Remote Sensing of Tropospheric Pollutants Originating from 1997 Forest Fire in Southeast Asia

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Abstract

The massive forest fire in Indonesia in 1997 affected the whole Asian region by transporting large quantity of smoke plume. Malaysia bore the brunt due to its proximity, wind direction and weather conditions. Therefore, this study aimed at using coarse spatial but high temporal resolution Advanced Very High Resolution Radiometer (AVHRR) data of NOAA-14 satellite to detect and subsequently map the five primary fire pollutants i.e carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3) and particulate matter (less than 10 micron) (PM10) in Peninsular Malaysia. Regression analysis was used to establish a statistical relationship between above mentioned concentrations recorded at 5 stations around Peninsular Malaysia and reflectance values from AVHRR data. Among the 5 constituents, PM 10 showed a moderate correlation (R^2) of 0.51 whilst, other constituents revealed poor correlation with coefficient of less than 0.5. This model, was then applied to all the pixels in the image covering the whole peninsular Malaysia. The obtained values are in Air Pollution Index/ API values.

1. Introduction

In southeast Asia, it has become evident by estimates from satellite remote sensing data that biomass burning play an important role in air pollution and atmospheric chemistry. Palm oil plantations in Riau and other Sumatera provinces are the main source of the fires as many companies use fire as a cheap method to clear the land for the next planting season (UNEP, 1999). Emissions from forest fires represent a complex mixture of solid, liquid and gaseous compounds. Their composition varies widely depending upon the chemical and physical properties of the biomass burned, the combustion conditions and its efficiency (Heil, 1998). Combustion products of biomass burning include various hazardous gases such as carbon dioxide, carbon monoxide, nitrous oxide, oxides of sulfur, methane, non-methane hydrocarbons, nitric oxide and various types of atmospheric particulates. The proportion of particulate matter with a diameter smaller than 10 µm (PM10) to the total particulate emission in agricultural burning, is approximately 90 percent whereas organic carbon might contribute to over 90% of the dry mass of particulates emitted from biomass burning, with a maximum in the fine particle fraction (Heil, 1998).

Gases and atmospheric particulates are very efficient in scattering the sunlight. Scattering takes place by reflecting, refracting or defracting the radiation beam (Jacob, 1999). Scattering of solar radiation by gases and atmospheric particulates can limit human visibility in the troposphere; this phenomenon known as haze. Gases and particulate matter originating from Indonesian forest fire can be transported hundreds or even thousands of kilometres away. The 1997 and also the subsequent fire scenarios (1998, 1999 and 2000) have affected the whole Asian region with Malaysia bearing the brunt due to its proxity to Sumatera, wind directions (during monsoon season) and weather conditions. In Malaysia, the main pollutant contributing to the haze was PM10, besides CO, SO_2, NO_2 and O_3 (Vadivale, 1997). The fire constituents analysed in this study are assumed to be present in the lower atmosphere for about 1-2 weeks before it is deposited in the stratosphere (Jacob, 1999). The satellite data used in this study was acquired within 2 weeks from the fire occurrence in Sumatra province.

The ability to detect the extent and amount of the forest smoke plume during early stages of the disaster would greatly assist in the emergency response planning by responsible teams. Conventionally, the detection and amount of the constituents are identified using instruments such as air samplers, sun photometers and optical particle counters. However these techniques are limited by the large area covered by the smoke plume and obtaining data for multi-temporal purposes is logistically difficult, time consuming and costly. Satellite remote sensing can be used to determine the distribution and total content of the pollutants over large areas.

NOAA AVHRR satellite remote sensing data has become the workhorse for fire detection due to its coarse spatial but high temporal resolutions which makes it possible to detect and monitor the fast spread of fire

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emissions over countries, regions or even continents continuously. When illuminated by the sun, aerosols or gases backscatter a fraction of the radiation and this signal is detectable by satellites and the aerosol's magnitude is proportionally dependent on the amount of concentration of particulates or gases elements. This simple remote sensing principle allows the routine global scale monitoring of fire emissions.

A wide range of studies have been conducted using satellite remote sensing on biomass burning. Kaufman et al. (1990) used visible and near infra red wavelengths of NOAA AVHRR data to successfully quantify the gases and atmospheric particles originating from forest fire in Brazil with reasonable accuracy. Cahoon et al. (1994) and Christopher et al. (1995) used AVHRR data to estimate the particulates and trace gases originating from forest fire in China and south America respectively. Siegenthaler and Baumgartn (1995) developed a model to estimate the skylight caused by the haze particles in the lower troposphere.

In this study NOAA AVHRR data were used to map and measure the spatial distribution of PM10, CO, NO_2, O_3, and SO_2 from 22nd to 30th September, 1997 (period of thick haze episode) over peninsular Malaysia. The current study is an extension of previous work by Hashim and Ahmad (1997) who looked at the relationship between Total Suspended Particulates (TSP), measured on the ground and the digital number recorded by the NOAA 12 satellite.

2. Materials and Method

2.1 Satellite Data and Ancillary Information

NOAA 14 AVHRR data dated 22-30 September 1997 (short wavelengths; 0.58-1.10 µm) were used in this study. These dates were chosen because of the less cloud cover. Channels 1 and 2 of AVHRR data were used in the extraction of fire emission constituent information because atmospheric molecules and other tiny particles that are much smaller in diameter than the wavelength of the interacting radiation are efficiently diffuse the radiation. The effect of Rayleigh scattering is inversely proportional to the forth power of wavelength and therefore, there is much stronger tendency for short wavelengths to be scattered by this scattering mechanism than longer wavelengths Hence, the contribution of measured radiance at the top of the atmosphere from the path radiance is larger for shorter wavelengths. Smoke originated from wild forest fire is not observable in the mid-infrared (2.2 µm) due to the large ratio of wavelength to the size of the particles. Kaufman (1993) also used sun photometer/radiometer in the 0.44-1.03 µm range to make measurements of the path radiance and the aerosol optical thickness from the ground.

The data on fire emission constituents obtained via conventional methods were also used to establish a statistical relationship between reflectance values and fire emission constituents. The ancillary data on the 5 primary constituents of forest fire were provided by Alam Sekitar Malaysia Berhad (ASMA). These data were collected by 5 monitoring stations evenly distributed in Malaysia at, Kuala Lumpur (station A: 101°42.274' E, 03°08.286' N), Prai (station B: 100°24.194' E, 05°23.890' N), Pasir Gudang (station C:103°53.637' E, 01°28.225' N), Bukit Rambai (station D: 102°10.554' E, 02°15.924' N) and Bukit Kuang (station E: 103°25.826' E, 03°16.260' N). Locations of the 5 atmospheric constituents monitoring stations are shown in Figure 1.

2.2 Data processing

The methodology adopted in this study is shown in Figure 2. All data processing including calibration, pre-processing and mapping the amount of fire emission constituents were performed using the ERDAS IMAGINE (digital image processing system). The SPSS software was used for the statistical analysis.

(i) Data calibration

Raw digital numbers (DN) of channels 1 and 2 of AVHRR data were first converted into percent albedo values. Such conversion is important because the resulting reflectance compensating for the in-orbit degradation of DN as a result of weather changes before and after the launch of AVHRR sensor into the space. The conversion of DN to radiance governs the following relationship.

$$A_i = S_i C + I_i \qquad \text{Equation 1}$$

where, A_i is the percent albedo measured by AVHRR channel i, C is the input data value in digital number (DN), and S_i and I_i are the slope and intercept values for channel i, respectively. For channel 1, S_1 and I_1 values are 0.1318 and -5.4050 respectively. For channel 2, S_2 and I_2 values are 0.1657 and –6.7938 respectivel. These calibration coefficients (slope and intercept) were obtained from Rao and Chen (1998). These values are updated at NOAA/NESDIS in the 1B data stream at approximately one-month intervals.

(ii) Geometric correction

NOAA data were rectified by registering the raw image to a corresponding digital map (in raster format) of the area. In this context, the rasterized map acts as a master image, while the satellite data as a slave image. Pronounced recognizable features in both images like streams, confluence on rivers, islands, large man-made objects visible within the image were also selected as ground control points (GCP) to register the satellite image. A total of more than 20 GCPs were identified and used in the registration process employing the second degree polynomial transformation. This was followed by resampling (nearest neighbour) of the registered image using the same grid size i.e 1km to match the original NOAA AVHRR local areal coverage (LAC) data. The transformation accuracy /RMSE error achieved was 0.4862 pixel (Table 1). The rasterized and geometrically corrected images are shown in Figure 3.

(iii) Atmospheric correction

The atmospheric correction for this study was performed using radiative transfer model proposed by Jensen (1996) with ground truth parameters like temperature, relative humidity, atmospheric pressure, visibility, height from sea level (obtained from Malaysian Meteorological Service) and zenith angle (satellite parameter) determined from historic data (Table 2). An assumption of a Lambertian surface was made because it considers a perfect diffusion and therefore facilitate the calculation. Furthemore, for coarse resolution data like AVHRR, the effects of a non-perfect surface can be neglected. Reflectance values (after compensating for scattering and absorption of atmosphere) were obtained after performing the sequence of the following calculations:

(i) estimation of *total optical thickness,*
(ii) estimation of *atmospheric transmittance,*
(iii) estimation of *total irradiance at the surface* of the earth,
(iv) estimation of *the path radiance,*
(v) estimation of *the radiance sensed by the sensor* and,
(vi) estimation of *the reflectance.*

The atmospherically corrected satellite data was finally obtained using following equation:

$$R_{channel_i} = L_s - L_p/(1/\pi) T_\theta E_g \quad \text{Equation 2}$$

where, R *channel*$_i$ is the reflectance after compensating for atmospheric attenuation in channel 1/2, L_s is the radiance sensed by the sensor, L_p is the path radiance, T_θ is the atmospheric transmittance at θ zenith, and E_g is the global irradiance reaching the surface of the earth.

(iv) Cloud masking

Separating smoke plume from cloud pixels become difficult because of the bright backgrounds over which smoke is generated, lack of spectral separability between clouds and smoke and the limited number of spectral channels available from AVHRR imagery (Christopher et al., 1995). However various techniques have been developed to discriminate smoke plume from clouds. Among others are textural approach, pair-wise histogram approach, gross threshold technique, Q technique, coherence technique, New coherence technique and Tb4-Tb5 technique. In this study, a simple technique (Q technique), proposed by Saunders and Kriebal (1988) was used. This technique is based on the ratio between the reflectance in the NIR and visible bands of AVHRR data.

$$Q = R_2 / R_1 \quad \text{Equation 3}$$

where R_1 and R_2 represent the reflectivity of channels 1 and 2 respectively,

The Q values over cloud pixels are close to 1 due to quite similar Mie scattering effects of the reflectance for both channels. Over land/vegetated areas the Q values are higher than 1 due to the higher reflectivity in the near infra red than the visible. Over sea reflectance in the visible channel is much greater than the the infra red due to the effect of the absorption by water in the near infra red range (Franca and Cracknell, 1995). After performing the ratio calculation 'plume pixels' reveal values of less than 0.45 whereas cloud pixels exhibit values greater than 0.55. Subsequently, all the cloud pixels were masked out by assigning a value of 0 to cloud and a value of 1 to non- cloud pixels. The result is shown in Figure 4.

(v) Regression analysis

The measurement of space-borne remote sensing of gases and aerosol particles in this study are based on an assumed relationship between the ground measured Air Pollution Index values and the reflectance values of AVHRR channels 1 and 2. The amount of the five atmospheric constituents sampled at five monitoring stations

Table 1: Details of GCP selected for geometric correction

Point	x input	y input	x ref	y ref	type	x residual	y residual	RMSE	Contrib.
GCP #1	833.2844	-737.015	100.1297	6.568104	Control	0.085965	-0.60823	0.614275	1.263412
GCP #2	491.8191	-303.229	103.6255	2.663494	Control	0.211958	-0.23147	0.313855	0.645523
GCP #5	660.3253	-231.581	101.5565	2.045363	Control	-0.59666	0.227726	0.638641	1.313528
GCP #6	626.9347	-667.703	102.4825	5.918472	Control	-0.11111	0.033672	0.116104	0.238797
GCP #7	779.1338	-782.185	100.8248	6.951786	Control	-0.04061	0.56246	0.563925	1.159855
GCP #9	707.6934	-258.06	101.0177	2.289117	Control	0.450463	0.015843	0.450742	0.927065

Control Point Error (x) 0.3228 (y) 0.3636 Total RMSE = 0.4862 (dependent variables) and the calibrated reflectance from satellite data (independent variables) at the corresponding locations were used to establish empirical relationships between the atmospheric constituents and the reflectance. In this study, only 5 monitoring stations were employed due to the difficulty of obtaining pollution information over Malaysia during the haze period. The "Haze Committee of Malaysia" did not release much data to be published at that time. Furthermore, the data were collected and sold by Alam Sekitar Malaysia Berhad (Malaysia Environment Pvt. Lmt) which were expensive.

Therefore, a grouping sampling technique was used in this study to acquire more samples surrounding each monitoring stations. In this technique the population of the samples are divided into groups that occurs naturally. A locus of 2.75 km or 2.5 pixels was drawn surrounding each stations to acquire 25 sample pixels for each pollutants (Figure 5).

A regression analysis (using channels 1 and 2 of AVHRR) was carried out to learn more about the relationship in order to predict or check some of the common but not validated assumptions about the particle homogeneity, spatial distribution and estimation of the amount of the particles over Peninsular Malaysia. The model based on the best correlation coefficients (R^2) for each of the constituents was selected to be applied to every pixels of images of September 1997. The regression model expresses the best prediction of the dependent variable (fire emission constituents) at other locations all over peninsular Malaysia.

Root Mean Square Error (RMSE) was then determined from the computed constituents against the in-situ observations. Tables 4 and 5 summarize the results of the regression analysis and RMSE of computed PM10 and gases constituents. The scatter plots of each pollutant concentration versus reflectance is provided in Figure 6.

3. Results and Discussion

All the five pollutants revealed moderate to weak relationship with AVHRR reflectance value. The moderate relationship was exhibited by PM 10 and this is followed by NO_2, SO_2, CO and O_3. The models were then applied on calibrated images to map the spread and the amount of these pollutants over peninsular Malaysia.

For the determination of PM 10 from NOAA-14 AVHRR satellite, cubic regression gives the best result compared to other regression types tested. The R^2 value obtained is 0.51 whereas, the RMSE is 37. The R^2 and RMSE values obtained for other pollutants are shown in Tables 3 and 4 respectively. Figure 7 shows the amount and spatial distribution of the pollutants. The distribution of PM 10 for the date 26 September, 1997 is shown in Figure 7 (a) whereas, Figure 8 reveals the multi-temporal analysis of the 5 pollutants at the 5 monitoring stations for different dates. Among all the 5 pollutants, PM 10 was found to be the largest pollutant released during the fire. It exceeds an API value of 100, which is an unhealthy condition specified by the Malaysian Air Quality Index. It was also the concern of many people because it is respirable and can cause diseases like asthma attacks, chronic bronchitis, decreased lung function and etc. According to Figure 7 (a), the distribution pattern of PM 10 is more concentrated in south east and middle of Peninsular Malaysia with API values ranging from 50-150.

For SO_2, cubic regression model between SO_2 and reflectance of channel 1 gives a R^2 of 0.31 and RMSE of 19. The highest API value noticed on 29 September, 1997 is 16-20 in the middle and east coast of Peninsular Malaysia. This amount is identified as an insignificant level by the Malaysian Air Quality Index. A similar insignificant conditions are observed for other pollutants like NO2, CO and O3. The details of these pollutants can be seen in tables 3, 4 and Figures 6 and 7.

The reasons for the dispersion and transmission of these pollutants from Sumatera is the prevailing meteorological conditions in south east Asia in 1997. From August onwards, significant haze started accumulating in the lower atmosphere near the main fire locations, southern-east Sumatra and southern West- and Central-Kalimantan. Spreading and intensifying fire locations in the following months contributed to a further atmospheric enrichment. The enrichment was accelerated by the induced formation of inversion layers. Predominating south-east wind directions transported the haze to the north-west and caused subsequently high pollution levels in fire remote locations.

4. Conclusions

Remote sensing can be used for mapping air pollutants over large areas quickly Satellite sensors typically provide coarse resolution smoke plume maps which show the general location and extent of the phenomena. Monitoring the amount and the extent of the smoke plume requires analysis of visible and short wavelength infra-red channels of AVHRR. In this study the regression analysis using air pollutant readings obtained from in-situ observation stations and satellite reflectance shows moderate to poor correlation for all the pollutants. This could be due to the limited number of ground measured pollutant samples used to establish the regression between satellite reflectance and ground measured pollutant samples. Of all the five pollutants, PM10 was identified as the most hazardous pollutant present over Malaysian atmosphere during the 1997 forest fire scenario in south east Asia. The high level of this pollutant could also be contributed by construction activities and unpaved roads.

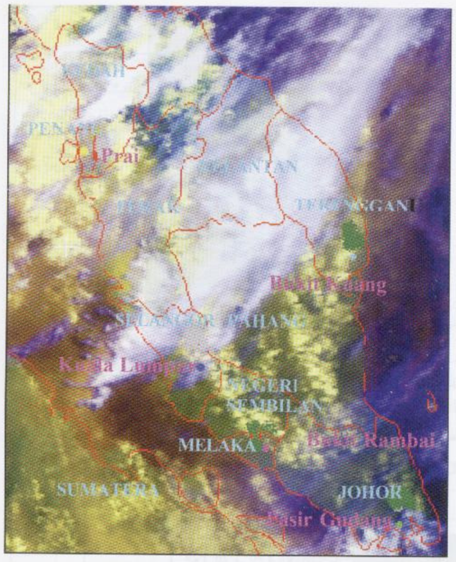


Figure 1: Locations of the 5 atmospheric constituents monitoring stations, overlaid onto geometrically corrected composite of channels 1, 2, and 3 in RGB. Writings in capital letters show the states in Peninsular Malaysia while, lower case writings represent the atmospheric constituents' monitoring stations in Malaysia.

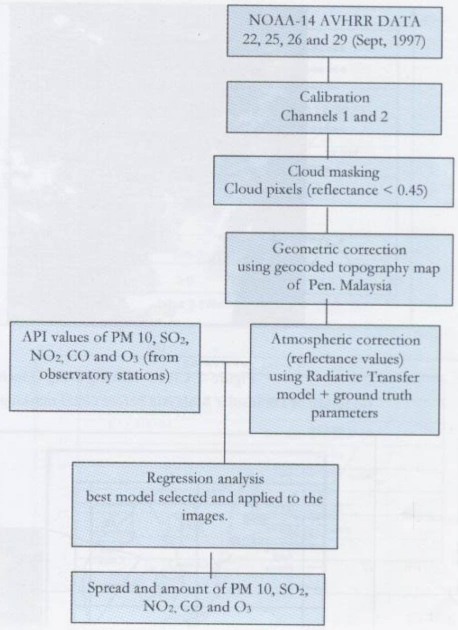
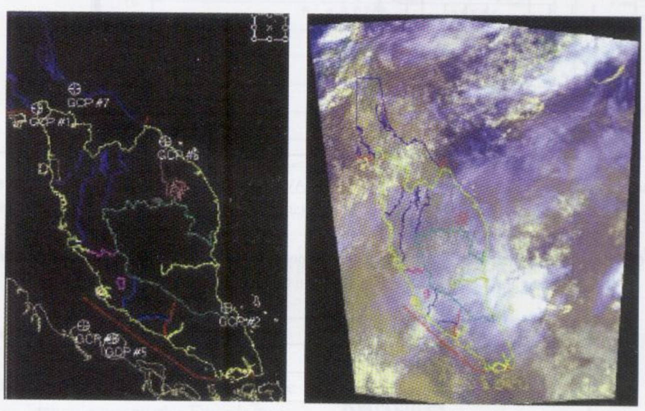


Figure 2: Procedures adopted to map and quantify atmospheric pollutant gases and particulates originated from 1997 forest fire.



(a) (b)

Figure 3: (a) The rasterized image of Peninsular Malaysia with GCP points selected for geometric correction and (b) the geometrically corrected AVHRR image dated 23 September, 1997 (overlaid by the rasterized image).

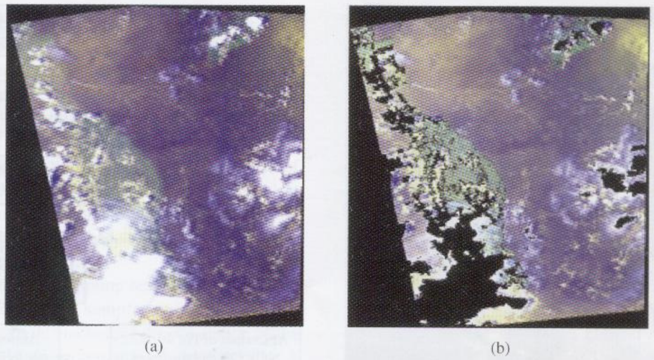


Figure 4: Cloud masking using Q technique on image dated 22 September, 1997
(a) image of Peninsular Malaysia before cloud masking (values in percent reflectance) and (b) after cloud masking.

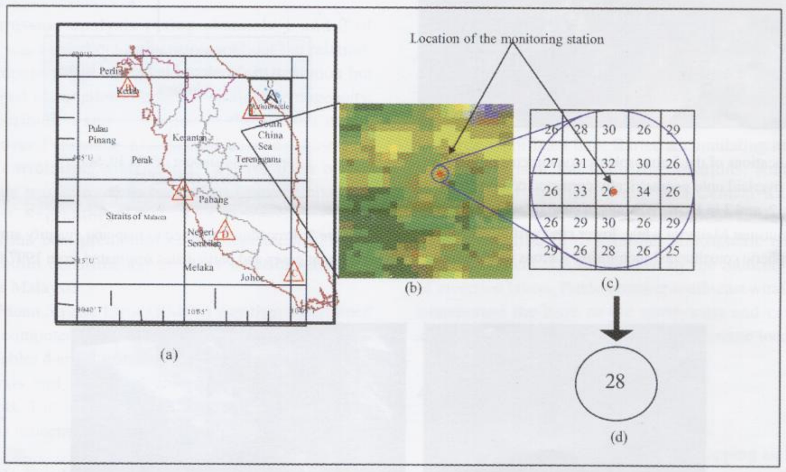


Figure 5: Reflectance samples taken from NOAA- 14 AVHRR.(a) Monitoring stations (b) zoomed station
(c) a 2.75 km locus surrounding the monitoring station and (d) average reflectance in the locus.

Table 2: Ground-truth parameters used in radiative trasfer model to estimate the reflectance values of AVHRR data. The values are averaged, measured values in the field from 22-30 September, 1997.

Parameters	Averaged value
Satellite zenith angle	36.52 °
Temperature	27.28 °C
Relative humidity	83.40 %
Atmosphere pressure	1011.86 mbar
Visibility	3.74 km
Altitude from sea level	14.16 m

(Source: Malaysian Meteorological Service, 1997)

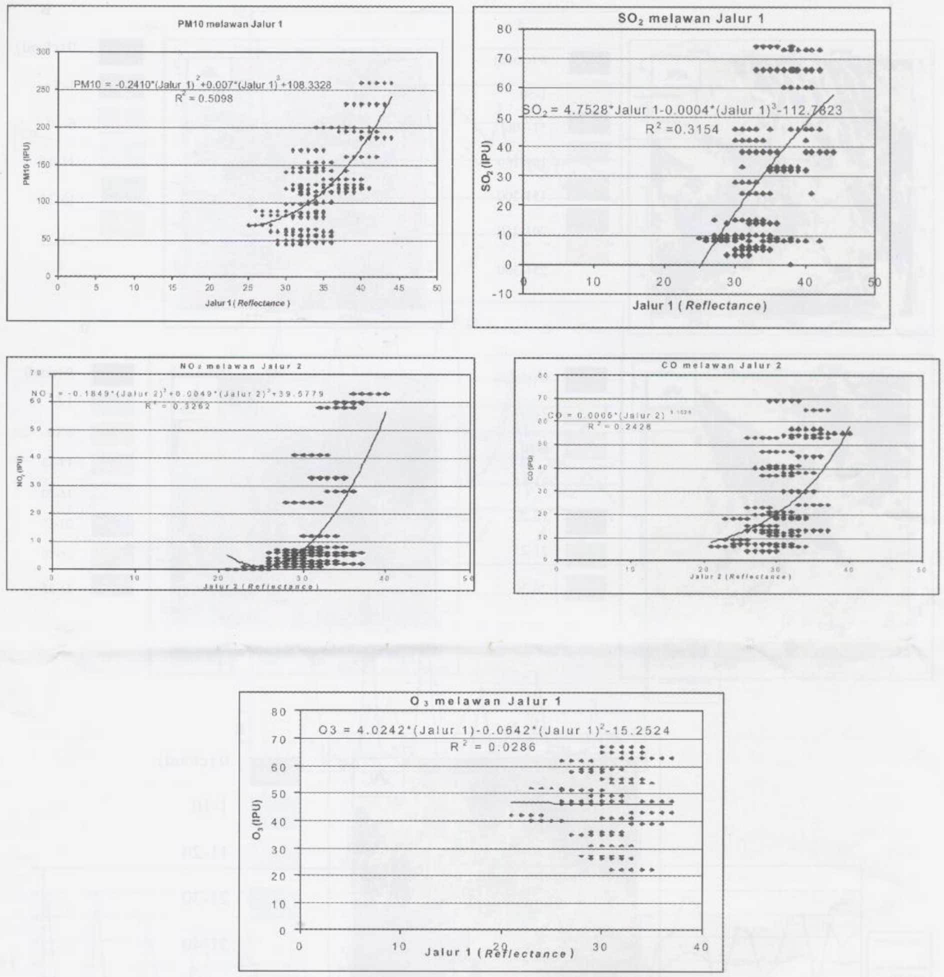


Figure 6: The scatter plots of each pollutant concentration versus reflectance.

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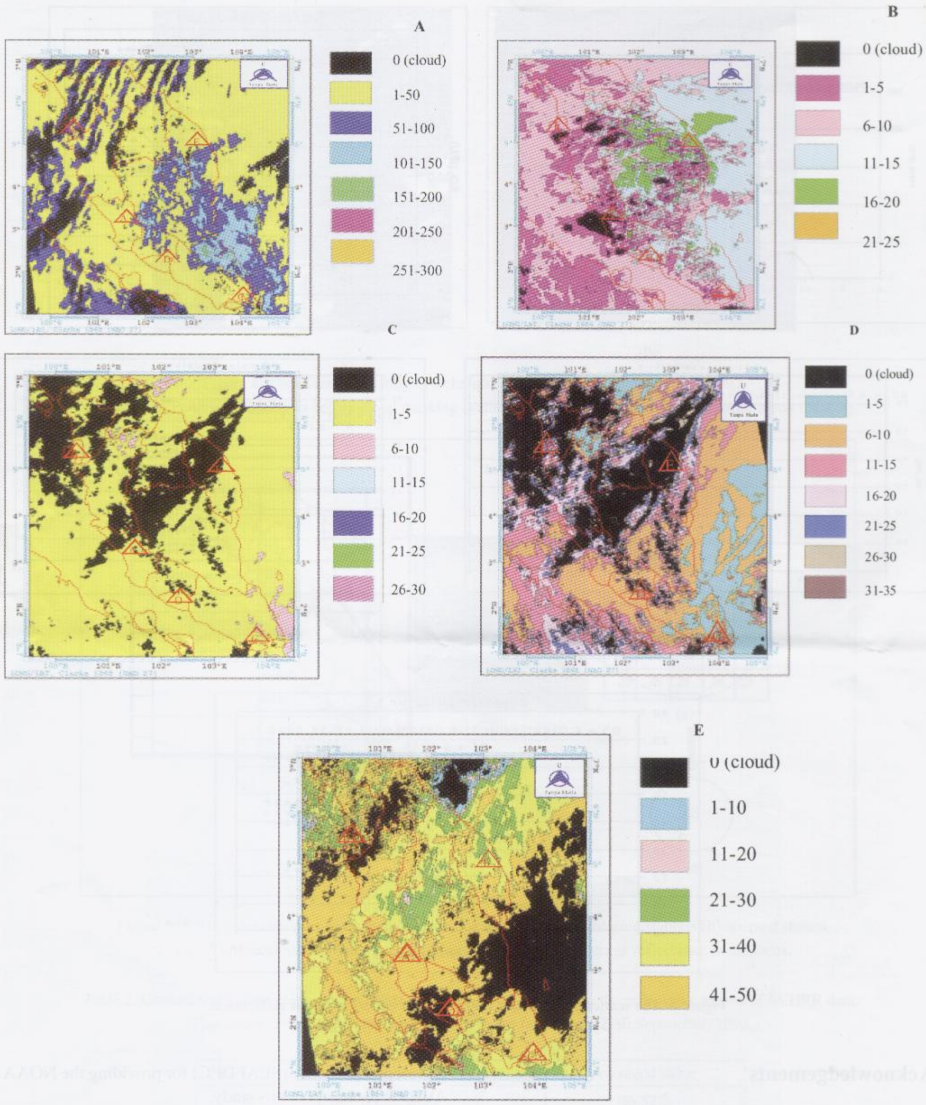

Figure 7: The spread and amount (A) PM10 (during 26 September, 1997) (B) SO2 (29 Sept), (C) NO2, (22 Sept), (D) CO (22 Sept), and (E) O3(25 Sept), over Peninsular Malaysia during September, 1997 haze episode.

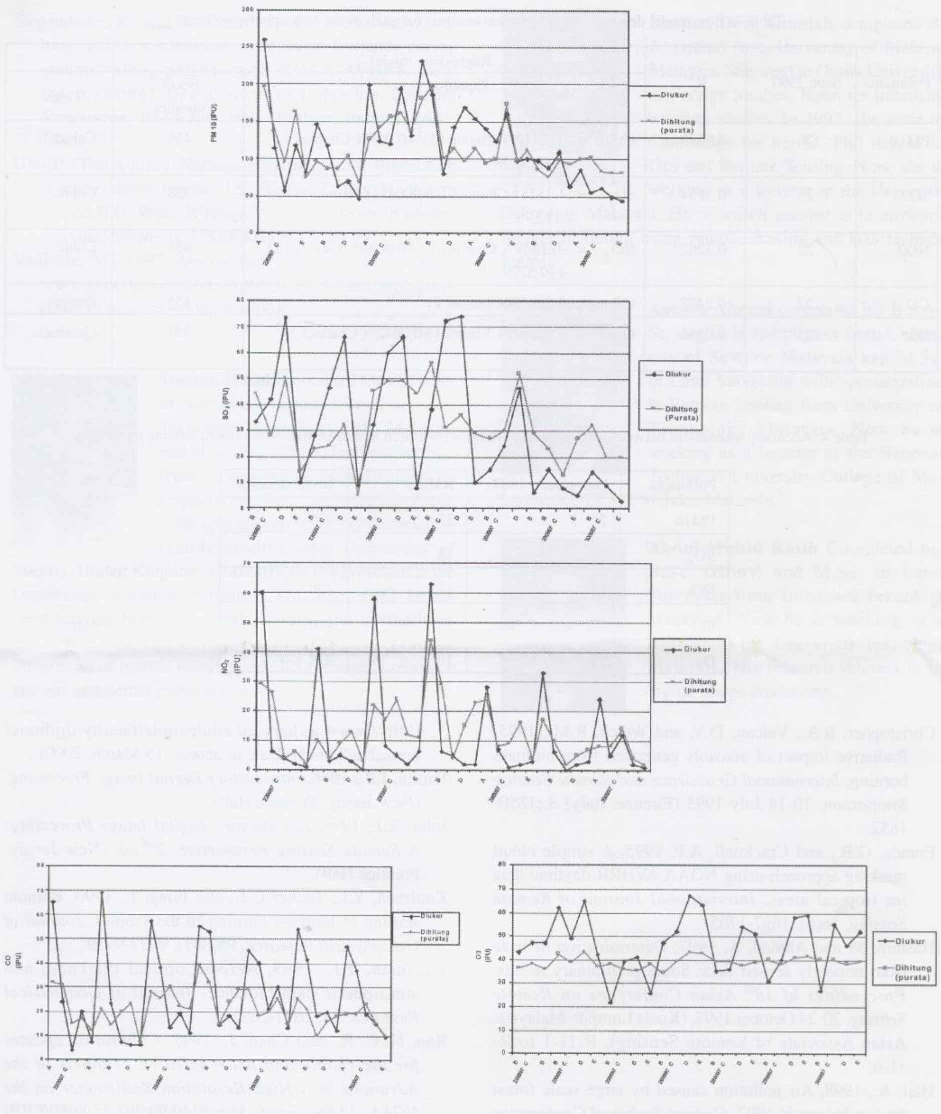

Figure 8: Multi-temporal analysis of PM 10, SO_2, NO_2, CO and O_3. X- scales represent the 5 monitoring stations at different dates during September 1997 while, Y-scales represent the pollutants in API values. Symbols: diamonds = measured values, squares = estimated (average) values. A, B, C, D and E represent the monitoring stations (Refer section 2.1).

Table 3: Best model derived from regression analysis for each of the atmospheric pollutants.

Pollutants	Sept, 1997	R^2	Regression model		
			Equation	No of samples	Types
PM10	26	0.5098	$PM10 = -0.2410*(\text{Channel } 1)^2+0.007*(\text{Channel } 1)^3 +108.3328$	455	Cubic
SO2	29	0.3154	$SO_2 = 4.7528*\text{Channel } 1-0.0004*(\text{Channel } 1)^3 -112.7823$	338	Cubic
NO2	22	0.3262	$NO_2 = -0.1849*(\text{Channel } 2)^2+0.0049*(\text{Channel } 2)^3 +39.5779$	455	Cubic
CO	22	0.2428	$CO = 0.0005*(\text{Channel } 2)^{3.1026}$	455	Power
O3	25	0.0286	$O_3 = 4.0242*(\text{Channel } 1)-0.0642*(\text{Channel } 1)^2 -15.2524$	351	Quadratic

Table 4: Accuracy assessment between atmospheric pollutants measured and estimated with remote sensing technique.

Pollutants	Dates/Sept, 1997	RMSE	No of samples
PM10	26	33	420
SO_2	29	18	312
NO_2	22	11	420
CO	22	13	420
O_3	25	10	324

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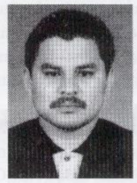

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