmospheric blocking dynamics: a global climatology. Clim Dyn 53(9):6159–6180
Sumaryati, Andarini, D. F., Cholianawati, N., & Indrawati, A. (2022, September). Smoke Propagation During Fire in Kalimantan and Sumatra in 2015 and 2019. In Proceedings of the International Conference on Radioscience, Equatorial Atmospheric Science and Environment and Humanosphere Science, 2021 (pp. 145–157). Singapore: Springer Nature Singapore.
Takemura T, Suzuki K (2019) Weak global warming mitigation by reducing black carbon emissions. Sci Rep 9(1):1–6
Xie X, Myhre G, Liu X, Li X, Shi Z, Wang H, Liu Y (2020) Distinct responses of Asian summer monsoon to black carbon aerosols and greenhouse gases. Atmos Chem Phys 20(20):11823–11839
Xu L, Zhang J, Sun X, Xu S, Shan M, Yuan Q, Li W (2020) Variation in concentration and sources of black carbon in a megacity of China during the COVID-19 pandemic. Geophys Res Letters 47(23):e2020GL090444
Yamineva Y, Liu Z (2019) Cleaning the air, protecting the climate: policy, legal and institutional nexus to reduce black carbon emissions in China. Environ Sci Policy 95:1–10
Yin S, Wang X, Guo M, Santoso H, Guan H (2020) The abnormal change of air quality and air pollutants induced by the forest fire in Sumatra and Borneo in 2015. Atmos Res 243:105027