Correlation between PM2.5 and meteorological variables in Chiang Mai, Thailand

P Anusasananan*, D Morasum, S Suwanarat and N Thangprasert

Department of Physics, Faculty of Science, Ramkhamhaeng University, Bangkok 10240, Thailand

*E-mail: panatcha.a@rumail.ru.ac.th

Abstract. Air pollution is a major concern for the population in Chiang Mai, northern Thailand, as it is for most people in other large cities around the world. Hazy skies and pollution alert have become normal during late winter and entire summer almost every year. Prolonged expose to PM2.5 can have acute and chronic effects on the respiratory and cardiovascular systems. This research aims to study the correlations between PM2.5 and meteorological variables (rainfall and temperature) in Chiang Mai during 2017 and 2020. The cross wavelet transform (XWT) and wavelet coherence (WTC) have been used to examine these relations by assessing the presence of common power and the relative phase in the time-frequency space. The XWT between PM2.5 and rainfall shows a significant common power in two dominant period bands, one in the period between 10-14 months and the other one between 5-7 months. The first common power occurs during all observed time intervals, so it is obviously related to natural annual periodicities of PM2.5 and rainfall. The second band, which occurs only in the year 2019 may be connected with the beginning of the monsoon season which starts in May and brings a stream of warm moist air to Chiang Mai. Our data shows that PM2.5 typically begins to rise starting in November, and it remains high until March of the next year. The PM2.5 is low in rainy season since rain has a wet scavenging effect on PM2.5. The WTC, which is a measure of the correlation between two time series, indicate that there is a significant correlation between PM2.5 and rainfall in the 10-14 month band. The phase difference between these two time series is defined by arrows. The phase arrows pointing to the left indicated the anti-phase relation, when rainfall increases, PM2.5 decreases and vice versa. The correlation coefficient (r) between PM2.5 and rainfall in rainy season is equal to 0.8504. Our study also finds that there is a proven correlation between PM2.5 and temperature in a day time scale with the correlation coefficient equal to 0.9249. In a one-day period, PM2.5 is low in the day time and high at night. An understanding of how climate variability may impact PM2.5 concentration in Chiang Mai will help the government with better planning and preparation to prevent environmental hazard from PM2.5 pollution.

1. Introduction

In 2020 Chiang Mai not only had to fight the Covid19 pandemic as the rest of the world had to do, but also had to fight a different battle: air pollution. For several months, Chiang Mai was blanketed by haze and smoke from ravaging forest fires, making its air quality rank as one of the worst cities for pollution for many straight days with Air Quality Index (AQI) of more than 200. The AQI is a report on a broad spectrum of air pollutants for general public such as PM2.5, PM10, carbon dioxide, and so on. PM2.5 refers to atmospheric particulate matter (PM), which is a diameter of less than 2.5 micrometers. There are many different sources of PM2.5, including natural and anthropogenic sources. PM2.5 is hazardous to human health because it can get the residual in the lungs and into blood vessels, causing acute and chronic effects for the respiratory and cardiovascular systems [1-7]. In figure 1 smoke and haze blanket large portions of Southeast Asia on 12 April 2019, using the visible infrared imaging radiometer suite instrument (VIIRS) on the Suomi National Polar-Orbiting Partnership spacecraft.

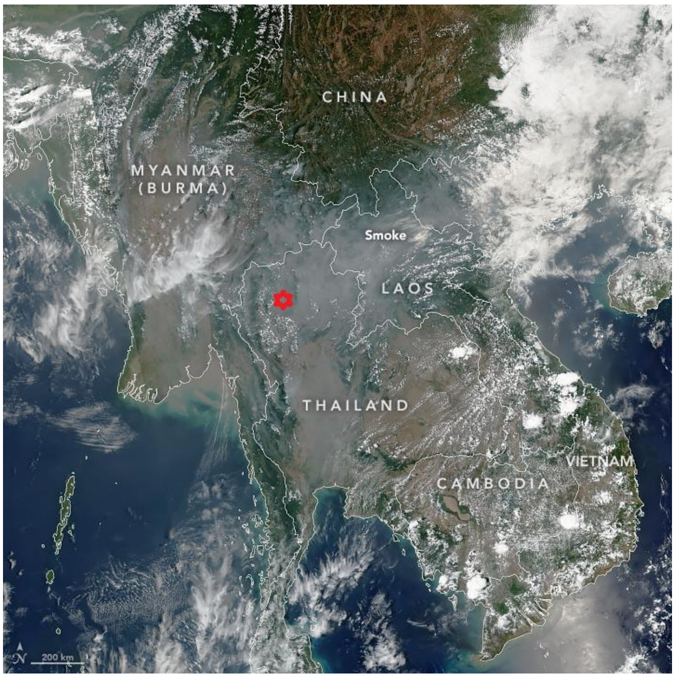

Figure 1. Unhealthy smoke over Thailand. Photo courtesy of the Earth Observatory – NASA.

There are several works that have studied the characteristic of PM2.5 and the impact of meteorological parameters on the mechanism of pollution creation. In this research, we will study the relation between PM2.5 and meteorological variables (rainfall and temperature) at Chiang Mai during the period 2017-2020 using the wavelet transform, which is developed and widely used as a time-frequency tool due to its ability to detect variations of power within the non-station data for information at different time scales. Mathematically continuous wavelet transform (CWT) of signal $d(t)$ is defined as follows [8, 9]:

$$W_c(a,b) = \int_{-\infty}^{\infty} d(t)\psi^*_{a,b}(t) \tag{1}$$

and

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{2}$$

where $\psi_{a,b}(t)$ is the mother wavelet and a and b are scale and translational position parameters, respectively. The location parameter of a defines how the scale is stretched and of b gives the exact position for the wavelet. The cross wavelet transform (XWT) is a common tool that examine the relationship between two individual time series. It can be extended to the analysis of the correlation in the form of a time-frequency space between two time series with a power spectrum and a phase difference with 95% confidence level. The XWT power spectrum is produced absolute magnitude $|W_{xy}|$ by using the cross wavelet spectrum W_{xy} between two time series $x(t)$ and $y(t)$ with the wavelet transforms W_x and the complex conjugate of W_y. These wavelet transforms also can use to construct the continuous relative phase to examine a consistent phase relationship causing between the times [10].

2. Methodology

2.1. Study area and data

The monthly PM2.5, rainfall and temperature data from the year 2017 to 2020 were used for this examination, taken from a meteorological station in Chiang Mai (~18.8°N, 98.8°E), Thailand. This area founded in 1296 and used to be the capital of the ancient Lanna Kingdom, is located 700 km north of the capital of Bangkok (~13°N, 101°E). Its terrain is in a verdant valley on the banks of the Ping River, surrounded by the mountain ranges of the highlands with an area of approximately 20,107 km^2. Its climate has a tropical wet and dry with warm to hot weather year-round and the nighttime conditions during the dry season are cool and much lower than daytime highs by recording the maximum temperature 42.2 °C (108.3 °F) in May 2005. The amounts of PM2.5, rainfall, and temperature were collected and recorded every hour (except rainfall for every three hours), comprising a total of more than 100,000 data points, which were analyzed. The PM25 data was collected by a tapered element oscillating microbalance (TEOM) with the Thermo Scientific 1405 TEOM Continuous Ambient Particulate Monitor.

2.2. Wavelet analysis

The daily and monthly mean of PM2.5, rainfall and temperature data were calculated. Then, the wavelet analysis were used to identify such time series with significant multi-temporal scales. The XWT power spectrum were taken to investigate the correlation between the PM2.5 and rainfall and between PM2.5 and temperature. The XWT spectrum is defined by:

$$W_{xy} = W_x(a,b)W_y^*(a,b) \tag{3}$$

where * denotes the complex conjugate of $W_y(u,s)$. The XWT spectrum uncovers areas in the common power of a time-frequency space which represent the local covariance between both time series.

The wavelet coherence (WTC) between two W can be perceived significant coherence of local correlation of the two time series in a time-frequency space with confidence levels against red noise. The WTC is defined as the squared absolute value of the smoothed XWT spectra normalized by the smoothed individual wavelet common power spectrum of each series with a smoothing operator S, given by

$$R^2(a,b) = \frac{\left|S(s^{-1}W_{xy}(a,b))\right|^2}{S\left(s^{-1}\left|W_x(a,b)\right|^2\right)S\left(s^{-1}\left|W_y(a,b)\right|^2\right)}, \tag{4}$$

The WTC phase difference is used to characterize the correlation between two time series, which gives details on the time-frequency space about delays of oscillation of the two time series, defined as follow:

$$\phi_{xy}(a,b) = \tan^{-1}\left(\frac{\Im\left\{S\left(s^{-1}W_{xy}(a,b)\right)\right\}}{\Re\left\{S\left(S^{-1}W_{xy}(a,b)\right)\right\}}\right). \tag{5}$$

The consistent phase relationship is indicated by arrows on the WTC plots. This work and wavelet plots use R programming language.

3. Results and discussion

The PM2.5 concentration, rainfall and temperature data were measured in Chiang Mai from 2017-2020 as shown in figure 2. All of the time series obviously show the periodicity in a one-year period. As can be seen in the distribution of the measured data, we can observe three clearly evident principles: 1) the higher the amount of rainfall, the smaller the average values of PM2.5, especially in the rainy season 2) the higher the temperature in summer, the higher the PM2.5 concentration, and 3) at other times of the year the relation between PM2.5 and temperature does not reveal any unique dependence and represents rather complex relations. The maximum daily PM2.5 in Chiang Mai from January 2017 to December 2020 is 126.44 μg/m^3, the minimum is 5.9 μg/m^3, and the average is 28.35 μg/m^3. During this period, the maximum daily rainfall is 124.8 mm. and the average is 7.76 mm. And the temperature is highest in summer (34.7°C) and lowest in winter (15.8°C), with the average at 26.77°C. In figure 2, the amount of the PM2.5 concentration and rainfall move in opposite directions. However the rainfall decreases, the PM2.5 increases.

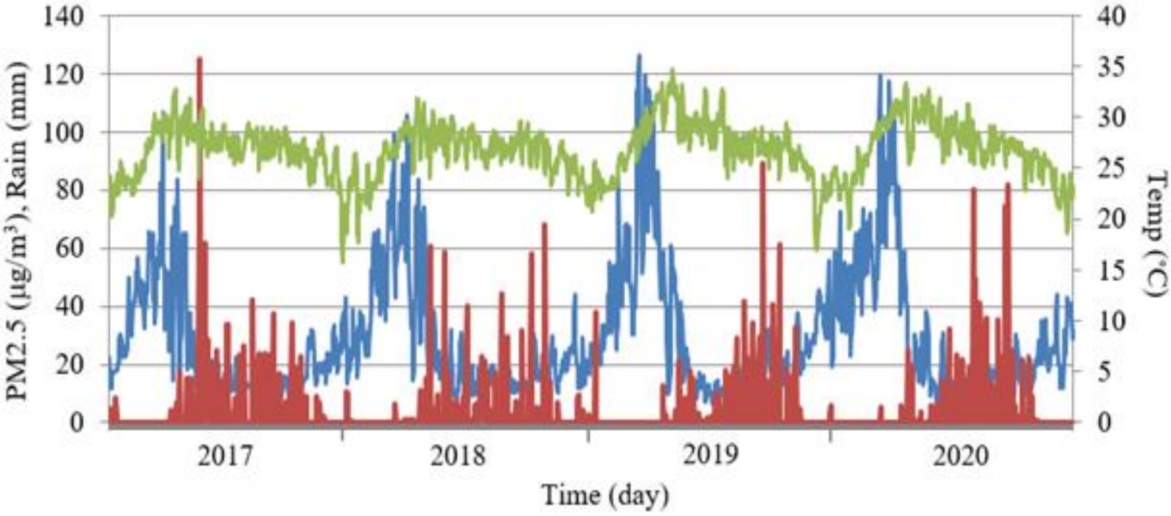

Figure 2. Time series of daily PM2.5 (blue), rainfall (red) and temperature (green) in Chiang Mai between January 2017 and December 2020. The maximum daily PM2.5 is 126.44 μg/m^3, which is higher than the recommended standard. PM2.5 is high in summer and low in rainy season opposite the amount of rainfall. On the other hand the temperature is high in summer and low in winter.

3.1. Relation between PM2.5 and rainfall

3.1.1. Wavelet power spectrum. The wavelet power spectrum (WPS) of the monthly PM2.5 concentration in Chiang Mai over a period of four years from Jan. 2.17 to Dec. 2020 is shown in figure 3. The horizontal axis is time in months and the vertical axis is the period in months. The colours with the power ranging from weak (blue shades) to strong (red shades) in the figure stand for the structure of the PM2.5 concentration variety. The relative power by the absolute value square gives the information at a certain period and in a certain month. The WPS of the PM2.5 is evaluated using four years of the data over from 2 to 6 months. The WPS shown in figure 3, analogous to temporally evolving spectrum, for PM2.5 shows two bands of high variance near a wavelength of 6 months from 2018 to 2019 and an annual seasonal trend of one year through the complete observed time series. The WPS of monthly rainfall in Chiang Mai between Jan. 2017 and Dec. 2020 is also shown in figure 3. It shows two high variance bands, one near a wavelength of 3 months for very short time in the beginning of 2017 and another one at one year period from 2017 to 2020 at the same time as PM2.5. Another significant cycle in the rainfall records occurs between 5 and 7 months with less power in the middle of 2019 to 2020.

Overall, the modes of PM2.5 and rainfall variability in Chiang Mai are wavelength varying from 11 to 13 months. As we can see, the patterns look similar, suggesting that there is a correlation between rainfall and PM2.5 in one year periods.

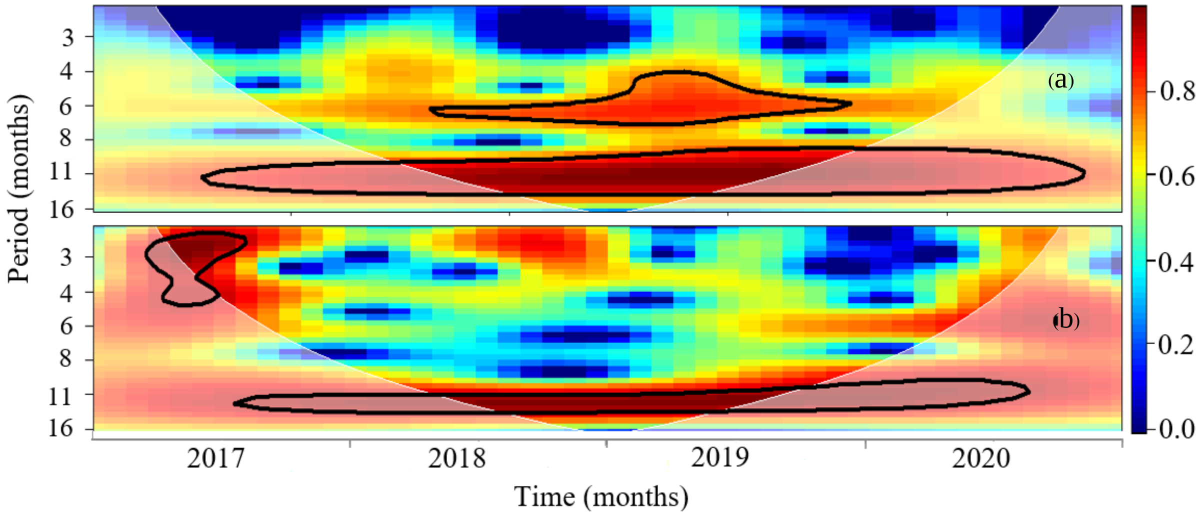

Figure 3. WPC of the PM2.5 (a) and rainfall (b).

3.1.2. Cross wavelet transform and wavelet coherence. The XWT between the PM2.5 concentration and rainfall in figure 4 shows at what frequencies and times the two series both have high variance, regardless of whether variations in one series are synchronous with those in the other. As we can observe from figure 4 PM2.5 and rainfall demonstrate significant correlation at an annual frequency between 10-14 months from 2017 to 2020 and between 5-7 months in 2019.

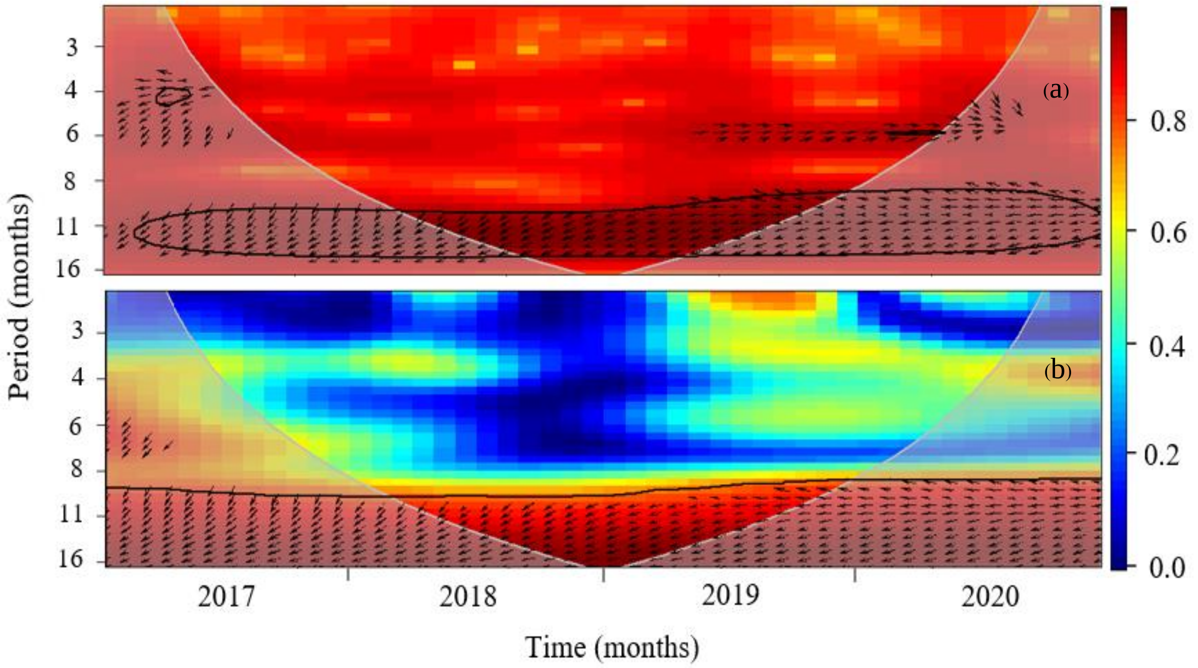

Figure 4. XWT (a) and WTC (b) between PM2.5 and rainfall time series.

The WTC shows whether variations in the two series are coherent (red corresponding to highest coherence) and in-phase or anti-phase (arrows to right, perfectly in-phase; arrows to left, anti-phase). As we can see from the figure, the red colours and right-pointing arrows through-out the time axis (near a wavelength of one year for WTC) indicate that variations near the one year period in PM2.5 and rainfall are approximately anti-phase and coherent through out the observed record, 2017-2020. The PM2.5 and rainfall are anti-phase with the pointing arrows to the left. Such phase different indicate that when the rainfall increases, the PM2.5 decreases. The high power spectrum are shown in the period band of 9-16 months between the two ends of the entire observation period.

3.1.3. Annual PM2.5 and rainfall. Since we can observe from WTC that there is a relation between PM2.5 and rainfall annually, as shown in figure 5, we plotted a graph between the average monthly PM2.5 and the average monthly rainfall over the period of four years from 2017 to 2020. As we can observe from this figure, rainfall has an effect on the PM2.5. Whenever there is a change in rainfall, there is a change in the PM2.5 because a raindrop in the atmosphere can attract tens to hundreds of tiny aerosol particles and coagulation before hitting the ground, which is a natural phenomenon to clear the air of pollutants. There is a significant negative correlation between the PM2.5 and rainfall. The higher the rainfall, the lower the concentration of PM2.5, which indicates that rainfall has a wet scavenging effect on PM2.5. The PM2.5 begins to rise from January to the maximum in March and linearly decreases until April. From March, the PM2.5 drops again to the lowest point in June since there is rain from the monsoon season. The PM2.5 is nearly stable from June until November in the rainy season Then its concentration increases linearly again to reach the high level in December. However, the rainfall is lowest in January, and February and then continues to increase to more than 200 mm in May. The rainfall is maximum in September at around 250 mm. From December to April, the amount of fine-particle dust in Chiang Mai is much worse than recommended standards reaching two times and March is the worst month.

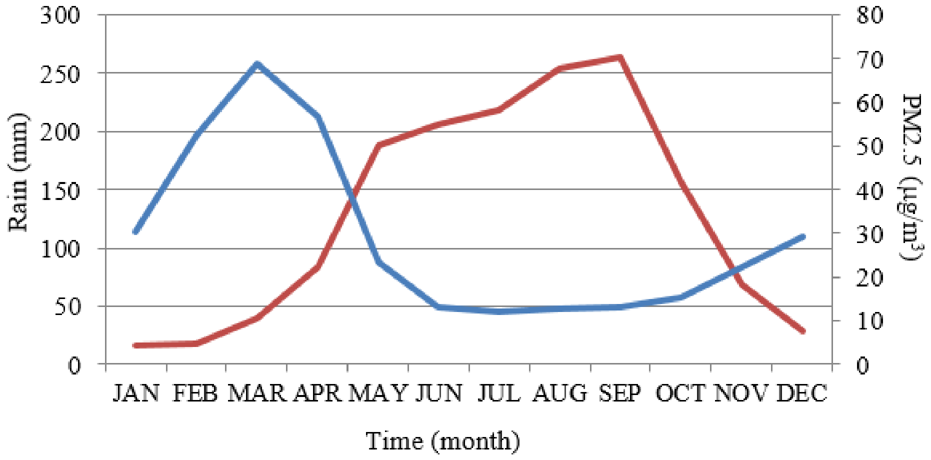

Figure 5. Average PM2.5 (red) and rainfall (blue) during 1 year period.

3.2. Relation between PM2.5 and temperature

3.2.1. Wavelet power spectrum. The WPS of the average hourly PM2.5 concentration and the average hourly temperature from 15-22 March 2020 is shown in figure 6 by the horizontal and vertical axis represents the time in hours and the period in hours, respectively. The colours with the power ranging from weak (blue shades) to strong (red shades) in the figure stand for the structure of the PM2.5 concentration variety. The relative power by the absolute value square gives the information at a certain period and in a certain month.

The WPS of the PM2.5 is evaluated over a period from 2 to 64 hours. The first oscillation is seen clearly between the entire observation period with the high power and the second oscillation occurs only 20 March 2020. Such periods are connected with natural annual periodicities. The WPS of the temperature is shown in figure 6 (b). The pattern looks similar to the WPS of PM25 in the diurnal cycle, which indicates a correlation between the temperature and PM2.5 in one day period.

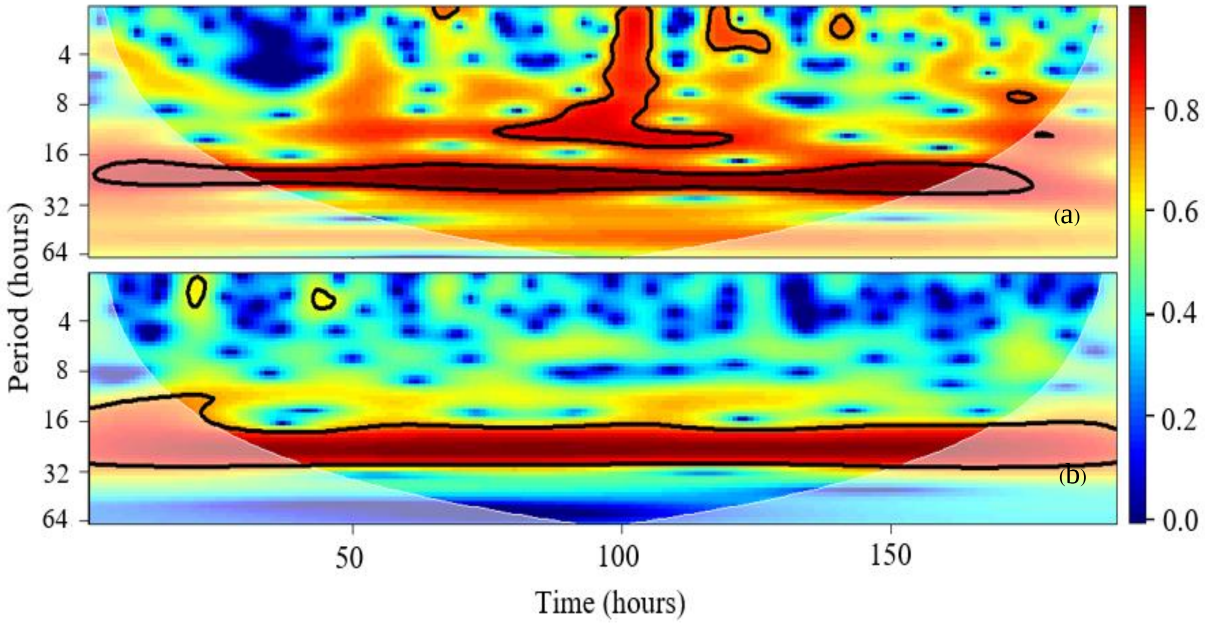

Figure 6. WPS of the average hourly PM2.5 concentration (a) and the average hourly temperature (b) on 15-22 March 2020. On the x-axis each unit means one hour.

3.2.2. Cross wavelet transform and wavelet coherence. The XWT between the PM2.5 concentration and temperature is shown in figure 7(a). Its significant common power spectrum appears clearly the first band covering 20-28 hours the entire observed period and the second band between 10-12 hours around 17-20 March 2020. The arrows of the phase difference in the significant band indicate the anti-phase (pointing to the left) correlation. The WTC is used to explore co-movement and the phase difference between such time series, as shown in figure 7 (b). The colored shading and the thick black line represent the squared coherence and the 95% significant level, respectively. Its high power spectrum is obviously with the period band of 20-28 hours between the entire observation periods with the temperature is leading, and 10-14 hours from 17 to 21 March 2020. The arrow of the phase relationship between are anti-phase. When the temperature increase, the PM2.5 decreases, and vice versa.

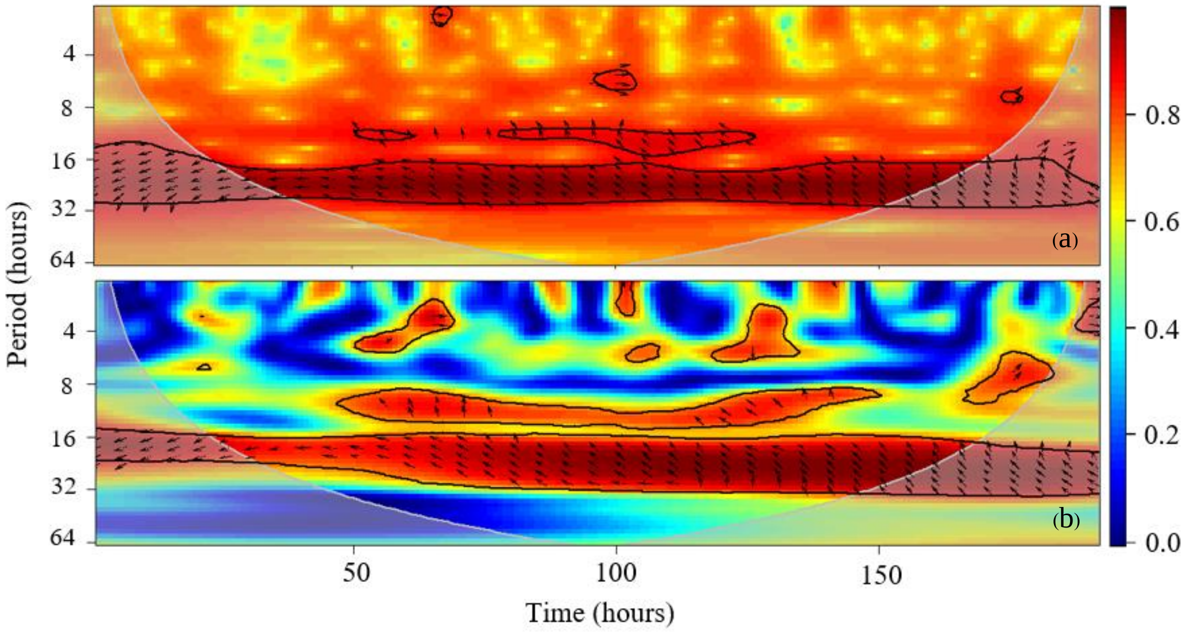

Figure 7. XWT (a) and WCT (b) between PM2.5 and temperature time series from 15-22 March 2020. On the x-axis each unit equals one hour.

3.2.3. Diurnal PM2.5 and temperature. To study the PM2.5 concentration and temperature in a one-day period, we calculated the average hourly the PM2.5 and temperature in each day over a period of 192 days in 2020, as shown in figure 8. The graph is seen clearly the trends of the PM2.5 and temperature move in opposite directions. The PM2.5 is high between 5 to 6 a.m. and linearly decreases to reach the lowest between 13-15 p.m. But the temperature is minimum between 5 to 6 a.m. and linearly increases to reach the highest between 1 to 3 p.m. As hot air from the earth's surface rises, it also takes the PM2.5 to higher altitudes. It is noticeable that at about 8 to 9 a.m. the PM2.5 is constant instead of decreasing since at these hours the activity outdoors is increasing, causing the pollution from tuk-tuks, cars, and trucks to add up.

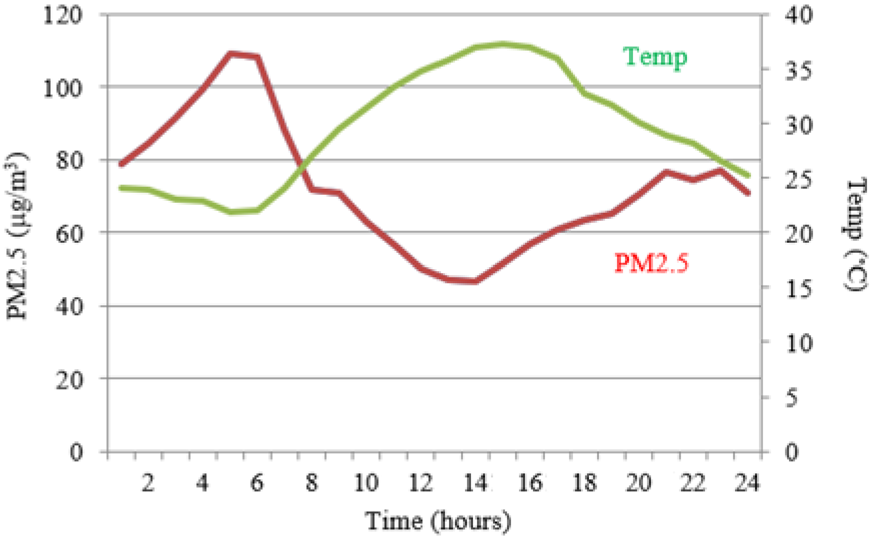

Figure 8. Average hourly PM2.5 (red curve) and temperature (green curve)

4. Conclusion

In this work, the correlation between the PM2.5 and meteorological parameters (rainfall and temperature were studied by using the wavelets. The results show that the PM2.5 and rainfall correlated annually with the correlation coefficient of 0.8504 in the rainy season. The XWT indicates that the PM2.5 and rainfall co-vary anti-phase. The PM2.5 is high between January and April, while the rainfall is low during these months. Rains conclude in Chiang Mai by the end of October, so there are no showers to clean the air until late April. In these four months in northern Thailand, the frames burn their fields to prepare for planting in the following year. Although it is illegal due to harm to the environment and people's health, their farmers continue this practice due to the lack of cheaper alternatives. With Chiang Mai is surrounded by mountains, namely Doi Saket, Doi Suthep, Doi Khun Tan, and Doi Inthanon, this area traps the smog over such months. The XWT analysis indicates that the average hourly PM2.5 and the average hourly temperature are co-varied out of phase. Since the correlation coefficient between these two variables is negative and close to 1, it also indicates that PM2.5 and the temperature tend to move in opposite directions i.e., when the temperature increases, PM2.5 decreases and vice versa. The PM2.5 is high around 5-6 a.m. and linearly decreases to reach the lowest level between 1 and 3 p.m. But the temperature is low between 5 and 6 a.m. and linearly increases to reach its highest points between 1 and 3 p.m. In order to avoid being affected by PM2.5 pollution, the key for the populace is to stay put indoors and use fans and filters to purify the poor indoor air quality. In case that it is necessary to do some activities out door, people should wear a pollution filtering mask and choose the time when the PM2.5 concentration is low. N95-grade masks protect person from 95% of the harmful particles the size of 0.3 microns or larger. As for the authorities, the Ministry of Natural Resources and Environment should be aware of the problem and try to control and prevent the burning of agricultural materials and waste in forests on plantations and in preserved areas before and during the burning season from January until April as shown by our data.

Acknowledgments

The authors are grateful to Department of Physics, Faculty of Science, Ramkhamhaeng University, Bangkok, the Pollution Control Department, and the Department of Meteorology for the data, for their support.

References

[1] Du Y, Xu X, Chu M, Guo Y and Wang J 2016 *J. Thorac Dis.* **8(1)** E8

[2] Bell M L, Ebisu K and Belanger K 2007 *Environ. Health Perspect.* **115(7)** 1118

[3] Liang Y, Fang L H, Zhang K, Kan H, Brook J R and Sun Q 2014 *Environ. Health* **13(1)** 102

[4] Brunckreef B and Holgate S T 2002 *Lancet* **360** 1233

[5] Kloog I, Ridgway B, Koutrakis P, Coull B A and Schwartz J D 2013 *Epidemiology* **24** 555

[6] Young D E, Kim H, Parworth C, Zhou S, Zhang X, Cappa C D, Seco R, Kim S and Zhang Q 2016 *Atmos. Chem. Phys.* **16** 5427

[7] Zanonetti A, Franklin M, Koutrakis P and Schwartz J 2009 *Environ. Health* **8** 58

[8] Morlet J, Arens G, Fourgeau E and Glard D 1982 *Geophysics* **47** 203

[9] Torrence C and Compo G P 1998 *Bull. Am. Meteorolo. Soc.* **79** 61

[10] Bloomfield D S, McAteer R T J, Lites B W, Judge P G, Mathioudakis M and Keenan F P 2004 *Astrophys. J.* **617** 623