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Satellite data for upscalling urban air pollution in Malaysia

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Abstract. Air pollution has been recognised as one of risk factors that exert adverse effect on human health, climate change and environmental deterioration. Since particulate matter less than 10µm (PM_{10}) is used as an important air quality indicator in Malaysia, it is crucial to map the PM_{10} spatial distributions especially over Malaysian cities which encounter higher pollutant concentration due to trans-boundary and local sources. PM_{10} has been widely estimated using satellite data but the coarse resolution of 10km tends to average out the spatial variation especially in cities. Therefore, in this study we tested the Aerosol Optical Depth (AOD_{550}) product from Moderate Resolution Imaging Spectrometer (MODIS) sensor at 3km to estimate PM_{10} concentration over Peninsular Malaysia. The performance of AOD_{550} at 3km product was validated with AOD retrieved from AERONET stations and an accuracy of R^2 = 0.58 and RMSE= 0.13 was obtained. PM_{10} was estimated over the cities for the period 2007-2011 using MODIS AOD_{550} and meteorological variables (surface temperature, relative humidity, atmospheric stability, wind speed, wind direction). In consideration of their complicated relationship and non-linear mechanism that may exist between the variables artificial neural network (ANN) technique was utilized to develop an empirical model to estimate PM_{10} concentrations. Result shows that the empirical model developed using ANN was moderately robust with R^2 of 0.41 and RMSE = 12.99 μgm^{-3}. However, PM_{10} estimated with the model over the cities was validated using an independent set of field data produced an acceptable accuracy with R^2 = 0.39 and RMSE = 10.95 μgm^{-3}. The inclusion of meteorological parameters improved the prediction and the result obtained allow us to map pollution levels in Malaysia.

1. Introduction

A particulate aerosol in the atmosphere is known as Particulate Matter (PM). PM is also known as "aerosol particles" since it is suspended within the gases in the atmosphere [1]. PM can be divided into different sizes and PM_{10} (particulate matter less than 10µm) is an important air quality parameter measured in Malaysia. PM_{10} is referred to as thoracic particles since they are inhalable and can be deposited in trachea. These particles originate from roads, agriculture, dust, and construction activities [2]. Coarse mode (particle size<10µm) particle is generated from anthropogenic activities i.e. surface mining, agriculture and vehicle exhaust [3]. PM influences climate change by scattering and absorbing solar radiation, and it modifies our climate by altering radiation budgets, cloud properties and atmospheric circulation [2]. Furthermore, particulate matters originated from a natural or anthropogenic source can affect the air quality and cause respiratory problems [4], cardiovascular diseases [5], birth defects and premature death [6]. Due to environmental concern and health effects, PM_{10} concentration must be examined globally and remote sensing is the best approach to be used in Malaysia because only 74 PM_{10} monitoring stations are available to cover the entire Malaysian territory (330,290km^2).

Remote sensing retrieval of Aerosol optical depth (AOD) from multiple satellite sensors are commonly used to estimate PM_{10} and/or $PM_{2.5}$ from space. Among the available remote sensing data, MODIS AOD_{550} at 10km is found to have high retrieval accuracy over land (i.e. ±0.05*AOD under clear skies and ±0.15*AOD under moderate cloud cover), as well as nearly daily global coverage (Remer et al., 2008). Therefore, AOD data from MODIS sensor is widely used to estimate PM_{10} [7-11]. Nevertheless, this satellite data with coarse spatial resolution of 10 km tends to average out the spatial variation especially in cities. Other satellite data used to estimate PM_{10} are Multiangle Imaging Spectroradiometer (MISR) [12-13], Spinning Enhanced Visible and Infrared Imager (SEVIRI) [14], Medium Resolution Imaging Spectrometer (MERIS) [15-17] and Landsat [18]. In Malaysia not many studies have been attempted to retrieve PM_{10} at larger spatial scale using high spatial and temporal remote sensing data (see review paper by [19] and [20]). Therefore, this study we used MODIS AOD_{550} at 3km to estimate PM_{10} over Malaysia, where we focused to determine PM_{10} concentration over the state of Selangor in the west coast of peninsular Malaysia . In addition, meteorological parameters such as atmospheric stability (k index), relative humidity and surface temperature were also considered in the development of an empirical model since AOD-PM_{10} relationship is influenced by highly dynamic meteorological variables [7][15]. Artificial Neural Network (ANN) statistical technique has been used to associate MODIS AOD and other meteorological parameters for years 2007-2011. ANN techniques were implemented in this study because it consists of interconnected neurons that simplify the non-linear mapping between each set of inputs, thereby reducing the ambiguity of particulate matter estimation from satellite images [21]. The results obtained in this study allow us to map and study the pollution levels in Malaysia at large spatial and long temporal scales.

2. Study area

Southeast Asia (SEA) has the most complicated aerosol system in the world with complex meteorological data, heterogeneous land surface, high biological productivity, and various atmospheric pollutants [22]. Malaysia is a developing country in SEA that is undergoing rapid growth in industry and transportation, and as a result is experiencing increasing air pollution and PM_{10} concentrations [23-24], especially in big and industrial cities like Petaling Jaya, Shah Alam and Subang Jaya in the state of Selangor in the west coast of Peninsular Malaysia (Figure 1). Regional meteorology in Malaysia is characterized by four seasons, dry season (June-September), wet season (November-March) and two inter-monsoon seasons (April-May and October, respectively). In this study, we focused on Selangor since it has unhealthy air quality and experiences severe haze almost every year due to local sources and trans-boundary pollution [20]. Based on the State Structure Plan of Selangor 2020, about 36,592.52 hectares of land has been classified for development, where 80% of the restricted area will be mixed development [25]. The rapid urbanization in Selangor and its extreme changes would affect the air quality. In Selangor, PM_{10} concentration is measured at 5 stations strategically located in residential, traffic and industrial areas as shown in Figure 1.

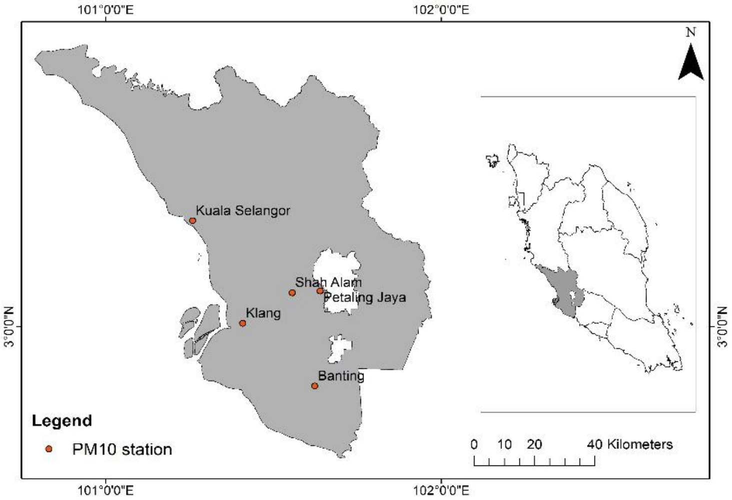

Figure 1. Map of the PM_{10} monitoring stations in Selangor, Malaysia

3. Methodology

3.1. Dataset

In order to estimate PM_{10} in the state of Selangor, both satellite and ground datasets were used. AOD_{550} data was acquired by MODIS sensor (MOD04_3K) at 3km spatial resolution while AOD_{500} from AERONET was obtained from 5 stations (USM, Tahir, Kuching, Songkhla and Singapore) for validation of MODIS AOD_{550}. Ground based hourly PM_{10} data were obtained from the Department of Environment (DOE) and the data was averaged from 10am-12pm to match with MODIS overpass time. The PM_{10} measurements from 29 stations were used for model development while another 16 stations were used for the validation of estimated PM_{10} from satellite data. In addition, we used the following dataset (i) Ground based ambient temperature and relative humidity from DOE (ii) MOD07_L2 (MODIS atmospheric profile) to obtain surface temperature and atmospheric stability (k index) (iii) MOD021km (MODIS level 1B Calibrated and Geolocated Radiance) for reflectance of Band 2, 5, 17, 18 and 19 (iv) Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) at 90m spatial resolution to calculate relative humidity that varies with elevation.

3.2. Methodology

The overall methods adopted to estimate PM_{10} concentration over Selangor are shown in Figure 2. First, we geo-referenced all the MODIS products to geographic latitude/longitude (WGS84) coordinate. Then, relative humidity was calculated by using bands 2 (0.865µm), 5(1.24µm), 17(0.905µm), 18(0.936µm) and 19 (0.940µm). Surface temperature and DEM from SRTM were used in equations provided by [26].

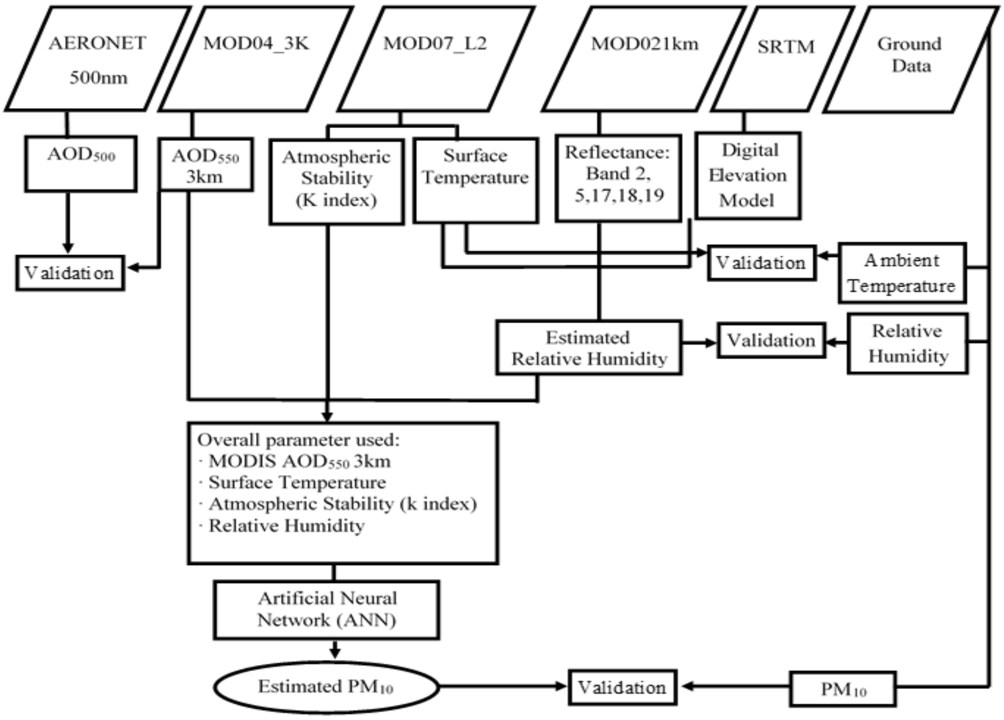

Figure 2. Flowchart of the overall method for PM_{10} estimation from space.

A Multiple Layer Perceptron (MLP) feed-forward ANN model was used in this study to estimate PM_{10}. In developing ANN model, we has carefully decided the important parameters to be used such as number of neurons in hidden layers, learning rate, momentum and stopping criteria. The ANN model used in this study consists of three layers (i.e. input, hidden and output). The input layer is composed of four nodes, AOD_{550}, RH, k index, and surface temperature. The output layer is the estimated PM_{10}. The 3 hidden nodes used after we started used one-two hidden layer however 3 hidden layer provided the optimum results. Theoretically, usage of many hidden nodes may lead more precise results but in our case 3 hidden nodes is adequate since we only has 4 inputs. In this study, the learning rate and momentum were used at 0.1 and we set the number of maximum training iterations (500 iterations) as the stopping criteria. It means, training will stop once the maximum number of iterations is exceeded. The ANN expected to provide better predictions because it is capable of analysing a pattern and minimizing error functions [27]. Finally, the estimated PM_{10} from space were validated against measured PM_{10} concentration from 16 stations. Root Mean Square Error (RMSE) and Mean Bias Error (MBE) were employed to assess the accuracy of the model developed.

4. Result and Discussion

4.1. Validation of MODIS AOD_{550} (3km) product

The MODIS AOD_{550} was validated against AERONET AOD_{550} acquired from 5 stations, 3 within Malaysia (USM Penang (5.36°N, 100.30°E), Tahir Penang (5.41°N, 100.19°E), Kuching (1.32°N, 100.35°E)) and 2 stations from neighboring countries (Songkhla (7.18°N, 100.60°E) and Singapore (1.29°N, 103.78°E)). The results of the validation are shown in Figure 3.

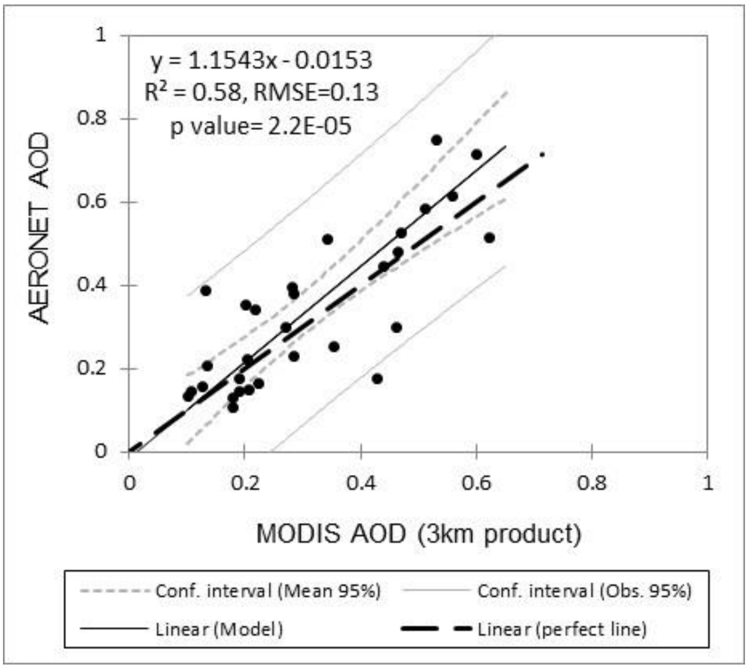

Figure 3. Validation of MODIS AOD_{550} 3km product retrieved by AERONET**.**

The overall performance of MODIS AOD_{550} yielded significant correlations with the AOD retrieved by AERONET. The number of MODIS AOD_{550} (N) used for this validation is 31. The small number of samples is due to the cloud cover and deficiency of long-term AERONET measurements [11]. Validation results show that MODIS AOD_{550} correlated well with AERONET AOD with R^2 = 0.58, p-value= 2.2E-05, RMSE = 0.13 (37.50%) and MBE = 0.13 as shown in Figure 3. Validation results from MODIS AOD_{550} at 3km resolution were slightly better than MODIS AOD_{550} at 10km from [11]. MODIS AOD_{550} at 3km was used to develop an empirical model to predict PM_{10} in Malaysia. The following section describes the empirical model developed to estimate PM_{10}.

4.2. Empirical model

An empirical model was developed in this study for PM_{10} estimations from space using MODIS AOD_{550}, and meteorological data (surface temperature, relative humidity and atmospheric stability) as shown in Equation 1 below.

$$PM_{10}= 55.19+ (34.04*H1) + (-3.24*H2) + (-22.19*H3) \quad (1)$$

where:
H1=TANH (0.5*((9.12) + (1.73*AOD) + (-0.08*surface temperature) + (-0.02*k index) + (-0.003*RH)))
H2=TANH (0.5*((148.62) + (-15.11*AOD) + (-2.33*surface temperature) + (-0.18*k index) + (-0.17*RH)))
H3=TANH (0.5*((69.88) + (-17.25*AOD) + (0.01*surface temperature) + (-0.15* k index) + (-0.15*RH)))

The accuracy of the model (equation 1) is R^2 = 0.41, RSME = 12.99μg m^{-3} and this developed model slightly over estimated the measured PM_{10} in the field with MBE= 0.17μg m^{-3}. The result obtained is promising since ANN improves PM estimates compared to linear models in previous studies [21] [15]. In addition, inclusion of meteorological parameters in the model (equation 1) is reliable to obtain better accuracy compared to AOD_{550} alone [7] [15]. The ANN technique produces significant result for estimations of PM_{10} concentrations as shown in Table 1.

Table 1. Statistical results (R^2, RMSE, MBE) of the Artificial Neural Network model used for PM_{10} estimation

R^2	0.41
RMSE (μg m^{-3})	12.99
MBE (μg m^{-3})	0.17
Sample size (N)	480

4.3. Model Validation

The ability of the model developed to predict PM_{10} concentrations over Selangor was examined by comparing them against PM_{10} concentrations measured at the 16 stations used for model validation. The correlation between measured and estimated PM_{10} using ANN exhibits statistically low accuracy with $R^2 = 0.39$, p-value = 6.5E-31, RMSE = 10.95μgm^{-3} (26.64%) and MBE = 0.24μgm^{-3} (Figure 4). Data points for both models are abnormally distributed within the 95% confidence interval, providing lower accuracy (Figure 4). The usage of 3km data may be contaminated by surface noise.

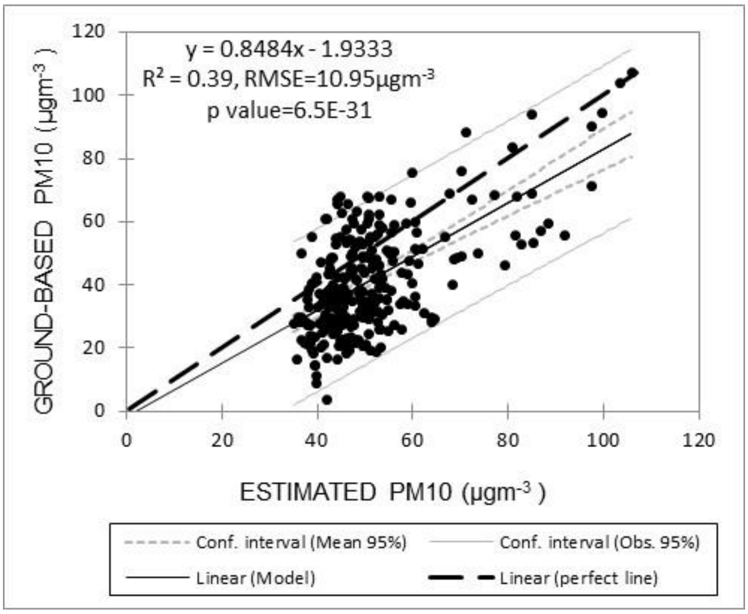

Figure 4. Validation of PM_{10} concentrations estimated using Artificial Neural Network techniques. The validations have been performed against measured PM_{10} concentrations at 16 stations over Malaysia during 2007-2011

4.4. Spatial distribution of PM_{10}

The seasonal-mean spatial distributions of the estimated PM_{10} during 2007-2011 are shown in Figure 5(a-d). During the dry season (Figure 5a) PM_{10} concentration over metropolitan area such as Klang, Shah Alam and Petaling Jaya (71-130 μgm^{-3}) were higher than the suburban areas like Kuala Selangor and Banting. According to DOE guidelines, PM_{10} concentrations of about 0-50 μgm^{-3} represent a relatively-clean "background" environment, while values of 51-100, 100-200, 200-300 and >300 μgm^{-3} correspond to moderate, unhealthy, very unhealthy and hazardous atmospheres, respectively. The atmosphere over Klang Valley (Klang, Shah Alam and Petaling Jaya) during dry season is "unhealthy" due to urbanization process, vehicle and manufacturing industries [28].

The mean spatial distribution of PM_{10} concentration during the wet season as shown in Figure 5b is much lower due to rain washout [29]. Heavy cloud cover during the wet season led to missing data as shown in Figure 5b. However, Klang Valley still showed an “unhealthy” air quality of about 91-100 μgm^{-3}. In the inter-monsoon season (April-May), PM_{10} spatial distribution is similar to that of the wet season, with the highest concentrations occurring over Klang Valley due to aerosol accumulation from vehicle emission, industry and biofuel burning [23].

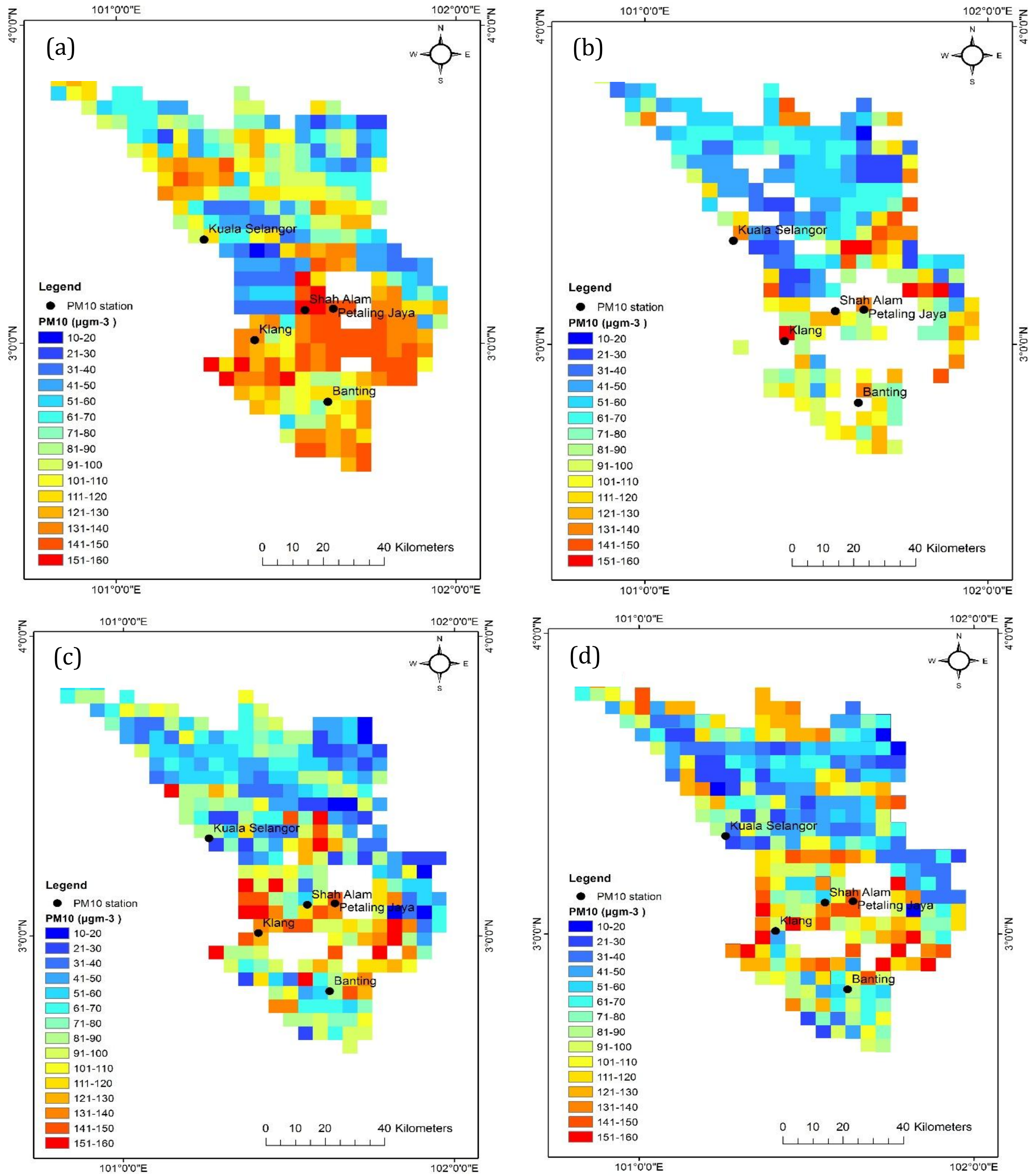

Figure 5. Spatial distribution of estimated PM_{10} concentrations over Selangor during 2007-2011 for (a) dry season (June-September), (b) wet season (November- March), (c) inter-monsoon (April-May) and (d) inter-monsoon (October).

This was proven when high hydrocarbon from vehicles and emission of sulphur dioxide (SO_2) were found in Klang Valley and other areas in Malaysia [30]. The inter-monsoon (October) exhibits high PM_{10} concentrations over many parts of Selangor. As expected, Klang Valley area has highest PM_{10} concentrations especially Shah Alam with value ~121-130 μgm^{-3}. According to [28] Shah Alam recorded the highest number of unhealthy days from 2001-2009 compared to other areas due to the high traffic volume. PM_{10} concentration during this period is higher also due to local sources and accumulation of biomass-burning aerosols from extensive agricultural fires that commonly occur during the dry season [31].

5. Conclusion

In this study, we developed an empirical model to estimate PM_{10} concentration over Malaysia by using MODIS AOD_{550} 3km product, surface temperature, relative humidity and atmospheric stability (k index) data. MODIS AOD_{550} 3km product was validated with AOD retrieved from AERONET and it was found that MODIS AOD_{550} correlated well with AERONET AOD with R^2 = 0.58, RMSE = 0.13 (37.50%) and MBE = 0.13. The model developed for PM_{10} estimation using the Artificial Neural Network was trained using measured PM_{10} concentration at 29 stations over Malaysia, yielding an accuracy of R^2 = 0.41, RSME = 12.99$\mu g\ m^{-3}$ and MBE= 0.17$\mu g\ m^{-3}$. However, the model's accuracy (R^2 = 0.39, RMSE = 10.95μgm^{-3} (26.64%) and MBE = 0.24μgm^{-3}) is only moderate when validated against PM_{10} concentration obtained from another 16 stations. Examination of the mean spatial distribution of PM_{10} concentration over Selangor showed that the urbanized area (Klang, Shah Alam and Petaling Jaya) has higher PM_{10} concentration due to local sources and trans-boundary pollutant. PM_{10} concentration pattern over Selangor shows that MODIS AOD_{550} at 3km is quite promising to be used for urban area, but it should be cautiously used in future since this product has high level of surface noise [32]. Finally, this study shows that meteorological parameters improved the results further and inclusion of other meteorological parameters such as wind speed would provide better PM_{10} estimation in future.

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