Introduction

Currently, Thailand, especially in the northern region, is encountering air pollutions due to smokes, accumulation of smokes or dust in the air, which are mostly caused by the burning of forest area and open area for agricultural purpose. Also, the terrains in many areas in the northern region are characterized by “pan” shape, with plain areas surrounded by mountains, and the weather is quite still and dry for a long period of time; these are the reason of the accumulation of pollution which cannot be ventilated, therefore, the concentration of pollution is quite high especially in the urban area. This causes such area to encounter the problem of air pollution (Suwanprasit, Charoenpanyanet, Pardthaisong & Sinampol, 2018). Also, there are other causes including more transportation, more burning of forest area and open area (Supasri, Intra, Jomjunyong & Sampattagul, 2018).

Particulate matter (PM) is the particles consisting of nitrogen oxide (NOx), sulfur dioxide (SO2), ammonia (NH3), polycyclic aromatic hydrocarbons (PAHs) which are combined and floating in the air in form of dust; it can be divided by size – the one smaller than 2.5 μm, is called PM2.5, and the one smaller than 10 μm is called PM10 (Porter & Clarke, 1997; Meng et al., 2019). Dust is the pollution that mostly affects human than other air pollutions. Particulate matter comes from both nature such as soil dust, sand dust, and from the matter on the ground blown by wind, smoke from wild fire, salty particles from seawater
and comes from human activities such as dust from construction, dust from transportation on road, smoke released from exhaust pipe of car and motorcycle, dust and smoke from chimney from crematorium, incinerator of industrial plant, and the burning of agricultural residues in open area (Pollution Control Department [PCD], 2004; Nathapindhu, Sthetheam & Ketkowit, 2011; World Health Organization [WHO], 2017). The danger of dust traveling into the respiratory system depends on the size, quantity, chemical properties, and biological qualities. Dust, once travelling into the respiratory system, would accumulate in various parts of the respiratory system, depending on its size; the rough dust would be filtered by nose hair and thus falling onto the primary respiratory system, and the fine dust and the very fine dust would pass into the bronchus, bronchiole, and deep into the alveoli. If a large quantity of dust is inhaled, it would affect health a lot accordingly (Adams, Greenbaum, Shaikh, van Erp & Russel, 2015; GreenFacts, 2018; United States Environmental Protection Agency [USEPA], 2018).

Particulate matter PM$_{10}$ is the serious problem of air pollution in the northern region, which is mostly caused by the burning of forest area and open area and is clearly seen during January–April of every year (Amphanthong & Busababodhin, 2015). The monitoring of PM$_{10}$ quantity can be done by the inspection performed at the Ground Monitoring Station of Pollution Control Department (PCD) and the Thai Meteorological Department (TMD); it is not possible to install the station in all critical areas due to the fact that the air monitoring device is large, the expense spent in the operation and maintenance is high, and in some monitoring stations it is not possible to perform real-time monitoring which results in the limitation on the monitoring of dust in terms of space and time (Outapa & Ivanovitch, 2019). However, the problem related to dust or PM in the northern region needs to be solved immediately.

According to the related researches, it was found that at present, the remote sensing technology was applied by using data received from the satellite in monitoring and following the air quality situations (Liu, Sarnat, Kilaru, Jacob & Koutrakis, 2005; Kloog, Koutrakis, Coull, Lee & Schwartz, 2011; Nguyen, Cressie & Braverman, 2012; Benas, Belconci & Chrysoulakis, 2013; Vienneau et al., 2013; Phayungwiwatthanakoon, Suwanwaree & Dasamanda 2014; He & Huang, 2018). The remote sensing is the modern and efficient technology that can be applied to monitor and inspect various phenomena on Earth in time (Sukitpaneenit & Oanh, 2014; Emetere, Sanni, Okoro & Adeyemi, 2018; Rotjanakusol & Laosuwan, 2018, 2019; Uttaruk & Laosuwan, 2019). Due to the importance of monitoring and following up the air quality circumstance, this study aims to find patterns of relationship between PM$_{10}$ from the air quality station and AOT data received from MODIS sensor onboard of Terra satellite in Phrae Province, the northern region of Thailand.

**Studying area and satellite data**

**Studying area.** Phrae Province (Fig. 1) is located in the northern region of Thailand, with the area of 6,538.59 km$^2$, between the latitude of 17.70° to 18.84°N
to the longitude of $99.58^\circ$ to $100.32^\circ$E; it is 155 m high from moderate sea level. The province is surrounded by mountains in four directions; most of the area, about 80%, are mountainous with the plain area of only 20%. The average air temperature in Phrae in the whole year is about 26.4°C, with the average minimum temperature of 21.6°C and with average maximum temperature of 33.2°C.

**Data used in the study.** Data of Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, the aerosol optical thickness (AOT) on land and ocean would be of the Level 2 Product with the resolution of the image of $10 \times 10$ km$^2$ at and is the near-real-time product data. Therefore, in this study, the data from MODIS sensor onboard of Terra satellite was applied with the code of MODO4_L2 Aerosol Product (Optical_Depth_Land_And_Ocean). The MODO4_L2 Aerosol Product file covers a five-minute time interval. The

![Figure 1. Phrae Province, the northern region of Thailand](image-url)
output grid is 135 pixels in width by 203 pixels in length. Every tenth file has an output grid size of 135 by 204 pixels. The MOD04_L2 Aerosol Product files are stored in hierarchical data format (HDF). The data was downloaded from web interface LAADS DAAC (https://ladsweb.modaps.eosdis.nasa.gov); the duration of 10.00–11.00 am at local time was selected when the MODIS sensor onboard of Terra satellite orbit passes Thailand. Data used were on daily basis from 1st January to 30th April 2018.

**Ground temperature data.** In this study, the data of PM$_{10}$ on hourly basis was collected in the period from 1st January to 30th April 2018 during 10.00–11.00 am from the air quality station of the air4thai (http://air4thai.pcd.go.th/webV2) located at Mueang District, Phrae Province, located Na Chak Subdistrict, Mueang District, Phrae Province, with the latitude of 18.13°N and longitude of 100.16°E.

**Methodology**

Since AOT data received from MODIS sensor onboard of Terra satellite is in HDF or granule coverage, so before analyzing AOT data, it is necessary to adjust the projection systems by georeference. In this study, the projection systems were determined to be UTM WGS-84 zone 47; after that, the adjusted data were brought for numerical analysis of AOT further. In this research, the correlation analysis using software package was performed (Eq. 1) to study the relationship between PM$_{10}$ quantity from the air quality station of the air4thai with the AOT data received from Terra MODIS satellite.

\[
 r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}} \tag{1}
\]

where:

- $r = 1$ – perfect positive correlation,
- $r = -1$ – perfect negative correlation.

The result of the analysis would yield correlation coefficient ($r$) which indicated the extent of relationship of the data, for linear regression analysis (Eq. 2), which is one statistical method for examining the relationship between two or more variables; this is divided into independent variable $x$ and dependent variable $y$. In this research, $x$ is PM$_{10}$ quantity from the air quality station of the air4thai and $y$ is AOT data received from MODIS sensor onboard of Terra satellite at the coordinate of the ground monitoring station.

\[
 y = ax + b \tag{2}
\]

where:

- $x$ – independent variable,
- $y$ – dependent variable.

Besides, PM$_{10}$ quantity obtained from the monitoring station was brought to replace the value in the linear regression equality of each month in order to see the density of PM$_{10}$ in spatial term. Finally, the distribution map of PM$_{10}$ was created in spatial term under AQI which is the report on the weather in simple and easy-to-understand form in order to disseminate such data to the public so that they could be informed of the air pollution situations. Various countries would have their own AQI – Thailand in this study.
Result of the study

The results of the analysis into the relationship between PM$_{10}$ and AOT by using statistical method that is correlation analysis are shown in Table 1. According to Table 2, it was found that in overall, PM$_{10}$ and AOT are highly related, with the correlation coefficient in January of $r = 0.928$, in February of $r = 0.919$, in March of $r = 0.916$, and in April of $r = 0.927$. The results of the linear regression analysis of duration between January and April are shown in Figures 2–5. In January, the data collection from MODIS sensor onboard of Terra satellite (AOT) and air quality stations (PM$_{10}$) was shown in Table 2.

From Figure 2, it shows the relationship between the quantity of PM$_{10}$ and AOT in January of Phrae Province; when PM$_{10}$ increased, AOT would increase accordingly. On the contrary, when PM$_{10}$ decreased, AOT would also decrease. According to the linear regression analysis, it was found that the minimum PM$_{10}$ was $30 \mu g\cdot m^{-3}$ and maximum PM$_{10}$ was $79 \mu g\cdot m^{-3}$. The linear regression equality $y = 97.679x - 0.7215$ and the coefficient in making decision of $r^2$ was 0.983.

In February, the data collection from MODIS sensor onboard of Terra satellite (AOT) and air quality stations (PM$_{10}$) was shown in Table 3.

TABLE 1. Correlation coefficient ($r$) between PM$_{10}$ and AOT in Thailand in 2018 in selected months

| Month   | $r$  |
|---------|------|
| January | 0.928|
| February| 0.919|
| March   | 0.916|
| April   | 0.927|

TABLE 2. Data collected from MODIS sensor onboard of Terra satellite and the air quality stations in Thailand in January 2018

| Date | AOT | PM$_{10}$ $[\mu g\cdot m^{-3}]$ |
|------|-----|--------------------------------|
| 5    | 0.309 | 30                             |
| 6    | 0.325 | 31                             |
| 7    | 0.358 | 34                             |
| 8    | 0.601 | 59                             |
| 9    | 0.481 | 45                             |
| 10   | 0.449 | 42                             |
| 11   | 0.426 | 41                             |
| 12   | 0.384 | 36                             |
| 14   | 0.393 | 36                             |
| 15   | 0.452 | 44                             |
| 16   | 0.391 | 38                             |
| 17   | 0.486 | 46                             |
| 18   | 0.479 | 43                             |

| Date | AOT | PM$_{10}$ $[\mu g\cdot m^{-3}]$ |
|------|-----|--------------------------------|
| 19   | 0.408 | 41                             |
| 20   | 0.457 | 46                             |
| 21   | 0.498 | 48                             |
| 22   | 0.553 | 52                             |
| 23   | 0.715 | 71                             |
| 24   | 0.708 | 70                             |
| 25   | 0.562 | 55                             |
| 26   | 0.821 | 79                             |
| 27   | 0.801 | 76                             |
| 28   | 0.547 | 57                             |
| 29   | 0.485 | 49                             |
| 30   | 0.491 | 45                             |
| 31   | 0.624 | 57                             |
FIGURE 2. Linear regression between PM$_{10}$ and AOT in Thailand in January 2018

TABLE 3. Data collected from MODIS sensor onboard of Terra satellite (AOT) and the air quality stations (PM$_{10}$) in Thailand in February 2018

| Date | AOT  | PM$_{10}$ [μg·m$^{-3}$] |
|------|------|-------------------------|
| 1    | 0.603| 61                      |
| 2    | 0.521| 51                      |
| 3    | 0.694| 68                      |
| 4    | 0.635| 62                      |
| 5    | 0.782| 75                      |
| 6    | 0.891| 86                      |
| 7    | 0.973| 91                      |
| 8    | 0.987| 96                      |
| 9    | 1.108| 102                     |
| 10   | 0.921| 93                      |
| 11   | 0.902| 94                      |
| 12   | 0.915| 97                      |
| 13   | 0.841| 81                      |

| Date | AOT  | PM$_{10}$ [μg·m$^{-3}$] |
|------|------|-------------------------|
| 14   | 0.726| 71                      |
| 15   | 0.887| 89                      |
| 16   | 0.862| 84                      |
| 17   | 0.712| 70                      |
| 18   | 0.631| 68                      |
| 19   | 0.993| 97                      |
| 20   | 0.922| 93                      |
| 21   | 0.876| 85                      |
| 23   | 0.472| 44                      |
| 25   | 0.486| 47                      |
| 26   | 0.553| 52                      |
| 28   | 0.476| 48                      |

From Figure 3, it shows the relationship between the quantity of PM$_{10}$ and AOT in February of Phrae Province; when PM$_{10}$ increased, the AOT would increase accordingly. On the contrary, when PM$_{10}$ decreased, AOT would also decrease. According to the linear regression analysis, it was found that the minimum PM$_{10}$ was 44 μg·m$^{-3}$ and maximum PM$_{10}$ was 102 μg·m$^{-3}$. The linear regression equality $y = 97.679x - 0.7215$ and the coefficient in making decision of $r^2$ was 0.983.
In March, the data collection from Terra MODIS satellite (AOT) and air quality stations (PM10) was shown in Table 4.

From Figure 4, it shows the relationship between the quantity of PM10 and AOT in March of Phrae Province; when PM10 increased, the AOT would increase accordingly. On the contrary, when PM10 decreased, AOT would also decrease. According to the linear regression analysis, it was found that the minimum PM10 was 58 μg·m⁻³ and maximum PM10 was

![Linear regression between PM10 and AOT in Thailand in February 2018](image)

**TABLE 4.** Data collected from Terra MODIS satellite (AOT) and the air quality stations (PM10) in Thailand in March 2018

| Date | AOT  | PM10 [μg·m⁻³] |
|------|------|---------------|
| 2    | 0.587| 76            |
| 3    | 0.596| 77            |
| 4    | 0.773| 93            |
| 5    | 1.064| 118           |
| 6    | 1.663| 184           |
| 7    | 1.134| 139           |
| 8    | 0.981| 112           |
| 9    | 0.394| 58            |
| 11   | 0.403| 59            |
| 13   | 0.449| 63            |
| 14   | 0.561| 76            |
| 15   | 0.846| 107           |
| 16   | 0.908| 112           |
| 17   | 0.795| 97            |

| Date | AOT  | PM10 [μg·m⁻³] |
|------|------|---------------|
| 18   | 0.681| 86            |
| 19   | 0.807| 98            |
| 20   | 0.954| 112           |
| 21   | 1.136| 132           |
| 22   | 0.975| 101           |
| 23   | 0.682| 88            |
| 24   | 0.691| 88            |
| 25   | 0.741| 91            |
| 26   | 0.809| 100           |
| 27   | 0.748| 92            |
| 28   | 0.759| 92            |
| 29   | 0.862| 102           |
| 30   | 0.754| 93            |
| 31   | 0.783| 91            |
184 μg·m⁻³. The linear regression equality $y = 98.355x + 18.588$ and the coefficient in making decision of $r^2$ was 0.9777.

In April, the data collection from MODIS sensor onboard of Terra satellite (AOT) and air quality stations (PM₁₀) was shown in Table 5.

From Figure 5, it shows the relationship between the quantity of PM₁₀ and AOT in April of Phrae Province; when PM₁₀ increased, AOT would increase accordingly. On the contrary, when PM₁₀ decreased, AOT would also decrease. According to the linear regression analy-

TABLE 5. Data collected from MODIS sensor onboard of Terra satellite (AOT) and the air quality stations (PM₁₀) in Thailand in March 2018

| Date | AOT | PM₁₀ [μg·m⁻³] |
|------|-----|---------------|
| 1    | 0.782 | 56           |
| 2    | 0.754 | 52           |
| 3    | 0.761 | 50           |
| 4    | 0.857 | 66           |
| 5    | 0.731 | 53           |
| 6    | 0.586 | 37           |
| 7    | 0.706 | 51           |
| 8    | 0.701 | 47           |
| 9    | 0.864 | 65           |
| 10   | 0.947 | 78           |
| 11   | 1.065 | 84           |
| 12   | 1.075 | 82           |
| 13   | 1.063 | 85           |
| 14   | 0.725 | 54           |
| 15   | 0.526 | 32           |
| 16   | 0.572 | 37           |
| 17   | 0.754 | 56           |
| 18   | 0.952 | 74           |
| 19   | 1.132 | 90           |
| 20   | 1.053 | 87           |
| 21   | 1.204 | 99           |
| 22   | 1.426 | 114          |
| 23   | 0.857 | 65           |
| 24   | 0.535 | 32           |
| 25   | 0.554 | 31           |
| 26   | 0.493 | 21           |
| 27   | 0.482 | 24           |

FIGURE 4. Linear regression between PM₁₀ and AOT in Thailand in March 2018
sis, it was found that the minimum PM$_{10}$ was $21 \mu g\cdot m^{-3}$ and maximum PM$_{10}$ was $114 \mu g\cdot m^{-3}$. The linear regression equality $y = 99.137x - 21.28$ and the coefficient in making decision of $r^2$ was 0.9861.

Furthermore, the result of the distribution map creation of PM$_{10}$ in spatial term under AQI of Thailand (Table 6) to show that whether PM$_{10}$ has effect on the health or not can be seen from the entire Figure 6. According to Figure 6a, it was found that Phrae Province had air of good quality and moderate quality in January; the people can do outdoor activities and tour normally. From Figure 6b, it was found that Phrae Province had good quality of air and moderate quality of air and the quality of air affected the health in February. The people who live in the blue area and green area can do outdoor activities and tour normally; and the people who live in yellow zone can do outdoor activities normally except for someone who is vulnerable was found to have primary symptom such as cough, being hard to breathe, eye irritation; so, the period of time to do outdoor activities should be reduced. According to Figure 6c, it was found that Phrae Province had moderate quality and the quality of air affected the health in March. The people who live in the blue area and green area can do outdoor activities and tour normally; and the people who live

**TABLE 6. Criteria for AQI in Thailand**

| AQI   | PM$_{10}$ [μg·m$^{-3}$] | Levels of health concern | Colors |
|-------|------------------------|--------------------------|--------|
| 0–25  | 0–50                   | very good                | blue   |
| 26–50 | 51–80                  | good                     | green  |
| 51–100| 81–120                 | moderate                 | yellow |
| 101–200| 121–180               | unhealthy                | orange |
| > 200 | 181                    | very unhealthy           | red    |
in yellow zone can do outdoor activities normally except for someone who is vulnerable was found to have primary symptom such as cough, being hard to breathe, eye irritation; so, the period of time to do outdoor activities should be reduced. From Figure 6d, it was found that Phrae Province had good quality of air and moderate quality of air and the quality of air affected the health in April.
The people who live in the blue area and green area can do outdoor activities and tour normally; and the people who live in yellow zone can do outdoor activities normally except for someone who is vulnerable was found to have primary symptom such as cough, being hard to breathe, eye irritation; so, the period of time to do outdoor activities should be reduced.

In addition, PM$_{10}$ is a major air pollution problem in Northern Thailand. The problem is evident during the dry season from December to April each year. As a result of this study, it was found that the most common problem of PM$_{10}$ was in March, during which time. However, the main causes of PM$_{10}$ in Northern Thailand are caused by open-air burning activities, forest fires, agricultural waste incineration, incineration, and the occurrence of forest fires in neighboring countries.

**Conclusions**

According to the study into the pattern of relationship between PM$_{10}$ from the ground monitoring station of the air4thai with AOT data received from MODIS sensor onboard of Terra satellite in Phrae Province, the northern region of Thailand during January–April 2018, it was under the objective. It was found from the research that in March, PM$_{10}$ was highest equal to 184 $\mu$g·m$^{-3}$. In January, where PM$_{10}$ was lowest was equal to 79 $\mu$g·m$^{-3}$, the change of PM$_{10}$ quantity and AOT was highly related (near 1) in every month. Besides, when the linear regression analysis was performed, it was found that independent variable ($x$) and dependent variable ($y$) were consistent, with the coefficient of decision of $r^2$ being near 1 in every month also. In February–April period in Phrae Province, it was the time when quantity of PM$_{10}$ affected health according to the AQI standard of Thailand. In addition, the result from this research was consistent and was in the same direction with the research on “Satellite measurements of aerosol optical depth and carbon monoxide and comparison with ground data” by Lalitaporn and Mekaumnuaychai (2020), which indicated PM$_{10}$. High levels of PM$_{10}$ occur more frequently from March to April. Furthermore, PM$_{10}$ is higher in the morning than in the afternoon.

In bringing AOT data obtained from MODIS sensor onboard of Terra satellite to be applied in this research, the advantage was that this was near-real-time data and covered wide area (10 $\times$ 10 km$^2$ per 1 pixel). However, AOT data were classified by passive remote sensing system, with disadvantage of that in some days, there might be cloud over the area making it impossible to monitor AOT quantity. On part of PM$_{10}$ data from the ground monitoring station, the advantage was that it was PM$_{10}$ which was monitored by direct sensor; but with disadvantage that was that the PM$_{10}$ monitoring tool cannot be installed in the station of all critical area since such air monitoring tool is large and the budget to be spent on the operation and the maintenance is high.

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Patterns of relationship between PM$_{10}$ from air monitoring quality station and AOT data from MODIS sensor onboard of Terra satellite. Thailand, especially in the northern region, often encounters the problem of having PM$_{10}$ exceeding the normal standard level, which could do harm to people’s health. Mostly, such problem is caused by the burning of forest area and open area; this is clearly seen during January–April of every year. Also, the problem as mentioned is caused by the meteorological conditions and the terrains in the northern region that make it easy for PM$_{10}$ to be accumulated. The aim of this study was to analyze the patterns of relationship between PM$_{10}$ measured from the ground monitoring station and AOT data received from MODIS sensor onboard of Terra satellite in Phrae Province located in the northern region of Thailand. The method performed was by analyzing the correlation between PM$_{10}$ data obtained from the ground monitoring station and the AOT data received from the MODIS sensor onboard of Terra satellite during January–April 2018. It was found from the study that the change of the intensity of PM$_{10}$ and AOT in the climate was highly related; it appeared that the correlation coefficient ($r$) in January–April was 0.92, 0.91, 0.91 and 0.92, respectively. This research pointed out that during February–April, the areas of Phrae Province had the level of PM$_{10}$ that affected health. Besides, from the method in this research, it revealed AOT data received from MODIS sensor onboard of Terra satellite could be applied in order to follow up, monitor, and notify the spatial changes of PM$_{10}$ efficiently.

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