Application of Wavelet Transform on Airborne Suspended Particulate Matter and Meteorological Temporal Variations

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Abstract: - Malaysia has experienced several haze periods since early 1980s in which suspended particulate matter (SPM) was the major components. The temporal variations observed are the result of interactions of various meteorological variables and pollutants emissions in different time scale. In order to study the relationship between particulate matter, temperature, rainfall and wind speed, non-decimated wavelet transform is applied to the time series. The low frequency components of the meteorological time series showed significant relationship with PM_{10} while the high frequency spectrums showed no significant relationship with PM_{10}. The findings also support the suggestion that during the dry season, one of the major sources of particulates was from outside the country.

Key-Words:- PM_{10}, Wavelet, Rainfall, Temperature, Wind speed, Non-decimated wavelet transform.

1 Introduction

Concern over air quality in Malaysia has been initiated by the occurrence of several haze episodes. The episodes have created great interest since its harmful health effects and social economic consequences. The most immediate effect is the reduction of visibility. One of the earliest haze episode was recorded in April 1983 [4]. The others were during August 1990 [3,16], June and October 1991 [3]; August to October 1994 [21]. The most severe haze episode was in 1997 [2,7]. During the haze periods, suspended particulate matter was found as the major pollutant while other parameters remained within standard [2]. During haze periods, the main sources of suspended particulates were from forest fire outside the country. Besides that, smoke from inside the country also has been recorded in several occurrences. During non-haze period, most particulate sources were from vehicular emission [2,7].

The variations observed in time series of suspended particulate matter are due to various processes of emissions, dilutions and accumulations operated in different time scales such as intraday, diurnal, several days, seasonal, annual and long terms [12,20]. Dilution and accumulation processes are affected by meteorological processes which caused the time series to become noisy and showed periodicities of different scales. Short term variations may be due to local meteorological factors and the changes in emission rate from the sources such as road traffic. Intermediate term variations may be due to more regional meteorological and seasonal factors. On the other hand, long term variations could be due to economic and policy factors which affect the emission of pollutants in the long run, thus time series may present trend and non stationary characteristics [12,20]. Annual and inter-annual variations may be due to the weather and climate factors such as monsoon cycles in the tropical countries [5]. In fact, the variation due to weather and meteorological factors are larger than variation due to long term changes in pollutant emissions. Thus, to investigate the effectiveness of air pollution policy, one may need to separate the variations due to meteorological factors in the time series [20].

Suspended particulate tend to be higher under high temperature and stable atmosphere. Conversely, wet season has cleaning effects over the suspended particulate. Strong wind will increase the intensity of the vertical transport, thus reduce suspended particulate concentration in atmosphere.

A few studies to find the relationship between meteorological and suspended particulate matter have been done in Malaysia. Most of the studies investigated the correlation between suspended particulate with temperature, rainfall, wind speed and relative humidity. These studies focused in Kuala Lumpur and Petaling Jaya urban areas which are located in high density Klang Valley. The original, non composed time series were used in order to find the relationships.

In this study, we temporally decomposed the time series prior to correlation analysis as the time series show variations in multiscales. Temporal decomposition method such as wavelet has the ability to demonstrate and analyze the variations among different scales in a time series. Wavelet transform has been used for data analysis since its application in Geophysics in early 1980s [6,8,9]. The ability of wavelet transform to decompose a time series into its different spectral of scales of is a useful tool for such applications. At low scales (high frequency), the wavelet has small time support, enabling it to zoom in on details such as spikes and high frequency changes. At high scales (low frequency), wavelet capture long term changes such as periodicities and trends.

This paper investigates the correlations between suspended particulates of size less than 10µm (PM_{10})

and meteorological variables namely temperature, rainfall and wind speed. By decomposing the time series into their temporal components, one can gain additional information as at which frequency spectrum do these components correlate. Additional knowledge gained from wavelet analysis could enhance the understanding on how meteorological factors affect PM_{10} fluctuations and thus be used for air quality management.

1.1 Previous studies on suspended particulates and meteorological variables in Malaysia

One of the earliest studies was recorded for Kuala Lumpur–Petaling Jaya areas. Weak negative correlations were found between suspended particulate and meteorological variables (precipitation and wind speed) [13]. For data between 1983 to 1997, correlation coefficients, *r* between wind speed and suspended particulate were found in a range between -0.06 in the morning and -0.51 in the evening data [23]. Generally, negative correlations were found in Klang Valley [19, 22].

A field survey in Sandakan, East Malaysia revealed weak correlation between rainfall and suspended particulate matter. Even though it is understood that the effect of rainfall capability to scavenging particulate from the atmosphere, there are still redelivery of particulates into the atmosphere. In fact the atmosphere seem to become stable after rainfall thus promotes the reaccumulation of suspended particulate matter [14]. Correlations coefficient, *r* between total suspended particulate (TSP) and mean daily rainfall were found -0.14 for Bangi (20 km to the south of Kuala Lumpur), -0.043 to -0.567 in Kuala Lumpur-Petaling Jaya during 1983-1997 which were not statistically significant [22]. Other study recorded *r* = -0.36 for Klang Valley during 1984-1999 [19]. Sham, [17] explains the weak relationship between TSP and rainfall could be due to the scavenging effect which is not normally linear.

For temperature, *r* values were found between 0.02-0.612 and were not significant at 0.05 level [23]. The study for TSP data between 1990-1994 however recorded strong relationships between 0.5-0.807 [18].

1.2 Meteorological conditions and weather in Malaysia

The weather of Malaysia is characterized by southeast monsoon regime, high temperature, high humidity and high rainfall. It is situated in the equatorial doldrums, where surface wind are generally light. For equatorial regions it is the change of wind direction and flow pattern, rather than temperature, that determine the seasons [5].

Wind speed in the Klang Valley at 6 sites reported annual average wind speeds of only 0.5 – 1.3 m/s. One of the site reported a prevalence of calm conditions of less than 0.4 m/s for more than 50% of the time [5]. The seasonal wind flow pattern and local topographic features affect the rainfall distribution over the country. Thus, the influence of wind speed as an agent for pollutant dispersion in Klang Valley is limited [4].

Klang Valley rainfall pattern records two periods of maximum rainfall separated by the two periods of minimum rainfall. The primary maximum occurs in October – November while the secondary maximum generally takes place in April – May.

Southwest monsoon	May/June- September
Inter-monsoon	September – November
Northeast monsoon	November – March
Inter-monsoon	March – May

Table 1: The four seasonal experienced by Klang Valley.

The country experiences uniform high temperature throughout the year, with annual variations of less than 2^{o}C. The daily range varies between 8^{o}C to 10^{o}C. April and May are the months with the highest average monthly temperature while December and January are the lowest average monthly temperature for Klang Valley. The effect of temperature on the concentration of suspended particulate matter according to Sham, [12] is inconclusive.

2 Methodology

In this paper, the relationships between PM_{10}, rainfall, temperature and wind speed are investigated by applying non-decimated wavelet decomposition. Non-decimated (discrete) wavelet transform (MODWT) is chosen in this study rather than continues form since it has better characteristics in the statistical point of view. In this work, Daubechies (db8) is used [6].

2.1 Data used

PM_{10} time series consists of average daily observations of PM_{10} concentration in microgram/m^3 (μg/m^3) recorded in Petaling Jaya Air Quality Station by Malaysian Meteorological Department from year August 2000 to December 2004. Daily mean rainfall (in mm), daily mean temperature (in ^{o}C) and daily mean wind speed (in m/s) time series for the same duration were also recorded for the same station except wind speed was recorded at Subang station which is located less than 10km to the north-west of Petaling Jaya. Suspended particulate was sampled using High Volume Air Sampler (HVAS) located on the top of three-store building. Petaling Jaya is located to the 15km to the south-west of Kuala Lumpur. Petaling Jaya and Subang are considered as residential and commercial areas. These areas are situated in highly populated Klang Valley. The Klang Valley is surrounded by hills to the north, east and south, and this impedes the horizontal transport of surface generated pollutants. The sources of local pollution are due to rapid urbanization and industrial expansion [15]. Hence, meteorological variables have strong influence on the concentration and transport of PM_{10}. These factors have resulted in Klang Valley becoming the most polluted area in Malaysia [1,18].

2.2 Wavelet

Wavelet transform has its root in widely known Fourier analysis. The Fourier transform gives spectral information about a signal, but not the location in time of a particular frequency. The Fourier transform uses sine and cosine at different wavelengths to represents a given function. However, sine and cosine are periodic functions that are inherently non-local. Wavelet transform is a powerful tool since it is localized in scale and time. The capability of wavelet transform to perform a multi-resolution analysis makes it as a suitable tool for this study. This enables a signal to be examined at different level of focus.

The wavelet transform is a convolution product of the signal with the scaled and translated version. The translation actions are performed by two parameters; the scale parameter j and the location parameter k. The wavelet fundamental building block functions is the mother wavelet. In order to a function to be a wavelet, it must satisfy two conditions;

1.The integral of the function must be zero (admissibility condition);

$$\int_{-\infty}^{\infty} \psi(t)dt = 0 \qquad (1)$$

2. The function must have unitary energy;

$$\int_{-\infty}^{\infty} |\psi(t)|^2 \, dt = 1. \qquad (2)$$

2.3 Non-decimated wavelet transform (MODWT)

MODWT is a modification of discrete wavelet transform (DWT), achieved by avoiding down sampling as in DWT. MODWT has better adapted to statistics due to its better resolution at coarser scales [10]. Thus, MODWT is similar to DWT except it is highly redundant non orthogonal transform. It is also more flexible as it is well adapted to sample size J while DWT needs the sample size to be a multiple of 2^j. As it avoids down sampling, direct comparison can be made between the decomposed series and the original time series. MODWT is also insensitive to the starting point of a time series [10]. The advantages of MODWT are:
1.well suited for statistical analysis since it has better resolution at coarser scales compared to ordinary discrete wavelet transform 2.time series can be decomposed in a more direct way since the number of data in all decomposed time series remain the same.

The different scales in a time series are estimated by translating and dilating the mother wavelet $\psi(t)$ producing $\psi_{j,k}(t)=2^{j/2}\ \psi(2^j t-k)$, where $j,k \in Z$. The dilation parameter j control the size of the wavelet, the translation parameter k shifts the wavelet along the t-axis. For the set of $\{\ \psi_{j,k}(t)\ \}_{j,k}$ the function f can be expanded as;

$$f(t) = \sum_{k=-\infty}^{\infty} c_{0k}\varphi_{0,k}(t) + \sum_{j=1}^{J}\sum_{k=-\infty}^{\infty} d_{j,k}\psi_{j,k}(t) \qquad (3)$$

where φ_0 is the scaling function. The maximum J scale is determined by the number of data. c_{0k} denotes the lowest frequency smooth, coefficient d_{jk} deliver information about the behavior of the function f concentrating on effect of scale around 2^{-j} near time k X 2^{-j}.

One particular disadvantage with discrete wavelet transform is that it is translation invariant. The MODWT of the data ($f(t_1),\ldots, f(t_n)$) at equally space points $t_i=i/n$ is defined as the set of all DWT's formed from all n possible shifts of the data by amounts $i/n; i=1,\ldots,n$. Thus, unlike the ordinary DWT, there are 2^j coefficients on every resolution level, there are n equal spaced wavelet coefficients in the non-decimated wavelet transform:

$$d_{jk} = n^{-1}\sum_{i=1}^{n} 2^{j/2}\psi\left[2^j (i/n - k/n)\right] y_i \text{ , k = 0,…., n-1,} \quad (4)$$

on each resolution level j. This results in $\log_2(n)$ coefficient at each location. Hence, non-decimated wavelet transform becomes translation invariant [10].

The smooth signal S_0, and the detail signals D_j ($j=1,\ldots,J$) are defined as;

$$S_0(t) = \sum_{k=-\infty}^{\infty} c_{ok}\varphi_{0,k}(t) \text{ and } S_j(t) = \sum_{k=-\infty}^{\infty} d_{jk}\psi j,k(t) \quad (5)$$

Sequentially, the temporal multi resolution decomposition of a signal is derived from;

$$D_{j-1}(t) = S_{\mathbf{j(t)}} - S_{j-1}(t)$$

The low scale oscillations (high frequency) are captured by the fine scale components D_j and D_{j-1}. The coarse scale components S_0, D_1, and D_2 correspond to lower frequency (high scale) oscillations of the signal. Each band is equivalent to a band-pass filter [10].

3 Results and Discussions

Non-decimated wavelet decomposition (MODWT) was applied to PM_{10}, temperature, rainfall and wind speed time series which separated the variances in each time series into 10 consecutive series according to their time scale producing series from *D1-D10*. The significant relationship between the components of PM_{10} and meteorological variables are indicated by correlation coefficients (r). The original time series are shown in Fig. 1-4.

Generally, the mean and variance for PM_{10} are increased throughout August 2000 to December 2004, Fig. 1. PM_{10} concentration is higher during the month of June, July, August and September during Southwest monsoon season. Lower concentration of PM_{10} was registered for November, December and January during Northwest monsoon. This is the wet duration where the amount of rainfall recorded is the highest throughout a year, Fig. 3. The variance in temperature, rainfall and wind speed time series looked more stable for the same duration of August 2000 to December 2004, Fig. 2,3 & 4.

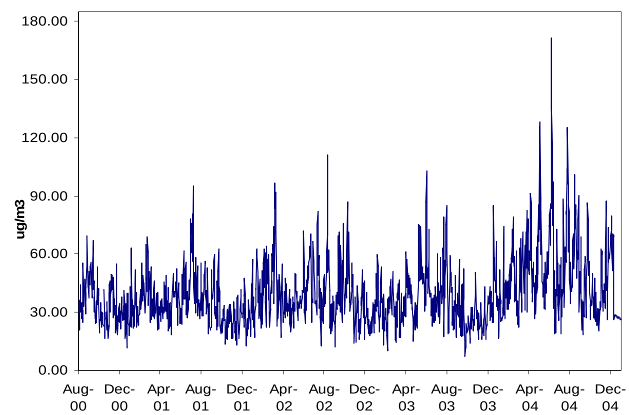


Fig. 1: The original time series of PM10 during August 2000 to December 2004.

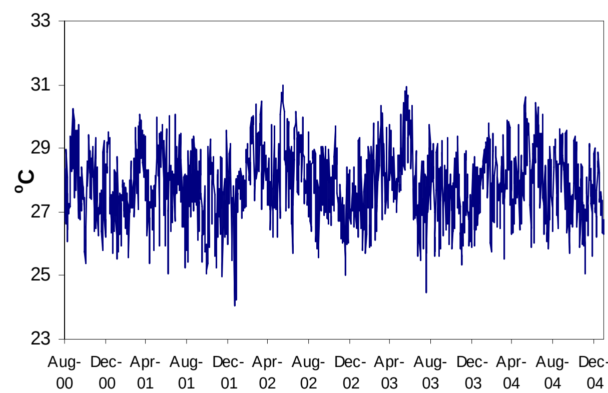


Fig. 2: The original time series of ambient temperature during August 2000 to December 2004.

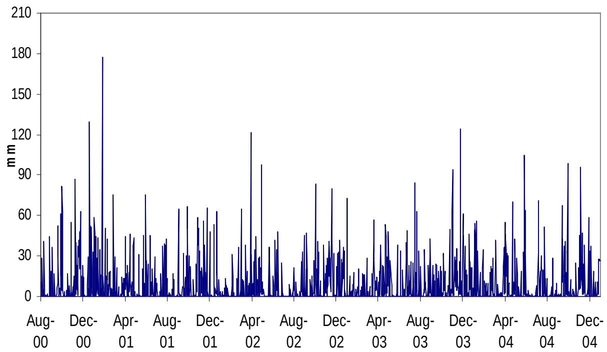


Fig. 3: The original time series of rainfall during August 2000 to December 2004.

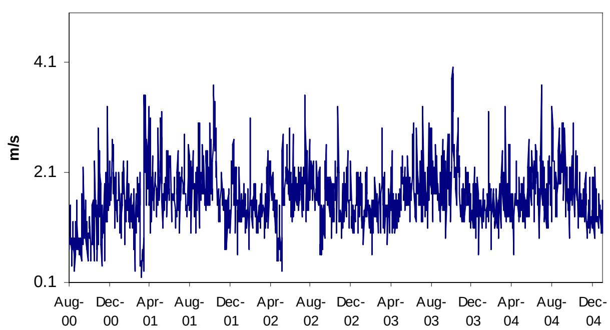


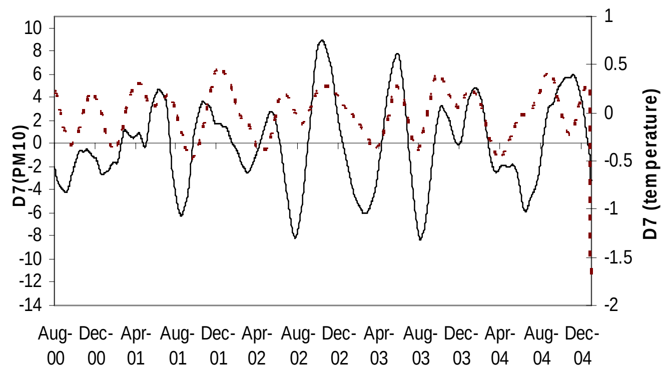
Fig. 4: The original time series of wind speed during August 2000 to December 2004.

3.1 Relationship between PM_{10} and temperature

The time series were decomposed using MODWT prior to correlation analysis. The significant positive correlations are registered for the low-frequency spectrums (*D5-D9*) as shown in Table 2. The correlations increased from *D5* towards *D9* with *D8* (256 days) registered the highest value. The correlation between the detailed component D8 is depicted in Fig. 5. The original time series (without decomposition) gives a weak *r* values of 0.167. Using wavelet, one can show that instead of weak *r* value with the original time series, there are components in the variations that show stronger relationship. However, previous study using non decomposed time series also recorded strong correlation where r = 0.5 for Petaling Jaya [18]. In the study, temperature was correlated with total suspended particulate (TSP) instead of PM_{10} for a period of 1990-1994. By using wavelet transform, it has been shown that short term temperature fluctuation (less than 30 days) has no significant influence to PM_{10} variations. Short term fluctuation do not have immediate effect may be due the fact that suspended particulate matter is not chemical reaction process like the effect of temperature has over ozone [8]. The low frequency spectrum (near annual) suggests a more regional aspects and the seasonal influence.

	Details components				
	D5	D6	D7	D8	D9
Period (days)	32	64	128	256	512
r	0.07	0.26	0.31	0.58	0.41

Table 2: Significant correlation coefficients (*r*) at the 0.01 level and periodicity between detail components of PM_{10} and temperature.



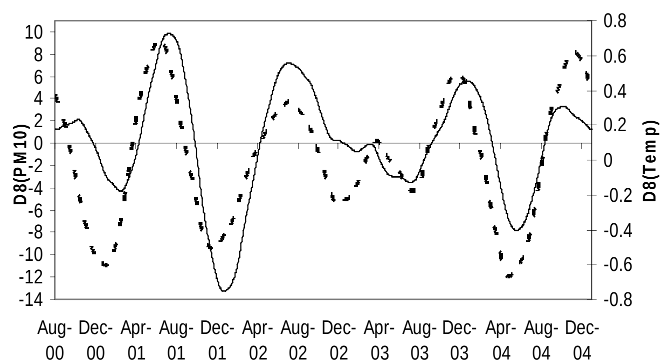


Fig. 5: The detail component *D8* for PM_{10} (solid) and temperature (dashed) during August 2000- December 2004.

High temperature of low frequency is linked to high PM_{10}. This could be associated to the suggestion that forest fire is one of the major sources of particulate beside road traffic [1,3]. The influence of seasonal factors as high temperature in a long run will promote forest fire which is a major contributor to particulate during the dry season. This is in agreement with other findings which pointed out that during the dry season the major sources of particulate was from outside the country [1,3].

3.2 Relationship between PM_{10} and rainfall

The relationship was investigated by applying wavelet transform to PM_{10} and rainfall time series for the period of August 2000 to December 2004 prior to analysis. Significant negative relationships between PM_{10} and rainfall are registered for low frequency detailed components *D5-D10* (Table 3). The negative correlation between rainfall and PM_{10} is an indication of the role of rainfall as wet deposition which removes particulates from the atmosphere. The highest correlations were found in *D8* (256 days), *D9* (512 days) and *D10* (> 512 days) with *r* values of 0.41, 0.47 and 0.49 respectively. The original series has a weaker significant negative correlation, *r* = 0.119. The value is somewhat similar to *r* = 0.0127 found by Sham, [13] for Kuala Lumpur-Petaling Jaya areas.

Field study in Sandakan (in Sabah, West Malaysia) observed that despite the cleansing capability of rainfall, the re-injection of particulates into atmosphere, after the rain negated the cleansing effect. In fact the atmosphere tends to be more stable after rainfall event, thus inhibiting dispersion and promote re-accumulation of particulates [14]. This may explain why the high frequency component of rainfall and PM_{10} shows no significant relationship. By decomposing the time series into several consecutive series of different time scales, it has been shown that it is the low frequency components that are correlated quite strongly. Without decomposing the series, the uncorrelated temporal components somehow resulted in lowering the overall correlation coefficient.

Since the episodes of high PM_{10} in this region are associated with forest fire, the long duration of rainfall event does not only have the ability to remove the particulates from the atmosphere. The more regional rainfall also has the influenced on the source of particulate *ie.* the forest fire. The more localized rainfall events may replenish the particulate from the atmosphere, however the PM_{10} concentration will be in high level again in the next few days as the source of the particulate is not affected by the local rainfall. This may contribute to the overall low correlation between suspended particulates and rainfall from previous studies.

	Details components					
	D5	D6	D7	D8	D9	D10
Period (days)	32	64	128	256	512	>512
r	-0.09	-0.1	-0.25	-0.41	-0.47	-0.49

Table 3: Significant correlation coefficients (*r*) at the 0.01 level and periodicity between detail components of PM_{10} and rainfall.

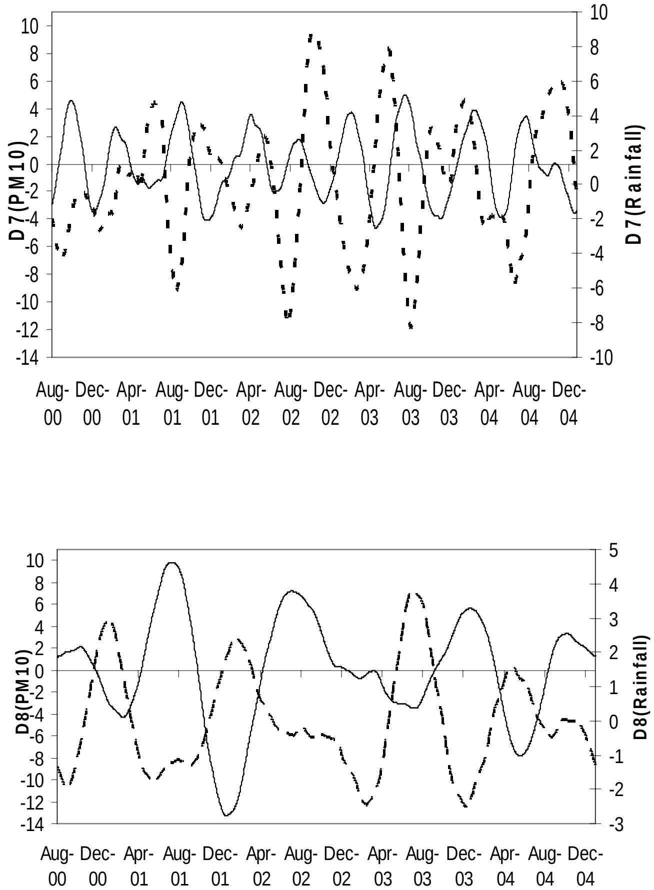


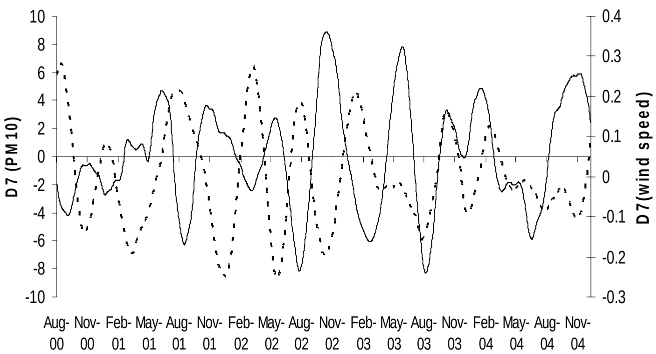
Fig. 6: The detail component *D7* and *D8* for PM_{10} (solid) and rainfall (dashed) during August 2000-December 2004.

3.3 Relationship between PM_{10} and wind speed

Significant relationships between PM_{10} and wind speed are registered for components *D4-D9* where both negative and positive correlations were recorded, Table 4. The strongest correlations are registered for *D7* (*r* = -0.358) and *D8* (*r* = 0.366). The higher frequency spectrum recorded negative correlation, while lower frequency recorded a positive correlation. However the correlation between the original PM_{10} between wind speed time series is insignificant at 0.05 confidence level. The combination of positive and negative correlations have resulted the overall correlation to become insignificant.

	Details components				
	D4	D5	D7	D8	D9
Period (days)	16	32	128	256	512
r	0.076	-0.058	-0.358	0.366	0.087

Table 4: Significant correlation coefficients (*r*) at the 0.01 level and periodicity between detail components of PM_{10} and wind speed. The *r* value for the original PM_{10} and wind speed is insignificant r = -0.012.



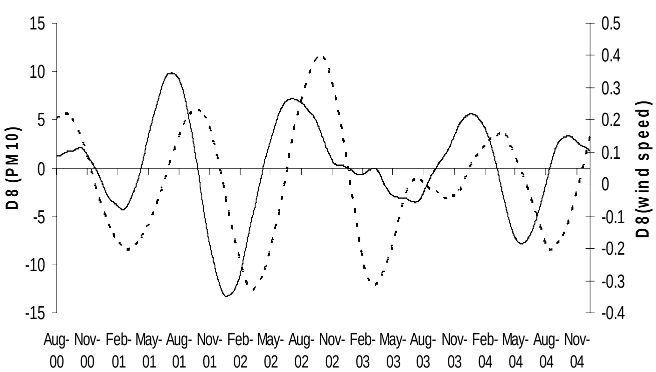


Fig. 7: The detail component *D7* and *D8* for PM_{10} (solid) and wind speed (dashed) during August 2000-December 2004.

By decomposing the time series, the significant components can be extracted from the original time series of PM_{10} and wind speed. Wavelet transform shows that only low frequency spectrums of wind speed have significant correlation with PM_{10}. This is an indication of the seasonal role in dispersing suspended particulate particulates. Day to day, short term variation in wind speed is not effectively acting as dispersion factor.

Generally, the negative correlation indicates the dilution effect of wind while positive correlation indicating the accumulation of pollutant. Thus component *D7* (128 days) indicates the wind speed has diluting effect while *D8* (256 days) has accumulating effect for particulates into the atmosphere.

Most of the previous studies on relationship between suspended particulate and wind speed have found either weak or strong negative correlations. Sham, [13] found a weak correlation, r = -0.1273 for Kuala Lumpur-Petaling Jaya areas. Other study found correlation coefficients was insignificant at 0.05 level for Petaling Jaya [23]. However, strong negatives correlations ranged from r = -0.742 to -0.362 were reported between 1990 to 1994 for Petaling Jaya [18]. The strongest correlation was registered during August to October while the lowest for the general 1990-1994 with r = -0.362.

It has been reported that during haze period, the high suspended particulate in Klang Valley was correlated with the injection of pollutants from outside the country *ie.* fire burning from Sumatera, Indonesia. This is the case during May-September when southeast monsoon is dominant. During other periods the source of suspended particulate is from internal especially from vehicular traffic. It can be understood, when particulates are solely from internal, the wind has a diluting effect thus produces negative correlation. When the injection of pollutant was from the external sources, it could be a positive correlation. During this period, wind was slow and acted as agent for injecting pollutants from outside the country [18]. This is indicated by the low frequency spectrum approaching annually spectrum registered for the process; 256 days, while negative correlation is registered for higher frequency spectrum of 128 days.

4. Conclusions

Meteorological parameters have great influences to suspended particulate variations. Using non-decimated wavelet decomposition, the relationships between PM_{10} and meteorological variables (temperature, rainfall and wind speed) have been examined. The correlation between PM_{10} and temperature was found positive. The correlations between PM_{10} and rainfall were negative while for PM_{10} and wind speed, positive and negative correlations were registered. In general, significant correlations were registered for components with lower frequency spectrums. Components of high frequency spectrums for meteorological variables have been found to have insignificant correlation with PM_{10}. The significant correlation coefficients for lower frequency spectrum support the influence of season for the variation in PM_{10} time series. This could be related to the previous studies which found that forest fire outside the country as the major source of particulates during dry season when southwest monsoon dominant. Short term changes have less influence on PM_{10} variation. This information was enabled using wavelet transform which decomposed the time series into several consecutive time series according to their time scale.

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