Trends of Climate Variables and Aerosol optical Depth in Thailand

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Abstract. This study analysed climate variables data in four stations over Thailand. Aerosol optical depth (AOD) obtained from Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) were also used to determine climatic trends in the areas under focus. The linear regression, Mann-Kendall trend, and Sen’s slope tests were applied. Rain (R) gave higher values in July to October for most regions except in the Songkhla. Amount of R increased in all regions. Rainy season is caused by the Southwest monsoon, which is a normal occurrence in Thailand from June to September. However, this monsoon tended to begin earlier and last longer (May to October) than expected. Mean temperature (Tmean) values were found to be significantly higher from March to May and increased in all stations. The highest significant increases of annual Tmean were found in the North. There was no significant trend in annual R (Rainfall) at the 1% and 5% significance level in all stations. The AOD values were likely to increase in almost all stations. The highest significant increase of annual AOD was observed in Ubon Ratchathani.

Keyword: trends of climate variables, climatology, aerosol optical depth, atmospheric aerosols

1. Introduction
The Earth’s climate system is an interactive system consisting of the atmosphere, the hydrosphere, the cryosphere, the land surface, and the biosphere. Climate change generally refers to a change in the atmospheric component of the climate system. It is usually described in terms of a change in the statistical distribution of weather patterns over an extended period ranging from months to million years. In a study conducted by the Intergovernmental Panel on Climate Change (IPCC), it was shown that the tendency in the intensity and frequency of extreme weather events in Asia have increased over the last century and into the 21st century. Prior studies have noted the importance of the relationship between climate variables change and atmospheric aerosols. Because aerosol particles play an increasingly deleterious role in global climate change, ecosystem process, and human health as they critically change the balance between the radiation entering and leaving the Earth’s atmosphere. Atmospheric aerosols have a short lifetime, resulting in their properties varying from one region to another across time. In recent years, there has been an increasing amount of literature on the relationship between atmospheric aerosols and climate variables. In addition, aerosols concentration in the atmosphere depends on environmental conditions. Rainfall is one of the most effective approaches to removing aerosol particles in the atmosphere by precipitation scavenging. The relative humidity is a key factor influencing the chemical composition, aerosol optical properties, and aerosols size.
higher temperatures lead to growth in aerosol concentration. Therefore, an objective of this study was to investigate trends of climate variables and AOD in Thailand.

2. Material and methods

Climate variables were obtained from the Thai meteorological department. $T_{\text{mean}}$ was produced from maximum and minimum temperature. Daily $R$ is the sum of rain measurements taken in a whole day. $R$ data were considered when the rain amounts on a single day were higher than 0.1 mm. AOD data were retrieved from the MODIS satellite data. MODIS has been installed on Aqua satellite, belonging to NASA earth observing system since 1999. MODIS sensor measures radiances at spatial resolutions of 0.25 km, 0.5 km, and 1.0 km (36 spectral channels between 0.41μm and 14.23μm) with a viewing swath of 2330 km. AERONET is a network of ground-based remote-sensing, retrieving radiative properties of the aerosol in the total atmospheric column. There are four sites for AERONET network in Thailand, including Nakhon Pathom (13.82°N, 100.04°E), Chiang Mai (18.77°N, 98.97°E), Ubon Ratchathani (15.24°N, 104.87°E), and Songkhla (7.18°N, 100.60°E) (Figure 1). Limitations of ground-based data, Aqua MODIS AOD were considered for long term AOD analysis.

Figure 1. Spatial distribution of synoptic stations in Thailand.

Linear trends in the time series at each weather station over the study period were extracted. Mann-Kendall trend analysis (MK test) was considered based on monthly averages of climatic variables. It was used to determine the trends of climate variables in all study regions at 5% and 1% significance level. To determine real slope of MK trend and Sen’s slope, two hypotheses factors (H_0 and H_1) were applied, where H_0 is no trend in the time series, and H_1 is a trend in the time series between variables.

2.1 AOD calculation

Solar radiation applied in this study are the visible light region where attenuation is mainly due to the aerosol and Rayleigh, so Beer’s law in the visible light range can be rewritten as:

$$I_{\lambda} = I_{0\lambda} E_0 \exp(-m(\tau_a + \tau_r))$$

where $I_{0\lambda}$ is irradiance at wavelength $\lambda$ at the earth’s atmosphere (W/m²), $I_{\lambda}$ is the extraterrestrial irradiance of the sun (W/m²), $E_0$ is the eccentricity correction factor, $m$ is the air mass, $\tau_r$ is the Rayleigh scattering, $\tau_a$ is the aerosol optical depth.

2.2 MODIS AOD validation against AERONET AOD

Validation of MODIS AOD at 550nm was addressed through a comparison with the AERONET AOD at 550 nm. A second-order polynomial was applied to the AERONET AOD data to intraplate to 500nm. A quadratic equation is equation having the form

$$\text{AOD}_{550} = a\lambda^2 + b\lambda + c$$

where $\lambda$ represents wavelength. The numbers a, b, and c are the coefficients of the equation.

2.3 Mann–Kendall

Mann–Kendall (MK) test is widely used for the significant trends in climate variables time series. To detect significant trends in climate variables, MK was applied. The Mann–Kendall test statistic (S) can be calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=1}^{n} \text{sgn} \ (x_j - x_i)$$
where \( n \) is the number of data points, \( x_i \) and \( x_j \) are the data values in time series \( i \) and \( j \) \((j>i)\), respectively and \( \text{sgn}(x_j-x_i) \) is the sign function as:
\[
\text{sgn} = \begin{cases} 
+1, & \text{if } x_j-x_i > 0 \\
0, & \text{if } x_j-x_i = 0 \\
-1, & \text{if } x_j-x_i < 0
\end{cases}
\]
(4)

The variance (\( S \)) of the statistic \( S \) is given by the following expressions:
\[
\text{Var } S = n(n-1)2n+5 - \sum_{p=1}^{q} t_p - 1 + \frac{2t_p + 5}{18}
\]
(5)

The variable \( q \) and \( t_p \) are the number of tied groups and the number of ties of extent \( p \), respectively. The standardized usual test statistic \( (Z_{mk}) \) is given as follows:
\[
Z_m = \frac{S-1}{\sqrt{\text{Var } S}}, \text{if } S > 0, \quad Z_m = \frac{S-1}{\sqrt{\text{Var } S}}, \text{if } S = 0, \quad Z_m = \frac{S-1}{\sqrt{\text{Var } S}}, \text{if } S < 0
\]
(6)

Positive values of \( Z_{mk} \) is an increasing trend while negative \( Z_{mk} \) is a decreasing trend. At the 5% confidence level the null hypothesis of no trend is rejected if \(|Z_{mk}| \geq 1.96\), and it is also rejected at the 1% confidence level if \(|Z_{mk}| \geq 2.576\).

3. Results and discussions

3.1 AERONET and MODIS validation

Aqua MODIS-AERONET AOD are validated by using the Pearson correlation coefficient, the root mean square error (RMSE), and the relative mean bias (RMB) as shown in Figure 2. The correlation coefficient between Aqua MODIS and AERONET AOD are equal to or above 0.77 except Nakhon Pathom and Songkhla. The highest value of Aqua MODIS-AERONET AOD has been found in Chiang Mai with \( R^2=0.78 \), slope=0.60, and RMB=0.62. The lowest value of the Aqua MODIS-AERONET AOD correlation coefficient is found in Songkhla with \( R^2=0.47 \), having slope with 0.78. Aqua MODIS AODs are both lower and higher than those of AERONET AODs. The Aqua MODIS underestimated AOD values are more noticeable in Chiang Mai due to the impact of surface albedo, and geography. The Aqua MODIS retrievals significantly overestimate the AODs at Nakhon Pathoma and Songkhla. This could be attributed to the large water body surrounding Songkhla, which should affect surface reflectivity. However, Aqua MODIS tends to underestimate AOD values under very low AOD conditions and slightly overestimates AOD values under medium or high AOD conditions.

![Figure 2. Linear regression between AERONET- Aqua MODIS AOD in Chiang Mai, Nakhon Pathom, Ubon Ratchathani, and Songkhla.](image)

3.2 Climate variables

\( T_{\text{mean}} \) gave higher values in March to May and reached a peak during April. It can be seen from the data in Figure 3 that \( T_{\text{mean}} \) was a slight rise during the period 2006-2016 for all regions. Higher values of \( R \) were observed in May to October, reaching a peak in June. These results are consistent with the number of storms for the years 2006-2016 which occurred frequently in August to October \(^{11}\). \( R \) decreased slightly in Nakhon Pathom and Chiang Mai, compared with Ubon Ratchathani and Songkhla during the period 2006-2016 (Figure 4). A possible explanation for this might be that \( R \) is associated with extreme weather in Ubon Ratchathani and Songkhla which were a significant increase in the frequency of extreme weather events \(^{12}\).
Figure 3. Average annual $T_{\text{mean}}$ values from 2006-2016 in Chiang Mai, Nakhon Pathom, Ubon Ratchathani, and Songkhla.

Figure 4. Average annual $R$ values from 2006-2016 in Chiang Mai, Nakhon Pathom, Ubon Ratchathani, and Songkhla.

Table 1 shows the output of the analyzed climatic variables for all sites. The highest significant increases of $T_{\text{mean}}$ at the 5% significance level was found in summer in Chiang Mai at the rate of 1.00°C/year. The magnitude of significant increasing trends in annual $T_{\text{mean}}$ ranged between 0.84°C/year in Songkhla and 2.35°C/year in Chiang Mai. Several reports have shown that the ENSO cycle has been the most prominent source of variability in surface air temperatures in Thailand. Th negative R trends were significant at the 5% significance level at Nakhon Pathom station in summer at the rate of -26.66 mm/year. There are no significant trends in annual $R$ for all stations at the 1% and 5% significance level.

Table 1. Results of the statistical tests for seasonal $T_{\text{mean}}$, $R$, and AOD for the years 2006-2016

| Stations          | Test | Winter | $T_{\text{mean}}$ | R    | AOD | $T_{\text{mean}}$ | R    | AOD | $T_{\text{mean}}$ | R    | AOD | $T_{\text{mean}}$ | R    | AOD |
|-------------------|------|--------|-------------------|------|-----|-------------------|------|-----|-------------------|------|-----|-------------------|------|-----|
| Chiang Mai        | Zs   | 2.90** | 1.71              | -1.22|      | 2.42’             | -1.40| 1.35 | 2.02’             | -0.78| -0.57| 2.73**            | -0.93| 0.78 |
|                   | $Q_{\text{med}}$ | 0.89** | 11.76             | -0.01|      | 1.00’             | -20.91| 0.06 | 0.47’             | -14.04| -0.01| 2.35**            | -27.55| 0.03 |
| Nakhon Pathom     | Zs   | 1.40   | -1.22             | 1.41 | 2.04’| 1.41              | 1.73 | -0.47 | 0.08             | 1.71 | -0.78 | 0.16              |
|                   | $Q_{\text{med}}$ | 0.27 | 9.57              | -0.02|      | 0.41              | -26.66| 0.04 | 0.30              | -8.1  | -0.01| 1.00              | -19.56| -0.01 |
| Ubon Ratchathani  | Zs   | 1.25   | -0.31             | 1.16 | 1.25 | 2.69**            | 2.04 | 0.78 | 0.47              | 0.31 | 1.24 | 2.00              | 2.20**|
|                   | $Q_{\text{med}}$ | 0.52 | -2.22             | 0.00 |      | 0.50              | -11.56| 0.15**| 0.26             | 13.70| 0.01| 1.40              | -9.22 | 0.14**|
| Songkhla          | Zs   | 1.80   | 0.47              | 0.00 |      | 2.18              | -1.09| -1.77| 2.42              | -0.16| 1.64| 2.74              | 0.00  | 0.62 |
|                   | $Q_{\text{med}}$ | 0.25 | 25.22             | 0.00 |      | 0.30              | -27.16| -0.04| 0.30              | -0.60 | 0.13| 0.84              | 10.29 | 0.11 |

Zs is Mann-Kendall test, $Q_{\text{med}}$ is Sen’s slope estimator

*Statically significant at the 5% significance level
**Statically significant at the 1% significance level

3.3 AOD

Higher values of AOD in Nakhon Pathom, Chiang Mai, and Ubon Ratchathani were found in summer (February to April) compared with rainy seasons (June to July) (Figure 5). AOD might be related to an increase of heat convection that uplifts dust particles from road traffic to the atmosphere. This result may be explained by the fact that high pressure governed through those months, with dry weather and plenty of sunshine, which keeps aerosol particles in the atmosphere for longer periods as there is no wet
deposition in summer. These results are in line with those of previous studies, which demonstrated that the AOD in Nakhon Pathom are higher in summer months. It might be associated with the seasonality of biomass burning as a major aerosol source in Thailand and neighbouring countries during the dry season months. Much higher values of AOD were found in Nakhon Pathom, compared with other provinces. A possible explanation for this might be that Nakhon Pathom is about 56km from Bangkok, which is the capital city of Thailand, with a population of 8.28 million suggesting higher levels of pollution compared to the others. In contrast, there was no clear seasonal pattern of AOD in Songkhla. However, AOD in Songkhla gave a higher value in October and has a high AOD value in October 2015, due to the largest forest fires in Sumatra island. Therefore, aerosol loading was associated to dry weather, forest fires and most importantly biomass burning in Chiang Mai and Ubon Ratchathani, transportation, factories, and human activities in Nakhon Pathom, and sea salt in Songkhla (Kumharn and Hanprasert 2016). It can be seen from the data in Figure 6 that AOD was a slight rise during the period 2006-2016.

**Figure 5.** Monthly average of AOD in Nakhon Pathom, Chiang Mai Ubon Ratchathani, and Songkhla from 2006-2016.

**Figure 6.** Average annual AOD values in Chiang Mai, Nakhon Pathom, Ubon Ratchathani, and Songkhla from 2006-2016.

The output of the analyzed climatic variables are presented for all sites (Table 1). The significant increases of AOD at the 1% significance level was found only at Ubon Ratchathani station in summer at the rate of 0.15/year. The significant increase of annual AOD at the 5% significance level was also observed only in Ubon Ratchathani, giving the rate of 0.14/year.

**4. Conclusions**

The trends of climate variables and AOD were investigated in Thailand for the years 2006-2016. The analysis was achieved by the non-parametric Mann-Kendall and Sen’s slope methods. The climate variables and AOD data are used from four stations with high quality datasets. The given results indicated that there are similarities between $T_{\text{mean}}$ and AOD patterns at all stations. The highest values for AOD and $T_{\text{mean}}$ were observed in summer months. AOD showed the lowest during the rainy season. This finding also confirms that R is efficient approaches to removing aerosols in the atmosphere. The results also revealed that $T_{\text{mean}}$ and R are directly related to atmospheric aerosols which remain longer in the atmosphere at high temperature and low rainfall. Furthermore, there was a significant increasing trend in annual $T_{\text{mean}}$ and AOD, however no significant trends were detected in annual R at all stations. The finding of this research can improve in future analysis of possible causes of the increase/decrease in other climate variables and Angstrom parameters.
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