Impact of Optical Aerosol Depth (AOD) on Light Pollution Level: a spatio-temporal analysis

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Abstract. Population dynamics and economical, also industrial, in Indonesia are growth as it increasing every years. It brings an environmental problems unconsciously. Increasing the amount of aerosol optical depth (AOD) has a considerable impact, one of them is light pollution increase due to uncontrolled scattering of particles in urban areas. Light pollution is a new problem, it can disturb the balance of the ecosystem. Increasing light pollution on trophosperic surface on the earth can cause the functional damage of natural light in the sky in providing guidance for animal nocturnal animals and human health. The consequence are emergencing problems with ecosystem imbalances that can be a new disasters in the future. Identification of the impact of increasing AOD with light pollution needs to be known to maintain the balance of the ecosystem in the future. Remote sensing has an effective, efficient and able to provide actual data on this problem. MODIS imagery was used as AOD and VIIRS DNB data sources were used for multi-temporal light pollution data in 2014, 2016 and 2018. Both data were then performed correlation tests using Rank Spearment methods and obtained very strong results, 0.8-1. The higher AOD in urban areas, the higher the level of light pollution in the region. Java and Bali have high AOD levels accompanied by high light pollution.

Keyword: VIIRS DNB, MODIS, AOD, light pollution, rank spearment

1. Introduction

The development of remote sensing technology bring a possibility for us to understand the spatial distribution and intensity of artificial night time light (NTL) in various regions of the earth's surface. The two most widely used data sources are DMSP OLS and VIIRS DNB. VIIRS DNB which was released in 2013, as a newer satellite, it shows more improvement and calibration with an automatic filter system that can eliminated stray lights, natural lights, such as fire sources, snow and cloud disruptions automatically. The results of the VIIRS data delivered as daily, monthly or annual data on a large scale (742 x 742 m²). The use of VIIRS data has been widely used in various fields, including demographic analysis, socioeconomic, settlement dynamics, nighttime atmospheric properties, multitemporal changes, and other topics such as light pollution and CO₂ emissions [1].

VIIRS is one of the key environmental remote-sensing instruments onboard the Suomi NPP satellite [2]. The VIIRS instrument observes and collects global satellite observations that span the visible and infrared wavelengths across land, ocean, and atmosphere. A whiskbroom radiometer by design, it has 22 channels ranging from 0.41 μm to 12.01 μm. Five of these channels are high-resolution image bands or I-bands, and sixteen serve as moderate-resolution bands or M-bands. VIIRS also hosts a unique
panchromatic Day/Night band (DNB), which is ultra-sensitive in low-light conditions that allows us to observe nighttime lights with better spatial and temporal resolutions compared to previously provided nighttime lights data by the Defense Meteorological Satellite Program [3]. The VIIRS DNB nightly images are affected by a number of factors including the atmospheric condition, moonlight, snow and clouds [4]. Atmospheric scattering [5] and absorption [6] (especially with high-concentration aerosols), the atmosphere can affect the results of the analysis of the light value of the DNB VIIRS imagery [1]. An aerosol optical depth (AOD) is an important parameter in measuring the degree of atmospheric extinction that can also be used as an effective substitute to track the evolution of the aerosol-induced airpollution [7]. Aerosols in the atmosphere have a significant effect on environmental pollution [8]. Different AOD quality can affect different sky conditions, especially the influence of the seasons in the Wuhan region [9]. Therefore, it is important to determine the atmospheric effect and its extent on the light pollution data.

It should be understood that there are still various factors that cause errors in the process of data recording by the NPP-VIIRS Suomi, one of that is an atmospheric problems such as the presence of aerosols in an area. Aerosol itself can play a role in the absorption and scatter of energy at certain sizes and densities, so that, there can be a decrease or increase of the value of artificial light in VIIRS. MODIS Optical Depth Aerosols (AOD) are used in understanding the global distribution and intensity of aerosols. It should be known that the VIIRS DNB sensor is very sensitive to aerosol dynamics in an area, even more sensitive than water vapor. Consideration of aerosol concentrations is especially important in studies that use artificial light data. Moreover, the highest contributor to artificial light radiation is in urban areas with high socioeconomic activity, similar things occur in the existence of air pollution which is also high in urban areas so that it plays a role in causing high aerosol thickness in the same urban area.

Previous research conducted by X. Wang, XihanMu and G. Yan, 2020 [1] has conducted quantitative tests on AOD and light pollution (NTL) in four cities (Beijing, Wuhan, Chengdu, and Meishan) of China. The research was only carried out by using one sample point in each city and using the Linear and log-linear models test to generate similar coefficients of determination (R^2) for AOD and NTL data. While in this study the test sample totaled 46 points with spearman rank test model. The test samples were not only placed in the city center but were scattered randomly throughout Java and Bali. The test model is also adapted to the type of data that is non-parametric. This study focuses on understanding that problem through analysis of the relationship between NTL and aerosols, especially those that occurred on Java and Bali, Indonesia in 2014, 2016, and 2018 through the distribution of random sample points that cover various regional conditions with varying levels of development.

2. Details Experimental

2.1 Research area

The measurements presented in this study were located at Jawa and Bali Island , Indonesia (7°30’ S, 115°42’ E). As a preliminary note, the study take an area in the tropical area with a fairly high level of cloud formation with a dry season in April - September and a rainy season in October - March. Java and Bali are islands with varying levels of development in various regions, as the most developed islands in Indonesia, those are functionally used as the center of government and the country’s economy. The island has many urban area as a “core” that take a role in the development of the surrounding area, such as Jakarta, Bandung, Surabaya and Semarang, with varying levels of socio-economic activity resulting in varying levels of artificial night time light (NTL) illumination and the formation of diverse air pollution in various regions. In its own territory, Java-Bali itself has varied reliefs, with the altitude range of 0 - 3,676 m asl. The socio-economics centers are in the lowlands in the central part of the island and along the coast of Jawa-Bali.
This study uses MODIS AOD (Aerosol of Depthness) and VIIRS DNB (Day-Night-Band) Data obtained through Google Earth Engine (GEE). Both took time in 2014, 2016, 2018 and produced 3 data by the monthly average data of VIIRS and MODIS AOD at 2014, 2016, and 2018. Note that the monthly average used is August because it has clear sky conditions. The resolution of the two image types are different so it should be resampled. Cloud masking on AOD and VIIRS is done to avoid the effect of impairment due to cloud cover that is too thick in the data used. More higher the VIIRS values indicate the higher light pollution. AOD are unitless, higher AOD means those areas are more polluted.

The Earth Observation Group in the National Oceanic and Atmospheric Administration’s National Geophysical Data Center (NOAA / NGDC) of the United States released the annual NTL data. Each file consists of 2 data, namely NTL radiation data and average number of cloud-free (NCF). Both are presented in 742x742 m² resolution. Light pollution data (NTL) is presented in units of nW /cm² sr⁻¹ which represents the value of artificial light radiation illumination at night. Pre-processing is not done on VIIRS data because it has been filtered by the system for the presence of data near the edges of the swath and data impacted by twilight, stray light, lightning, lunar illumination, and cloud cover [10].

The AOD data used from the recording of the Terra and Aqua MODIS sensor combined the Multi-angle Implementation of Atmospheric Optical Depth (MAIAC) of Land Aerosol Optical Depth (AOD) at a resolution of 1 km. So it is used as a reference of resample process of the VIIRS NTL data to produce uniformity in the area and location of the pixel grid. It’s done to avoid decreasing of correlation value. The AOD average data has been automatically entered from the annual average cloud cover at GEE.

2.3. Sample and method
As explained before, the pre-processing data is done by cloud masking on AOD data, while VIIRS has been corrected by the system. Resample is also done referring to the AOD data (1000 x 1000 m²). Then the two data were masked on the administrative boundary vector of Java and Bali in accordance with the experimental area. Data extraction is done by determining the sample points that presented the experimental area. The number of samples was determined as 46 sample points and randomly distributed to cover areas with different levels of development, such as urban, sub-urban, and rural area on the island of Java-Bali. Each sample point consists of AOD and VIIRS data which will be tested for correlation using Spearman’s Rho. Classification of AOD and VIIRS values were not used in this study. Correlation test was conducted in this study using Spearman’s Rho through one-tailed test with a significance level of relationship of 0.01. Furthermore, 46 sample points were also visualized in the form of scatter plot graphs to determine the pattern of relationships formed of VIIRS-AOD. Same method done for each 3 data in 2014, 2016, and 2018 to find out the dynamics that occur in the period of 2014.
– 2018. It also can present the socio-economic development of study area. Multitemporal data is also used to make a spatial distribution model of AOD and VIIRS each year before spatial relationship analysis is performed.

3. Result and Discussion
The results of the average AOD and VIIRS-NTL distribution model for Java-Bali Island in 2014, 2016 and 2018 can be seen in Figure 3 (a) and (b). Visualized data has been sampled before. Dark brown warma represents a high level of aerosol density referring to areas with high air pollution, while dark blue indicates low aerosol density. In VIIRS, yellow represents high artificial light illumination, referring to areas with few sources of illumination, while blue represents low artificially illuminated light.

Based on its visualization, the AOD data in 2014 still has a location with a blue indicator that shows a low AOD value and the VIIRS image shows that light pollution in the islands of Java and Bali is still clustered in major cities only. In 2016 the distribution of AOD in the north coast increased and was followed by widespread light pollution in the 2016 VIIRS image on Java and Bali. In 2018 the Jakarta, Banten and West Java regions have very high AOD levels with dark brown color indicators and have an even distribution. The island of Bali is also experiencing widespread AOD conditions. In 2018 the existing light pollution conditions on these two islands will increase in almost all regions and have the effect of the distribution of light pollution to adjacent regions.
Figure 3. (a) Distribution of AOD values in Java and Bali in 2014, 2016 and 2018 (b) Distribution of light pollution values in Java and Bali in 2014, 2016 and 2018

Areas with high aerosol values refer to the high density of material in the air that can be caused by various things, but most contributed factor are the presence of air pollution in an area. This also represents the high dynamics of human activity in these areas. While the value of high light pollution represents the level of socio-economic activity in an area at night, the higher the value means the area more developed and has been touched by humans.

The increase of light pollution in 2016 occurred because in 2016 the condition of dissolved air particles in Java and Bali experienced a significant increase compared to 2014. Dissolved particles in the air can increase light scattering, so that light pollution in the region is high. According to Lewin (2000) [11] the external lighting system still leaves more than 50% of the waste light emitted into the sky. If no light is scattered into the atmosphere, the problem is solved. However, the lighting system, however, emits light above the horizontal beam project so that it radiates directly into the night sky. This effect is known as sky glow which is a scattering of orange colors seen over urban areas caused by the emission of light through the atmosphere which is refracted and scattered by water or particle content (aerosols) in the form of dust, plant dust, bacteria, spores, salt content of bursts of sea water, light mineral particles from factory waste [12].

Based on the data obtained the average value of light pollution from the highest to the lowest in the Java-Bali Province sequentially is 2018> 2016> 2014. While on the AOD data, the highest to lowest aerosol thickness is respectively owned by 2018> 2016> 2014. This sequence is influenced by the condition of the Suspended Particulate Matter in each province in Java and Bali as shown in Figure 4. [13]. The average of Suspended Particulate Matter has increased every year. At the same time the distribution of light pollution on the two islands has also increased.

Annual dynamics shows the increasing AOD and VIIRS values. Spearman’s Rho correlation test results in 2014, 2016, and 2018 can be seen in Figure 5.
Figure 4. Value Graph of Suspended Particulate Matter in 2014, 2016, and 2018

![Graph showing average suspended particulate matter in Java and Bali Island (μg/m³) for 2014, 2016, and 2018.](image)

**Figure 5.** (a) Spearman's Correlation Test rho for 2018 VIIRS Data and AOD Data (b) Spearman's rho Correlation Test for 2016 VIIRS and AOD Data (c) Spearman's rho Correlation Test for 2014 VIIRS Data and AOD Data.

| Correlations | AOD 2018 | VIIRS 2018 |
|--------------|----------|------------|
| Spearman's rho | AOD 2018 | Correlation Coefficient | 1.000 | 0.992* |
| | Sig. (1-tailed) | | . | 0.000 |
| | N | | 46 | 46 |
| VIIRS 2018 | Correlation Coefficient | 0.992* | 1.000 |
| | Sig. (1-tailed) | | 9.000 | . |
| | N | | 46 | 46 |

**Correlations**

| Correlations | AOD 2016 | VIIRS 2016 |
|--------------|----------|------------|
| Spearman's rho | AOD 2016 | Correlation Coefficient | 1.000 | 0.997** |
| | Sig. (1-tailed) | | . | 0.000 |
| | N | | 46 | 46 |
| VIIRS 2016 | Correlation Coefficient | 0.807** | 1.000 |
| | Sig. (1-tailed) | | 0.030 | . |
| | N | | 46 | 46 |

**Correlations**

| Correlations | AOD 2014 | VIIRS 2014 |
|--------------|----------|------------|
| Spearman's rho | AOD 2014 | Correlation Coefficient | 1.000 | 0.919** |
| | Sig. (1-tailed) | | . | 0.000 |
| | N | | 46 | 46 |
| VIIRS 2014 | Correlation Coefficient | 0.819** | 1.000 |
| | Sig. (1-tailed) | | 0.000 | . |
| | N | | 46 | 46 |

**Correlations**
Based on the correlation test with the Spearman Rank Correlation method, the AOD-VIIRS correlation produce the R² of 0.819 in 2014; 0.807 in 2016; and 0.802 in 2018. This correlation value looks increasingly declining. Based on Table 1, the R² value of the VIIRS-AOD test shows a range of 0.8 - 1, indicating a very strong level of correlation at these different recording times. A positive (“+”) R² indicates a change in direction, or in other words, when the value of VIIRS rises it will be accompanied by an AOD value which also rises. This happened because of the highest contributor of artificial light illumination is an urban area with a variety of high socio-economic activities. In that same region, high levels of air pollution can also be found as a consequence of high levels of human activity.

The test results in this study are more complex considering the sample used covers the downtown area to the forest area without buildings, so the results obtained are different from the modeling carried out in China. Given the sample in the previous study was only one point with a different correlation model. Padalah particles in the air affects the level of light scattering in the city skyline [11].

| Table 1. Spearman’s rho Correlation Level |
|------------------------------------------|
| **R²** | **Strength of Correlation** |
| 0 – 0.19 | Very Weak |
| 0.2 – 0.39 | Weak |
| 0.4 – 0.59 | Moderate |
| 0.6 – 0.79 | Strong |
| 0.8 – 1 | Very Strong |

Spearman Rank Correlation Test is conducted in one-tailed relationship or one direction test with a significance level of 0.01, showing the fluctuation in the value of artificial light is influenced by an increase in aerosol thickness in the region. Fluctuations in the value of artificial light and aerosols can be understood by the phenomenon of decreasing the value of energy by absorption and adding value by scattering artificial light on the surface of the earth recorded by satellite sensors. Scatter plots are used to look at the distribution of samples and determine the pattern of relationships formed between artificial night light illuminations and aerosol thickness. Scatter plots in 2014, 2016 and 2018 can be seen in Figure 6.
Flat responses are shown at aerosol values <0.2 in the data of 2014, 2016, and 2018, then begin to show fluctuations up and down in the range of values 0.4 - 0.8. The 2016 data shows that there are bring the different responses compared to other years in the range of aerosol values of 0.2 - 0.3. It’s assumed that these values are outliers data. This fluctuating response can occur due to variations in composition that make up aerosols, both in terms of size and the particles. The operational limits in this study only examine the vertical column of the atmosphere that is realized in AOD, while the influence of the aerosol light extinction coefficient (the sum of the aerosol light scattering and absorption coefficients), aerosol single scattering albedo (the ratio of scattering to extinction coefficient), the aerosol upscatter fraction (the fraction of the incident solar radiation that is scattered upward to space), and aerosol size distribution [14] those are the outside of the study.

Schema of the effect of the presence of aerosols on artificial light energy propagation can be seen in Figure 7. Aerosol itself is a mixture of solid liquid particles suspended in the air, and affects other objects in the range of 0.001 - 100 µm [15].

In this study, we assume single scattering albedo (w) = 0.9, and scattering asymmetry factor (g) = 0.61, which are both representative of values typically observed for tropospheric aerosols [16]. the optical depths of aerosols and clouds probably exhibit some covariance. This covariance can arise from (1) the aforementioned indirect effect atmospheric aerosols on clouds, (2) dependence of both aerosol scattering efficiencies and cloud formation on relative humidity [17] and (3) the fact that the formation, accumulation, and removal of aerosols are affected by a host of meteorological conditions, including cloudiness. However, proper simulation of this covariance.

The occurrence of light scattering caused by a single particle in the air causes an increase of the NTL value, it cause the graph soaring up at a certain aerosol value. Aerosol play a role in interfering the
recording of data by optical sensors which are characterized by the appearance of bright objects that are similar to the artificial nighttime glow in the VIIRS image. This phenomenon is known as 'ghost light' or in the perspective of remote sensing known as 'pixel blooming') (Carey et al, 2004. Pixel blooming is a phenomenon commonly found in artificial night light data, as happened in DMSP-OLS data [18].

4. Conclusion
The distribution of Aerosol Optical Depth (AOD) in Java and Bali in 2014, 2016, and 2018 experienced an increase and widespread distribution. This can be seen through the AOD distribution map which shows that in 2018 there are no areas with low AOD classification, while in 2014 the central and southern parts of Java and the central part of Bali still have low aerosol conditions. Even in 2018 the distribution of AOD is getting more massive. This one was relevant to the existing light pollution conditions in the regions of Java and Bali which are also higher by the yellow indicator becoming wider from the position of the city centers, following the distribution of aerosols which is increasing. The relationship between these two variables is even very strong at 0.8-1 using the Spearman Rank correlation test. Based on the results of the correlation test the value of AOD and light pollution is directly proportional and strong.

This research is a correlation models that exist in Java and Bali, so as to be different values for different regions. This research is highly dependent on the quality of satellite image data and is carried out on a wide scale. It would be better if the research was carried out using field data with a more detailed scale. This study provides an overview of the snowball effect of increased air pollution which can affect light pollution levels and disrupt the brightness of the night sky. It can interfere with astronomical observations and even affect the activity of nocturnal animals and result in extinction. Based on this research, the government can find out the very large impact of pollution, and make the right policies to immediately solve the problem.

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