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Spatio-temporal variability of urban surface temperature during COVID-19 pandemic: A study from some selected cities in Indonesia and Singapore

Suhadi Purwantara[1]
Departemen Pendidikan Geografi, Universitas Negeri Yogyakarta, Indonesia

Arif Ashari
Departemen Pendidikan Geografi, Universitas Negeri Yogyakarta, Indonesia

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Abstract: *Regarding the COVID-19 outbreak, various countries have implemented strict restrictions on community activities to prevent the spread of this outbreak. This restrictions have a positive impact on the environment, especially the improvement of Land Surface Temperature (LST) and Surface Air Temperature (SAT). In this paper, the Spatio-temporal variation of LST and SAT in several cities of Indonesia and Singapore is investigated. This study utilizes secondary data from government data and the interpretation of remote sensing imagery. The data were analyzed using remote sensing and statistical analysis using an independent sample t-test. The results of this study indicate that LST in five cities decreased during the period of restriction of community activities. It can be seen from the average value of LST during the pandemic that it was lower than the same period in the previous year. The decline of LST in the zones of industrial activity centers, services, and commuter lines shows the effect of reduced transportation and industry. Meanwhile, the SAT in five cities did not show any difference from the same period in the previous year. The geographical characteristics of these cities in the archipelago are estimated to have contributed to the strong influence of the sea in stabilizing the SAT. In summary, this study provides alternative information on the impact of restrictions on community activities during the pandemic on LST and SAT in Southeast Asia. This study also presents new insights on the implications of the pandemic on the environment in the tropical island region cities.*

Keywords: *COVID-19 pandemic; Indonesia; Singapore; Urban surface temperature*

Introduction

The COVID-19 outbreak was first reported to occur in Wuhan in December 2019 (Kim & Castro, 2020; Santos, 2020), then developed into an epidemic in mainland China from January 16 to February 6, 2020 (Kang et al., 2020). In subsequent developments, this outbreak spreads to various countries quickly. On March 11, 2020, WHO declared this outbreak a pandemic (Chaudhry et al., 2020; Giuliani et al., 2020; Islam et al., 2021; Parry

[1] Korespondensi Penulis: Departemen Pendidikan Geografi, Universitas Negeri Yogyakarta, Indonesia
Email: suhadi_p@uny.ac.id

& Gordon, 2021) and even proclaimed it as the latest Public Health Emergency of International Concern (Parida, Bar, Roberts, et al., 2021a). In July 2021, COVID-19 impacted 223 countries, including Indonesia and Singapore, in the Southeast Asia Region. WHO data on July 29, 2021 showed that there have been 195 million confirmed cases worldwide with 4.1 million deaths. Southeast Asia is included in the top three, with the highest number of cases and deaths.

Various efforts have been made to stop the spread of the virus that has developed into multiple variants and end the pandemic. One way is to lockdown to limit people's mobility and activities. Mobility restrictions in Indonesia have been implemented several times between April 2020 and July 2021. These restrictions are imposed in all provinces, the islands of Java and Bali, the National Capital Territory of Jakarta, and even on the micro-scale. Meanwhile, in Singapore, the rapid response was carried out in various forms, including implementing strict health regulations and restrictions on mobility (Ansah et al., 2021). The quick response to the situation in Wuhan reduced the death to a deficient level in July 2020 (Abdullah & Kim, 2020).

Restrictions on people's mobility during the COVID-19 pandemic, on the other hand, have positive impacts on improving environmental quality. Studies conducted in various countries show that lockdowns reduce electricity demand, fuel supply, and demand for coal fuel (Mousazadeh et al., 2021). Different air, water, soil, and noise pollutants also show signs of a significant decrease (Loh et al., 2021). The reduced mobility of the people leads to a reduction in emissions from the transportation sector. Air quality is an aspect that was greatly improved during the lockdown with the decrease of various pollutants and aerosols as well as the increase in ozone concentration (Srivastava, 2021). Many studies have shown the positive impact of lockdowns on improving urban air quality worldwide (Faridi et al., 2021; Gayen et al., 2021; Kumari & Toshniwal, 2020; Prakash et al., 2021). Few studies have analyzed or provided recommendations to learn more about the climatic implications of reducing pollutants and aerosols during lockdowns (Ching & Kajino, 2020; Forster et al., 2020; Nakajima et al., 2021; Usman et al., 2021). This topic is exciting to study further, including in Southeast Asian cities that are vulnerable to the spread of COVID-19 and experiencing a significant reduction in aerosols due to the lockdown (Parida, Bar, Roberts, et al., 2021b).

Emissions from transportation are known to be the leading cause of urban heat islands, following changes in urban albedo due to land use conversion and industry. In this regard, the reduction in emissions that occurred during the lockdown should also positively impact reducing urban temperatures. This assumption was confirmed by the results of studies from various regions. A survey conducted by Kenawi et al. (2021) in 21 major Middle Eastern cities showed that during the lockdown, there was a decrease in atmospheric pollutant concentrations. In metropolitan cities, this decrease is more pronounced than in megacities. As a result, there is a decrease in the surface urban heat island, especially at night. Another study from Tehran (Roshan et al., 2021) also confirmed that the air temperature during the lockdown period from March 20 – April 20, 2020, was lower than the average air temperature from 1950-2020.

The same conditions were also found in Pakistan during the lockdown period from March 23 – April 15, 2020 (Ali et al., 2021), the United Arab Emirates from March 1 – June 30, 2020 (Alqasemi et al., 2021a), India from March-May 2020 (Pal et al., 2021; Parida, Bar, Roberts, et al., 2021b), and China (Cai et al., 2021). Learning from this experience, many studies recommend lockdown as a solution to improve air quality in urban areas (Alqasemi et al., 2021b). Lockdown offers an opportunity to examine the impact of reduced heat emitted from surface transportations and the reduction of air pollutants on land surface temperature (Parida, Bar, Roberts, et al., 2021b).

Indonesia and Singapore are countries in the Southeast Asia region that have implemented a policy of limiting people's activities to suppress the spread of the pandemic. Various cities in the area have varying demographic characteristics and population activities. It is interesting to study further the impact of limiting people's activities on LST and SAT. In this study, Singapore and four cities in Indonesia were selected, namely Jakarta, Surabaya, Bandung, and Yogyakarta. All cities in Indonesia are located in Java, which is the most affected by the policy of limiting people's activities. In addition, each city has various physical and socio-cultural characteristics. Spatio-temporal variations in meteorological conditions and air quality can be studied in more depth from various cities in this region during the pandemic, as a result of the restrictions on people's activities.

In this paper, we describe variations of Spatio-temporal land surface temperature and surface air temperature in several cities in Indonesia and Singapore during the pandemic. The condition is seen from the perspective of the impact of the COVID-19 pandemic, which is a result of the reduced people's mobility during the implementation of the activity restriction policy by the government. The objectives of this paper are to analyze as follows: (1) land surface temperature in various cities during the COVID-19 pandemic, (2) surface air temperature as indicated by the monthly average temperature, and (3) spatial and temporal variations between cities and between before-after the COVID-19 pandemic. This study intends to explain that the Covid-19 pandemic also affects environmental conditions, especially the air environment. This paper provides alternative information regarding the impact of the pandemic on environmental conditions so that it can be considered in environmental management in post-pandemic urban areas as proposed in other places in various previous studies.

Methods

Study Area

We selected five cities for this study; four are in Indonesia, and Singapore is a city-state on an island. Singapore has an area of 728.6 km2 and a population of 5.7 million. Singapore is an important commercial center in the Southeast Asian region. Meanwhile, the four selected cities in Indonesia were Jakarta, Surabaya, Yogyakarta, and Bandung. Jakarta and Surabaya represented metropolitan cities in lowland areas, Bandung represented metropolitan cities with a mountainous topography, while Yogyakarta represented megacities. Jakarta is the capital city of Indonesia, Surabaya is the capital of East Java Province which is located in lowland and coastal areas, Bandung is the capital of West Java Province which is located in the inter-volcanic basin morphology, while Yogyakarta is the capital of the Yogyakarta Special Region which is located in the plains morphology between the volcanoes and mountains. The entire city is in a monsoon climate region. The distribution of cities used in this study is shown in Figure 1.

Jakarta, Surabaya, and Bandung are cities based on services, trade, and industry. Based on data from the Indonesian Statistical Agency (locally known as Badan Pusat Statistik or BPS), the City of Jakarta has an area of 653.83 km2, with a population in 2020 reaching 10.5 million. The city of Jakarta is the center of the Greater Jakarta metropolitan area, with an area of 11,037.56 km2. Surabaya is the second largest city in Indonesia, with an area of 326.81 km2 and a population in 2020 of 2.8 million. Surabaya is also the center of the metropolis in East Java. Bandung, with an area of 167.31 km2, is the center of the Bandung Raya metropolis. A population of 2.5 million people occupies this city in 2020. The study on megacity was conducted in Yogyakarta. Yogyakarta is a big city with culture, tourism, and education characteristics. Yogyakarta has an area of 32.50 km2 and is occupied by a population of 436.000 people.

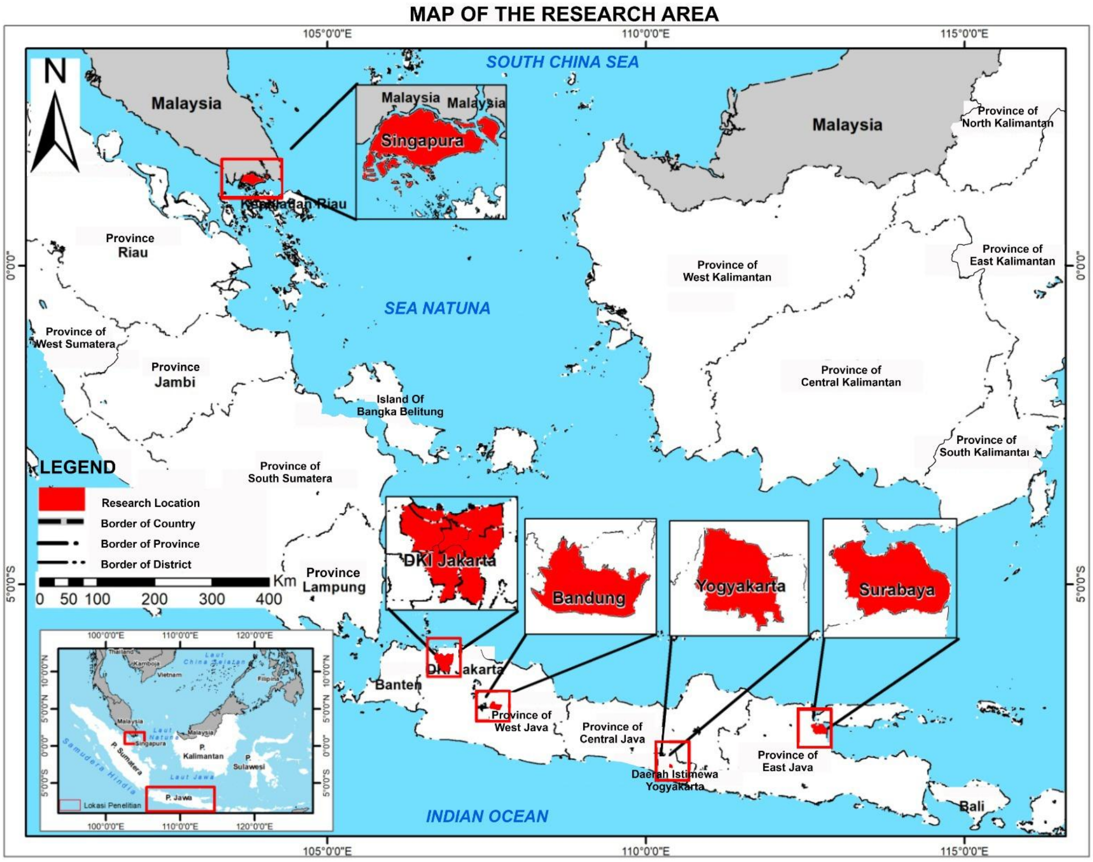


Figure 1. The Study Area

Data collecting techniques and data analysis

This study uses secondary data. Data were obtained from government documents and remote sensing image interpretation. Data on air temperature in Jakarta, Surabaya, Bandung, and Yogyakarta were obtained from the Meteorology, Climatology, and Geophysics Agency of the Republic of Indonesia. Singapore's air temperature data were obtained from the National Meteorological Agency Singapore, published through the Meteorological Service Singapore. Data regarding Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) were obtained from remote sensing image interpretation by processing Landsat 8 OLI/TIRS image. Western Indonesia and Singapore are in a monsoon climate region that recognizes two seasons, the dry and the rainy seasons. In the rainy season, there is a lot of covering clouds. For this reason, LST analyses were carried out using images taken during the dry season from March to October.

Before remote sensing imagery, the image pre-processing stage was carried out, including radiometric and geometric correction. The next step was to perform remote sensing analysis with further image processing to obtain NDVI and LST. The next stage was analyzing the surface temperature value using the Land Surface Temperature (LST) model. The LST value was determined using the thermal line on the atmospherically corrected Landsat 8 TIRS image. Data analysis was also carried out using statistics to show comparisons. The first step was to analyze air temperature conditions in each city between 2019, which represents the period before the pandemic, and 2020 which defines the period after the pandemic. At this stage, a further test analysis was performed using the independent sample t-test. The investigation at this stage showed a comparison between conditions before and after the pandemic in each city.

Results

Land surface temperature during the COVID-19 pandemic

The COVID-19 pandemic has dramatically impacted various aspects of global community life. In the recent period when the pandemic has begun to be controlled, primarily after vaccinations have been implemented around the world, many studies have been conducted to see the positive impacts of this pandemic. Lockdown that impacts the limitations of community activities in open spaces in urban areas affects the land surface temperature, ultimately affecting the surface urban heat island. Previous studies that have been carried out are Parida et al. (2021a) in Europe and North America, Nanda et al. (2021a) in big Indian cities, Firozjaei et al. (2021), who took case studies in Milan and Wuhan, Hadibasyir et al. (2020a) in Wuhan, Sahani et al. (2021a) in Kolkata, and Arrofiqoh and Setyaningrum (2021a) in Yogyakarta. These studies are responses to implementing the lockdown during the pandemic, which has an impact on the possibility of changes in land surface temperature conditions in urban areas.

In this study, we analyze Landsat 8 OLI/TIRS imagery in five cities with samples taken in the driest months, especially those close to the period when restrictions on community activities were imposed in Indonesia and Singapore. The findings of this study indicated a decrease in surface temperature in the five selected cities. The decline in temperature varied between the various cities. Data from satellite images taken on one sample day during the restriction period (or slightly after) showed a lower average ESG than the previous year's period. The most significant decrease was found in Yogyakarta. Among the five cities, there were variations in minimum LST, maximum LST, and average LST between the pre-pandemic period and the pandemic period, especially when restrictions on community activities were imposed. The lowest LST both before and after the pandemic was found in Bandung. This city is located in a basin between mountains with high elevation, so the temperature is relatively low. Meanwhile, the highest LST both before and after the pandemic was found in Surabaya. The city is located on the coast and serves as an industrial center and a base port for many trade shipping routes in eastern Indonesia.

Spatially, the decline in LST also covers a wide area and is spread over the city, not only limited to certain zones. Interestingly, the decrease in LST during this pandemic causes the temperature range in various cities to be lower than in the pre-pandemic period (Table 1). In cities that are metropolitan centers, such as Jakarta, Surabaya, and Bandung, high LST is often found in the city center, while low LST is found in sub-urban areas. Thus, the Urban Heat Island (UHI) in these metropolitan cities tends to decline during the pandemic. Parida et al. (2021a) stated that the lockdown has temporary implications in minimizing the UHI. The findings in this study also show that implementing restrictions on community activities has proven to have an impact on decreasing surface temperature and its spreading pattern. Lessen transportation, and industrial activities reduce emissions to the atmosphere, which affects the amount of heat absorption by the surface as expressed in LST.

Table 1. LST in Five Selected Cities before and during COVID-19 Pandemic

Cities	Min (^{0}C)		Max (^{0}C)		Mean (^{0}C)		Median (^{0}C)		SD (^{0}C)	
	Before	During	Before	During	Before	During	Before	During	Before	During
Jakarta	24,20	23,06	33,59	33,83	28,98	28,55	28,98	28,71	1,62	1,63
Surabaya	22,29	21,48	40,28	39,87	31,28	30,67	37,01	36,42	4,58	4,33
Bandung	15,73	16,82	34,32	32,77	26,62	25,15	28,85	27,33	2,90	2,70
Yogyakarta	23,20	21,74	30,95	27,44	27,03	24,59	27,58	23,86	1,00	0,68
Singapore	21,86	21,46	32,67	31,82	24,95	22,34	23,02	22,34	1,83	1,83

LST in Jakarta in the pre-pandemic period was dominated by temperatures of 29^{0}C to 31^{0}C. This LST has a wide distribution in the Jakarta area and dominates in the southern and eastern parts of the city. The lower LST is scattered in various places, especially in the border areas of Jakarta (Figure 2A). People's mobility seems to have significantly affected LST in Jakarta in the pre-pandemic period. Data from the 2019 commuter survey from the Indonesian Statistical Agency (locally known as Badan Pusat Statistik or BPS) (2019; 2023) shows that South Jakarta is the leading destination for commuters. This commuter movement comes not only from people who live in Jakarta but also from surrounding cities such as Depok, Tangerang, South Tangerang, and Bekasi. The high level of commuting activity influenced the high LST dominance in this region in the pre-pandemic period.

After the pandemic, LST in Jakarta decreased. Data from image processing in April 2020, at the time of the implementation of macro-scale social restriction (locally known as PSBB), show that some parts of Jakarta experienced a decrease in surface temperature even though it was only one or two degrees. The zone experiencing a temperature reduction is the commuter route area along the South and East Jakarta routes. Several locations do not show a decrease in temperature, but these areas are minimal and scattered, especially in downtown Jakarta (Figure 2B). Previously the hottest dominant site, the southern part of the city experienced a spatially significant temperature change. As an area with solid commuting activities, implementing restrictions on community activities has proven to affect reducing land surface temperatures in this area. Reduced anthropogenic emissions from commuting activities lead to lower surface temperatures.

Surabaya also experienced a decline in LST after the pandemic. Spatially, the pattern of decreasing surface temperature in Surabaya is more straightforward than in Jakarta. Image analysis for October 2019 shows that the highest surface temperatures are found in the city center with an expansion to the north and south. The northern part of Surabaya is the port area of Tanjung Perak, so it has busy transportation activities. This port is the base port that serves the most shipping routes in Indonesia.

Meanwhile, the southern part of Surabaya is a commuter zone just like Jakarta. Data from BPS (2017a) shows that most commuters in Surabaya come from Sidoarjo Regency, which is in the south. The second commuter zone is west of the city, with commuter flows coming from Gresik Regency. The spatial distribution of surface temperatures shows that high temperatures of 34^{0}C-37^{0}C are found in city centers, ports, and the southern and western commuter zones. The high surface temperature area in the southern part is wider than the western part due to the higher population mobility in this area (Figure 2C).

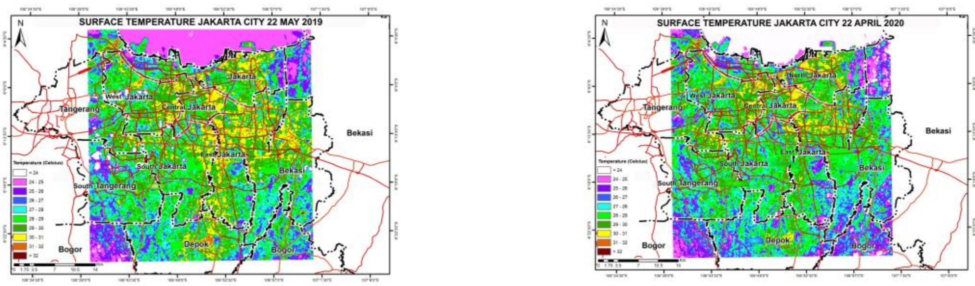
After the pandemic, there was a decrease in surface temperature in Surabaya. Based on image analysis in October 2020, when the transitional PSBB was implemented, there was a decrease in LST in the downtown area and both commuter lines. The reduction in LST was not found in the port area. Meanwhile, on the eastern and western edges, some zones did not experience many ESG changes before and after the pandemic, which were still at 31^{0}C-34^{0}C (Figure 2D). The lowest LST was found in the mangrove area, in the eastern part of Surabaya. This area did not experience changes in surface temperature before and after the pandemic, which was 26^{0}C-29^{0}C. Besides the mangrove vegetation factor, this area is also not a busy transportation zone.

Bandung has different LST characteristics from Jakarta and Surabaya. The May 2019 image analysis results show that the highest surface temperature is found in the city center, with expansion following the pattern of ring roads and main roads. The LST in the city center reaches 31^{0}C and then decreases gradually towards the city's edge. Besides the city center, high surface temperatures are also found in the eastern and northeastern city centers (Figure 2E). All areas with high LST are densely populated and economic activity centers, including industrial, trade, and residential areas. The commuter pattern in Bandung is also different from that of Jakarta and Surabaya. The commuter route, which tends to be dominant on specific routes, as happened in Jakarta and Surabaya, is not found in Bandung. The data of BPS (2017b) shows that most commuters in Bandung come from Cimahi City, which is in the west, and Bandung Regency, which limits Bandung to the south, east, and most of the north. This condition causes commuters to be not concentrated on specific routes but is spread evenly throughout the region.

LST in Bandung experienced a significant decline during the COVID-19 pandemic. The image analysis results in May 2020 showed that after the implementation of PSBB, there was a decrease in surface temperature of up to two degrees. Spatially, surface temperature decreases significantly because it covers a large area. The downtown area and around the city center, previously the highest temperature zone, have experienced a decrease in temperature. The place where the surface temperature remains is minimal (Figure 2F). This condition shows that the restrictions on people's activities during the pandemic affect the decrease in surface temperature in whole parts of the city. The reduction in surface temperature in Bandung is different from Jakarta, which still has several hot zones during the pandemic, and also different from Surabaya, which still has a hot zone around the port area.

Yogyakarta experiences a spatially significant decrease in LST. Compared to other cities in this study, Yogyakarta is a relatively small city with a small population. This city is synonymous with education and tourism activities. Based on the May 2019 image, the highest LST was found in downtown areas, tourist areas, and industrial areas in the southeast. High LST areas were also found in the northern part adjacent to the agglomeration area of universities in Sleman Regency. Outside these two areas, there is a spatial dominance of lower surface temperatures of 27^{0}C-28^{0}C (Figure 2G). During a pandemic, tourism activities cannot operate due to the implementation of restrictions on community activities to stop the spread of COVID-19. The temperature of 30^{0}C, which previously dominated the city center and southeastern part, decreased by three degrees after the PSBB was implemented in April. High-temperature areas are spreading in the central and northern parts of the city. Interestingly, the temperature of the southeast region experienced the most significant decrease (Figure 2H).

The decline in LST during the COVID-19 pandemic also occurs in Singapore. Analysis of pre-pandemic images taken in May 2018 shows that high-temperature zones are found in the West and East regions (Figure 2I). Both of these areas are busy areas with economic activity and transportation. In the pre-pandemic period, many locations were found with a surface temperature of 28^{0}C to 32^{0}C. Meanwhile, the high-temperature zone in the East Region is mainly found around Changi Airport. The COVID-19 pandemic has dramatically impacted the decline in surface temperatures in Singapore. Image analysis for July 2020, after the circuit breaker was implemented from April 7 to June 1, 2020, shows a reduction in high-temperature areas in the West Region. Places in the pre-pandemic period had temperatures of 28^{0}C to 32^{0}C. At this time, it decreases from 26^{0}C to 30^{0}C. The area around Changi Airport, which previously had a temperature of 28^{0}C to 32^{0}C, decreased to 26^{0}C to 30^{0}C (Figure 2J).



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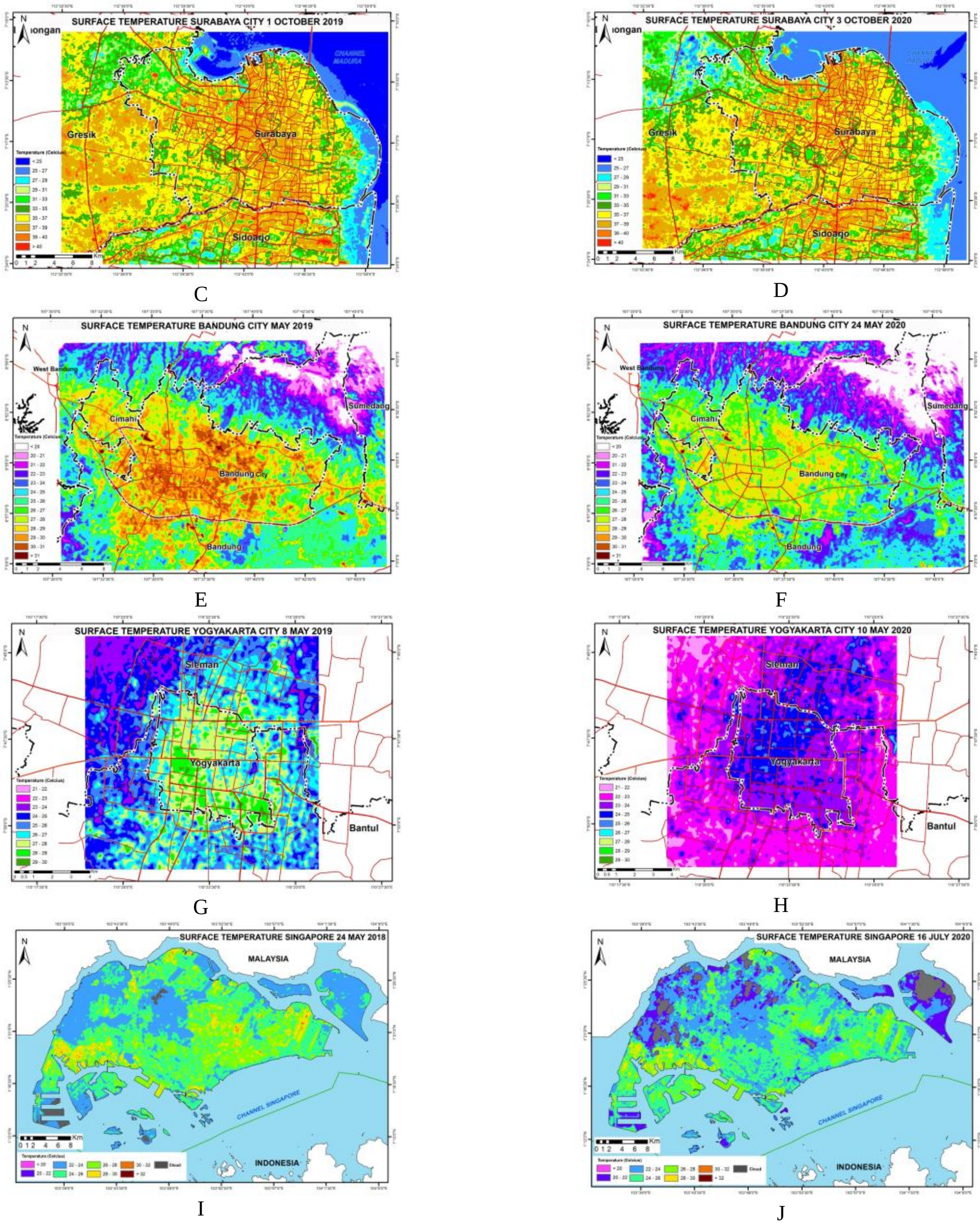
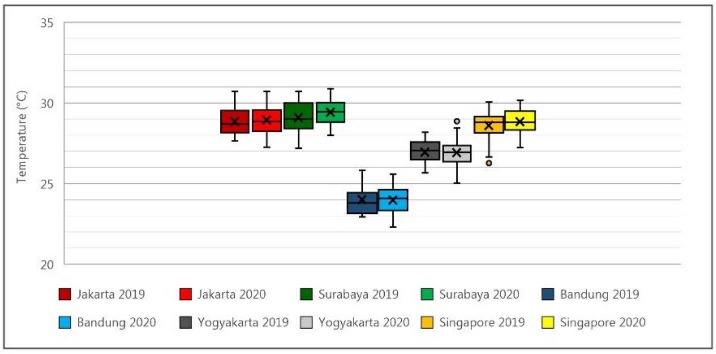


Figure 2. The Spatial distribution of LST in selected cities before and during the pandemic. The images on the left (A, C, E, G, I) show the conditions before the pandemic, and the images on the right (B, D, F, H, J) show the conditions after the pandemic. (A) Jakarta, May 2019, (B) Jakarta, April 2020, (C) Surabaya, October 2019, (D) Surabaya, October 2020, (E) Bandung, May 2019, (F) Bandung, May 2020, (G) Yogyakarta, June 2019, (H) Yogyakarta, May 2020, (I) Singapore, May 2018, (J) Singapore, July 2020.

Surface air temperature during the COVID-19 pandemic

Changes in community activities during the COVID-19 pandemic brought climatic consequences in the form of a decrease in air temperature near the surface. Previous studies have also shown that a decrease in population movement and a reduction in anthropogenic heat emission leads to a drop in air temperature near the surface. In this regard, Parida et al. (2021b) explained the relationship between LST and air temperature; the reduced LST during the lockdown period was corroborated by the negative anomaly of air temperature at ground stations. Aerosol particles, one of which is emitted from burning fossil fuels, significantly affect air quality, weather, and climate by disrupting the earth's radiation budget, cloud properties, and water cycle processes. Anthropogenic emissions, aerosols, and pollutants play an important role in rising temperatures in urban areas.

Based on the independent sample t-test analysis of the measured air temperature at the climatology station in each city, it is known that the surface air temperature before and during the pandemic is relatively the same. Data testing of temperature in four Indonesian cities in April 2020 (when PSBB was implemented), May 2020 (post-PSBB), October 2020 (when transitional-PSBB was implemented), and November 2020 (post- transitional PSBB) showed no significant differences. The air temperature during the PSBB period was higher or lower than before the pandemic. However, this difference was minimal. The same condition was also found in Singapore during the implementation of the circuit breaker in April 2020 and a month after. It did not show a significant temperature difference compared to the previous year's period. An interesting finding is that the monthly temperature range during the pandemic tends to be larger than in the last period (Figure 3).



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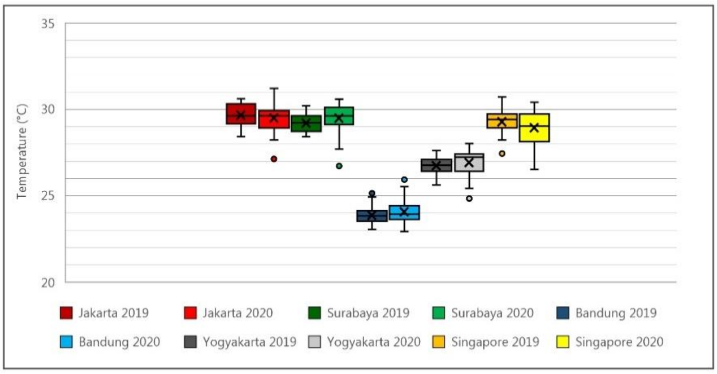

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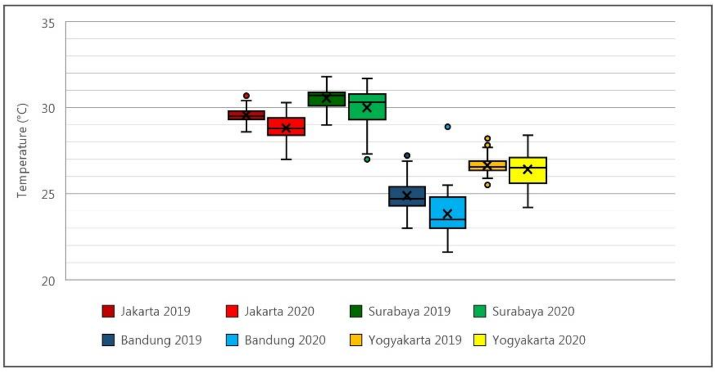

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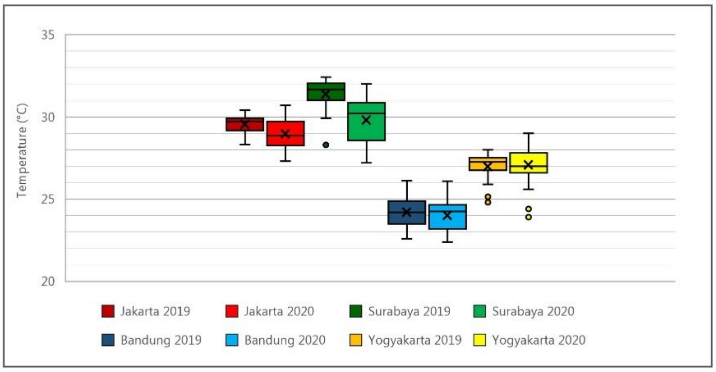

D

Figure 3. Comparison of air temperature during the pandemic in the same period with the previous year. (A) During the implementation of PSBB in Indonesia and circuit breakers in Singapore, (B) Post PSBB and circuit breakers, (C) During PSBB implementation in Indonesia, and (D) Post transitional PSBB.

Discussion

The findings of this study indicate that the COVID-19 pandemic has affected the decline in LST in five cities compared to the previous year. The average LST in five cities during the PSBB period or Transitional-PSBB showed a decrease in magnitude varying from 0.430C to 2.610C. This finding strengthens the results of previous studies showing a reduction in LST during the lockdown period due to the COVID-19 pandemic in various cities in the world, including Europe and North America (Parida, Bar, Kaskaoutis, et al., 2021b), Wuhan (Hadibasyir et al., 2020b; Parida, Bar, Roberts, et al., 2021b), Kolkata (Sahani et al., 2021b), as well as other big cities in India (Nanda et al., 2021b). The four cities in this study are located on the island of Java, Indonesia. Referring to the 2000-2018 Java Island LST study conducted by Susanti et al. (2019a), there are spatial and temporal variations of LST. The developed northern region of Java has a higher LST, especially in big cities. This condition is still happening during the COVID-19 pandemic, where metropolitan areas such as Jakarta and Surabaya have a higher LST than Yogyakarta, a megacity in southern Java, and Bandung, an urban located in the mountainous basin of central Java.

Furthermore, according to their findings, Susanti et al. (2019a) explained that LST in Java also varied according to seasons and was affected by El Nino and La Nina events. LST during high El Nino was high, but when La Nina was low. Based on the season, the highest LST WAs are found at the transition from the dry to the rainy season in September – November. Based on these results, this study is conducted based on satellite images of 2019 and 2020, which are normal years or not included in El Nino and La Nina years. In this normal year, the LST in four cities in Java during the COVID-19 pandemic turned out to be lower than the average LST for those cities between 2000-2018. The average daytime LST in Jakarta and Surabaya, according to Susanti et al. (2019b), ranged from 34-36^{0}C, while the findings of this study during the pandemic showed 28-30^{0}C. As well as for Bandung and Yogyakarta, the average daytime LST in these two cities is 32-34^{0}C compared to the findings of this study, showing 24-25^{0}C.

Another study by Agni et al. (2021) showed the same findings as ours. That is, LST in major Java cities experienced a decline due to social restrictions during the COVID-19 pandemic. The decrease in average LST was even greater than our findings, reaching 2,920C in Jakarta, 1,920C in Surabaya, 1,580C in Bandung, and 3,320C in Yogyakarta. However, this study does not analyze the causes of the decrease in LST during the PSBB period. In our findings, it is known that the decline in transportation and industrial activities is a factor that influences this LST decrease, as evidenced by the spatial distribution of LST with a significant reduction in industrial areas and commuter lines. This study also shows a significant decrease in LST in Yogyakarta. Yogyakarta, a city of culture, education, and tourism, has experienced a substantial reduction in people's activity, so it impacts a significant decline in LST. The same opinion is also proposed by Arrofiqoh and Setyaningrum (2021b) based on the results of their study in Yogyakarta.

In general, the findings of this study indicate several essential things. First, urban LST tends to be low during the pandemic due to changes in people's behavior concerning transportation and industry. The increase in LST during the pandemic in most European cities due to lower attenuation of solar radiation by aerosols (Parida, Bar, Kaskaoutis, et al., 2021b) is not found in this region. In this study, all cities in Indonesia and Singapore are influenced by local climates strongly influenced by the sea in both the hydrological cycle system and cloud characteristics. The location of cities in the inter-tropical convergence zone has a lot of cloud formation that can help reduce solar radiation. Thus, LST variations are more influenced by changes in anthropogenic heat sources. Second, restrictions on transportation and industry have an impact on decreasing LST. Southeast Asian cities with declining emissions (Parida, Bar, Kaskaoutis, et al., 2021b) also experience a decrease in LST. The evidence of this phenomenon is a significant decrease in LST on the Jakarta and Surabaya commuter lines.

Concerning the SAT, it turns out that there is no difference in the SAT between before the pandemic and after the pandemic. This study does not find temperature variations in urban areas due to changes in anthropogenic emissions, aerosols, and pollutants, as presented by Parida et al. (2021a). As well as in the relationship between LST and SAT, it turns out that a lower LST during the pandemic is not followed by a lower SAT as well. This is different from the findings proposed by Nanda et al. (2021b). An interesting result of this study is the nature of the monthly temperature range, which is similar to the daily temperature range found by Hu et al. (2021). During the pandemic, the temperature range is more significant due to the atmospheric conditions that are cleaner than aerosols. A more sterile atmosphere has an impact on the radiation budget. This condition describes the inverse relationship between aerosol presence and air temperature.

Conclusion

Restrictions on people's activities due to the COVID-19 outbreak provide an opportunity to see the positive impact of the pandemic on improving environmental quality. As previously reported by various studies, the COVID-19 outbreak has positively impacted the urban environment, including a decrease in temperature and a reduction in the impact of SUHI. This study has taken a sample of four cities in Indonesia and Singapore, showing that restrictions on people's activities during the pandemic decrease LST. However, this decrease in LST is not followed by a decline in SAT. The local climatology system of this area located in the archipelago around the equator strongly affects the stability of the SAT, instead of only being influenced by changes in the presence of anthropogenic emissions, aerosols, and pollutants in the atmosphere.

As an evaluation, this study has not discussed the combination of the influence of local climate with the variability of anthropogenic emissions, aerosols, and pollutants in influencing SAT during a pandemic. In this regard, several things need to be done in further research. The aspect most recommended being studied in future studies is the combination of various climatic controls with changes in anthropogenic emissions of LST and SAT in urban areas during the pandemic. With the research findings, this study provides alternative information regarding the spatiotemporal variations of LST and SAT in urban Southeast Asia, especially those in the archipelago.

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