Taylor & Francis
Taylor & Francis Group

The use of AVHRR data to determine the concentration of visible and invisible tropospheric pollutants originating from a 1997 forest fire in Southeast Asia

M. HASHIM*, K. D. KANNIAH, A. AHMAD, A. W. RASIB and A. L. IBRAHIM

Department of Remote Sensing, Faculty of Geoinformation Science and Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

Abstract. A massive forest fire in Indonesia in 1997 affected the whole Asian region by producing a large smoke plume, with Malaysia bearing the brunt due to the wind direction and weather conditions and because of its proximity to the source. The five primary fire produced pollutants were carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3) and particulate matter less than 10 μm (PM10). The first four of these are, of course, invisible to conventional satellite-flown multispectral scanners operating in the visible and near infrared regions of the electromagnetic spectrum. The fifth, PM10, is present in the haze and therefore makes an observable contribution to the signal received by the Advanced Very High Resolution Radiometer (AVHRR). The haze in AVHRR channels 1 and 2 data for the fires of September 1997 has been used to study the concentration of PM10 directly. It has also been used to study the concentration indirectly—as a tracer or surrogate—for the four remaining materials, the gases CO, SO_2, NO_2 and O_3. Data from ground observations have been used to calibrate the results and the distributions of the fire pollutants over Peninsular Malaysia have been plotted.

1. Introduction

In Southeast Asia it has become evident that biomass burning plays an important role in air pollution and atmospheric chemistry. Palm oil plantations in Riau and other Sumatra provinces are the main sources 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 their efficiency (Heil 1998). Combustion products of biomass burning include various hazardous gases such as carbon dioxide, carbon monoxide, nitrous oxide, oxides of sulphur, methane, non-methane hydrocarbons, nitric oxide and various types of atmospheric particulates.

The ability to detect the extent and amount of the forest smoke plume during

---

*Corresponding author; e-mail: mazlan@fksg.utm.my

the 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.

Research on forest fire pollutants has become an important component in atmospheric studies due to its tremendous implications to atmospheric chemistry, radiation budget, increasing greenhouse gases, loss of biodiversity, decreasing evapotranspiration and rainfall from altered general circulation patterns, increasing surface albedo, run-off, spread of plant and human diseases via colonization. Fire distribution frequency with ground-based information on particulate concentrations can be used to derive estimates of trace gas concentration from satellite data (Kaufman *et al*. 1990). Furthermore aerosol mass concentration per unit area can be used to study aerosol climatology, to monitor the sources and sinks of specific aerosol types and to serve as inputs for climate modelling and detection of finger prints of anthropogenic climate change and to perform atmospheric corrections of remotely sensed surface reflectance over the land (Kaufman and Tanré 1998).

National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite remote sensing data have become extremely important for fire detection because, despite their coarse spatial resolution, their high temporal resolutions enables the detection and monitoring of the fast spread of fire 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 concentration of particulates or gaseous elements. This simple remote sensing principle allows the routine global scale monitoring of fire emissions.

Gases and atmospheric particulates are very efficient in scattering the sunlight. Scattering takes place by reflection, refraction or diffraction of the radiation beam (Jacob 1999). Scattering of solar radiation by gases and atmospheric particulates can limit human visibility in the troposphere; this is the phenomenon known as haze. Gases and particulate matter originating from Indonesian forest fires can be transported hundreds or even thousands of kilometres away. The 1997 and also the subsequent fire scenarios (in 1998, 1999 and 2000) affected Malaysia where, 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 they are concentrated in the stratosphere (Jacob 1999). The satellite data used in this study were acquired within 2 weeks from the fire occurrence in the Sumatra province.

Kaufman *et al*. (1990) used visible and near infrared wavelengths of NOAA AVHRR data to quantify successfully the gaseous 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 fires in China and South America, respectively. Siegenthaler and Baumgartner (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 22 to 30 September 1997 (a

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

Channels 1 and 2 of NOAA-14 AVHRR data dated 22, 23, 24, 25, 26, 27, 28, 29 and 30 September 1997 (short wavelengths; 0.58–1.10 μm) were used in this study. These dates were chosen because of the lower 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 efficiently diffuse the radiation. The effect of Rayleigh scattering is inversely proportional to the forth power of wavelength. Hence, the contribution of measured radiance at the top-of-the-atmosphere from the path radiance is larger for shorter wavelengths. Smoke originating from wild forest fires 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 a 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 five primary constituents of forest fire were provided by Alam Sekitar Malaysia Berhad (ASMA). These data were collected by five 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 five atmospheric constituent 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 was performed using the ERDAS IMAGINE (digital image processing system). The SPSS software was used for the statistical analysis.

2.2.1. Data calibration

Raw data from AVHRR channels 1 and 2 data were first converted into reflectance. The conversion of DN to reflectance governs the following relationship.

$$A_i = S_i C + I_i \qquad (1)$$

where A_i is the reflectance 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.

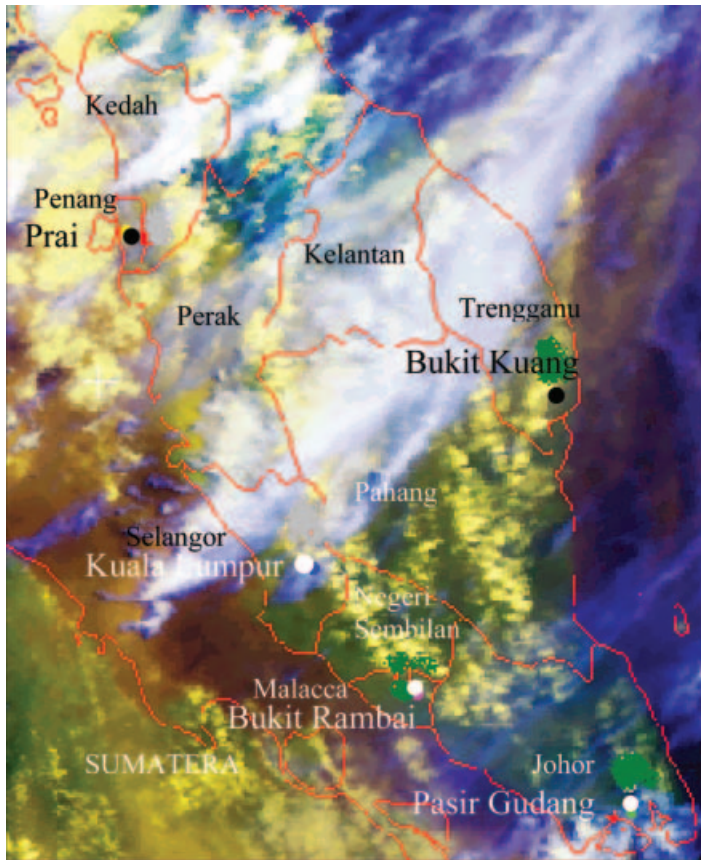The values of S_i and I_i for the AVHRR on NOAA-14 are given in table 1.

Figure 1.   Location of the five atmospheric constituent monitoring stations (●), overlaid onto a geometrically corrected composite of channels 1, 2, and 3 in RGB.

2.2.2. *Geometric correction*

The AVHRR data were rectified by registering the raw image to a corresponding digital map (in raster format) of the area using more than 20 ground control points and employing a second degree polynomial transformation. This was followed by nearest neighbour resampling of the registered image using the same grid size, i.e. 1 km, to match the original NOAA AVHRR local areal coverage (LAC) data. The transformation accuracy/RMSE error achieved was 0.49 pixels (table 2). The rasterized and geometrically corrected images are shown in figure 3.

2.2.3. *Atmospheric correction*

Solar radiation is affected as it travels through and interacts with the Earth's atmosphere. Serious atmospheric attenuation makes it difficult to relate ground measurements with satellite measurements and so it is necessary to perform atmospheric correction to allow for the effect of the atmospheric attenuation. The atmospheric correction for this study was performed using a radiative transfer model proposed by Jensen (1996: 115) with satellite zenith angle and ground truth parameters like temperature, relative humidity, atmospheric pressure, visibility, height from sea level determined from historic data, obtained from the Malaysian Meteorological Service) and zenith angle (satellite parameter) determined from
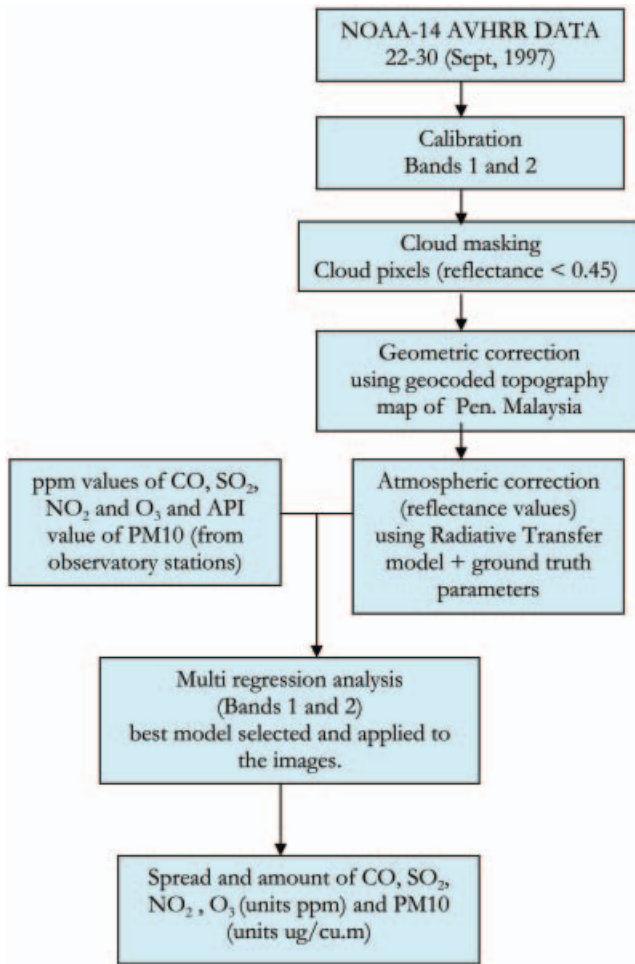
Figure 2. Procedures adopted to map and quantify atmospheric pollutant gases and particulates originated from the 1997 forest fire.

historic data (see table 3). An assumption of a Lambertian surface was made because it considers perfect diffusion and therefore facilitates the calculation. Furthermore, 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 following calculations:

(i) estimation of total optical thickness,
(ii) estimation of atmospheric transmittance,

Table 1. The slope and intercept values (S_i and I_i) for AVHRR data of NOAA-14 channels 1 and 2 used in this study. Subscripts indicate the corresponding channel. (Source: Rao and Chen 1998.)

Satellite	S_1	I_1	S_2	I_2
NOAA- 14	0.1318	−5.4050	0.1657	−6.7938

Table 2. Details of ground control points selected for geometric correction.

Point	x input	y input	x ref	y ref	Type	x residual	y residual	RMS error	Contribution
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$=$0.4862.

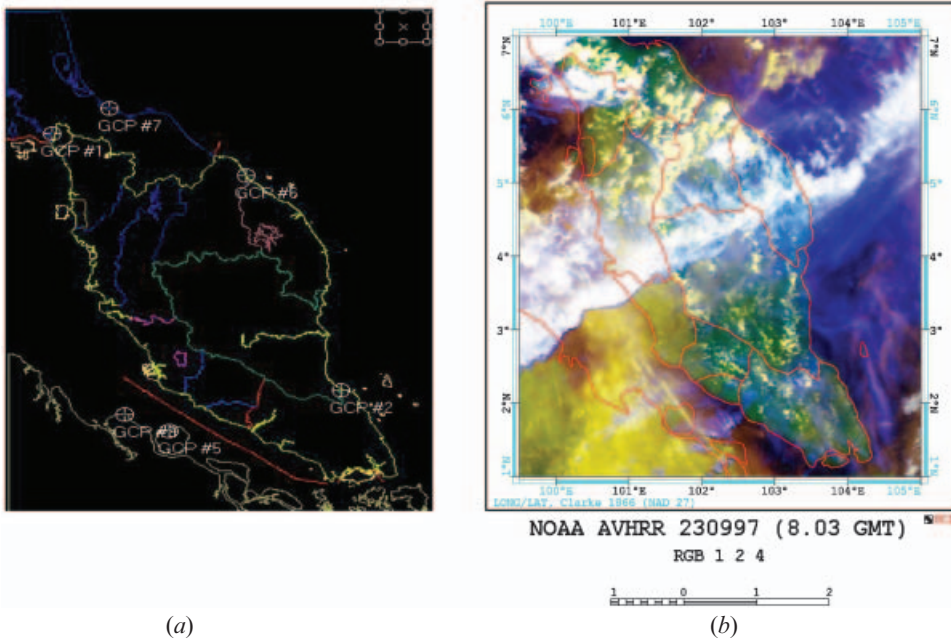(*a*)   (*b*)

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

(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,
(vi) estimation of the reflectance.

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

$$R_{\text{channel}i} = (L_s - L_p)/(1/\pi)T_\theta E_g \qquad (2)$$

where $R_{\text{channel}i}$ is the reflectance after compensating for the 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.

Table 3. Ground-truth parameters used in the radiative transfer model to estimate the reflectance values of AVHRR data. (Source: Hashim and Ahmad 1999.)

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

2.2.4. *Cloud masking*

Separating the smoke or haze plume from cloud pixels becomes 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 in AVHRR imagery (Christopher *et al.* 1995). However, various techniques have been developed to discriminate smoke plumes from clouds involving texture, histograms, thresholds, ratios, brightness temperature differences and coherence techniques (Coakley and Bretherton 1982, Saunders 1986, Saunders and Kriebel 1988, Theirmann and Ruprecht 1992). In this study, a simple ratio technique (*Q* technique), proposed by Saunders and Kriebel (1988) was used. This technique is based on the ratio between the reflectance in the NIR and visible channels of AVHRR data; i.e.

$$Q = R_2/R_1 \tag{3}$$

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 vegetated land areas the Q values are higher than 1 due to the higher reflectivity in the near infrared than the visible channels. Over sea, reflectance in the visible channel is much greater than the infrared due to the effect of the absorption by water in the near infrared range (França and Cracknell 1995). For the smoke plume pixels the calculated values of Q were less than 0.45 whereas for cloud pixels the values were greater than 0.55 and this was used to mask out the cloud pixels. The result is shown in figure 4.

2.2.5. *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 aerosols and the spectral reflectance. The concentration of each of the five atmospheric constituents (CO, SO_2, NO_2 and O_3 in ppm and PM10 in API (Air Pollution Index)) acquired at the five monitoring stations (dependent variables) and the
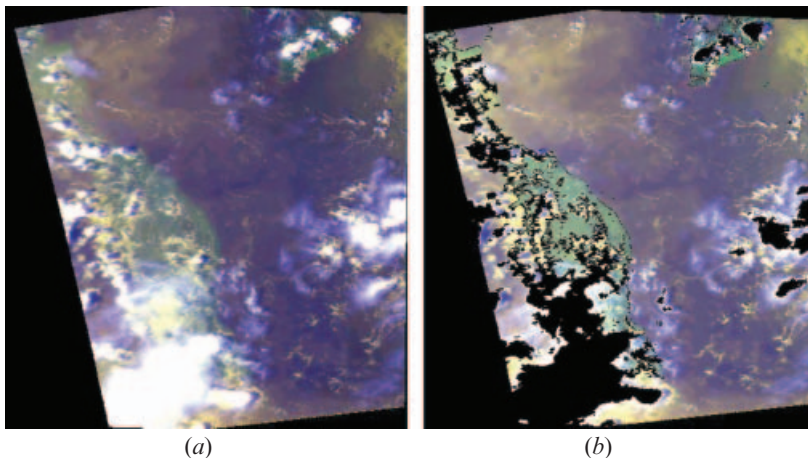

(*a*)   (*b*)

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

calibrated reflectance from satellite data (independent variables) at the corresponding locations were used to establish an empirical relationship between the atmospheric constituents and the scattered spectral reflectance.

Samples consisting of nine pixels (i.e. 3×3 pixels) selected around the monitoring stations were used in the regression analysis (see figure 5). The choice of this number of pixels was a compromise between the requirement of a larger number to improve the statistical significance and the natural spatial variability in the data. For each of the five atmospheric constituents a linear relation between its concentration and the reflectance in channels 1 and 2 was assumed and the coefficients were determined by a least squares fit using the mean radiance from five
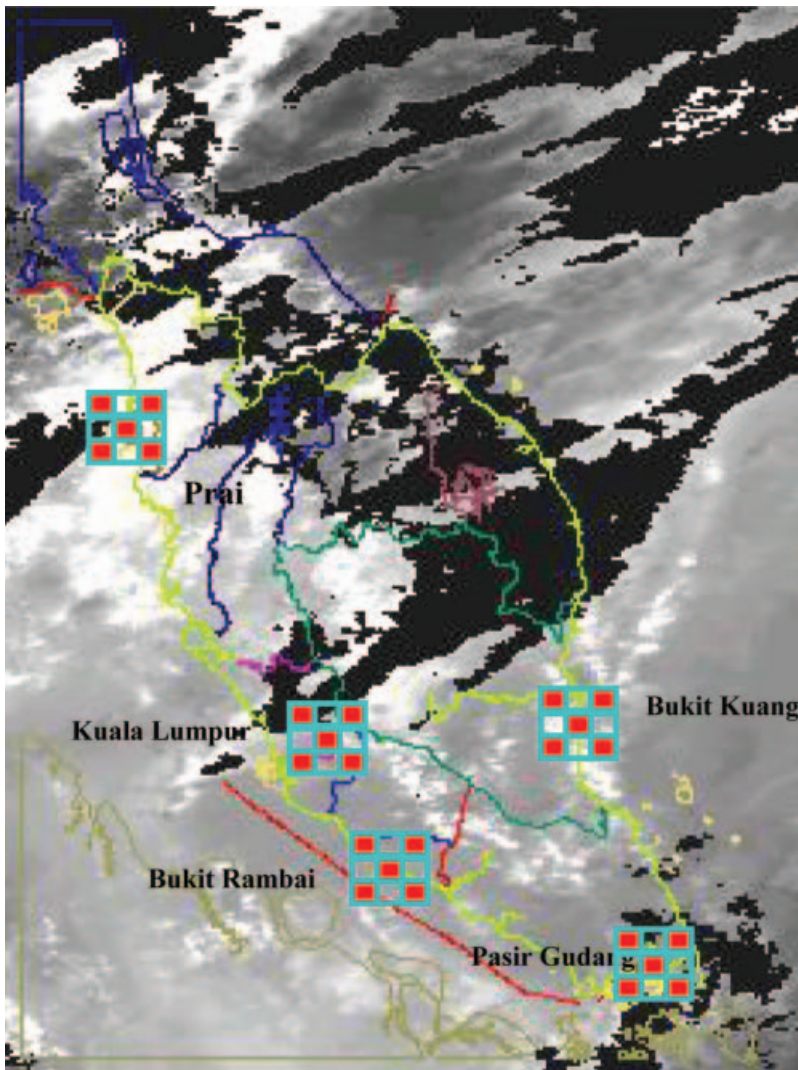
Figure 5. Location of the monitoring stations and the pixels selected for regression analysis and RMSE error. Pixels coloured in red are the pixels selected for regression analysis and the transparent pixels neighbouring the red pixels are the pixels/points selected for RMSE analysis. The middle pixel also represents the location of the monitoring stations.

Table 4. Best model derived from multi-regression analysis for each of the atmospheric pollutants and their RMS error.

Atmospheric pollutants	Best regression coefficients (r^2)	RMSE	Model
Nitrogen dioxide (NO_2)	0.977	0.006	$y = 1.900 \times 10^{-2}(DN1) + 1.192 \times 10^{-2}(DN2) + 0.236$
Carbon monoxide (CO_3)	0.939	0.162	$y = 3.076 \times 10^{-3}(DN1) + 2.346 \times 10^{-2}(DN2) - 1$
Sulphur dioxide (SO_2)	0.611	1.059	$y = 0.002(DN1) - 0.001(DN2) + 0.009$
Ozone (O_3)	0.844	0.017	$y = -1.002 \times 10^{-3}(DN1) + 2.740 \times 10^{-4}(DN2) + 7.452 \times 10^{-2}$
PM 10	0.958	17.834	$y = 11.281(DN1) - 5.045(DN2) - 138.893$
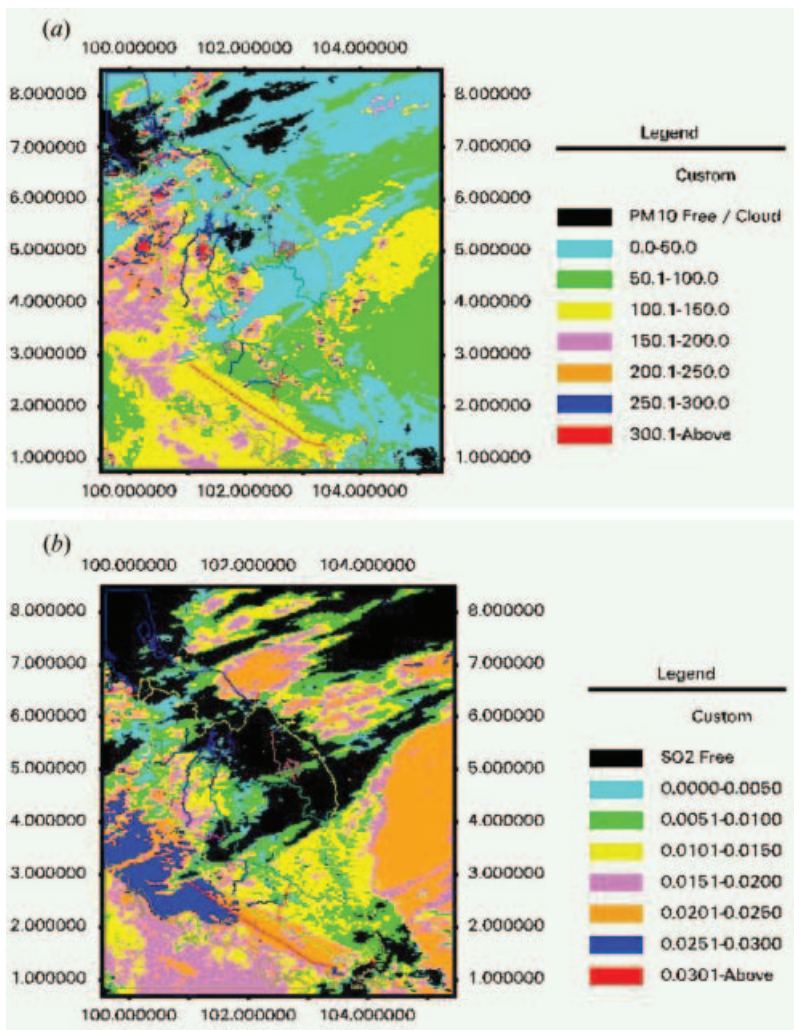
Figure 6. The spread and amount of (*a*) PM10 (during 26 September 1997) (*b*) SO$_2$ (29 September 1997), (*c*) NO$_2$ (22 September 1997), (*d*) CO (22 September 1997), and (*e*) O$_3$ (25 September) over Peninsular Malaysia during the haze episode.

of the nine chosen pixels at each of the five monitoring stations. These five pixels were the pixels containing the location of the ground monitoring station and its four next nearest neighbours. The means of the remaining four pixels, the nearest neighbours were then used to estimate the errors associated with the fitting.

Table 4 summarizes the results of the regression analysis and RMSE of computed PM10 and gases constituents.

3. Results and discussion

All five pollutants reveal a relationship with r^2 exceeding 0.6 and for three of them r^2 exceeds 0.93. The strongest relationship is exhibited by NO_2 and this is followed by PM10, CO, O_3 and SO_2 (see table 4). The generated regression models were then applied to calibrated images to map the spread and the amount of these pollutants over Peninsular Malaysia and the results are presented in figure 6.

With regards to the spatial distribution of the pollutants, NO_2 reached values more than 0.6 ppm especially on the south coastline (and small patches on the south west). Other places like Kuala Lumpur showed values between 0.3 and 0.4. The
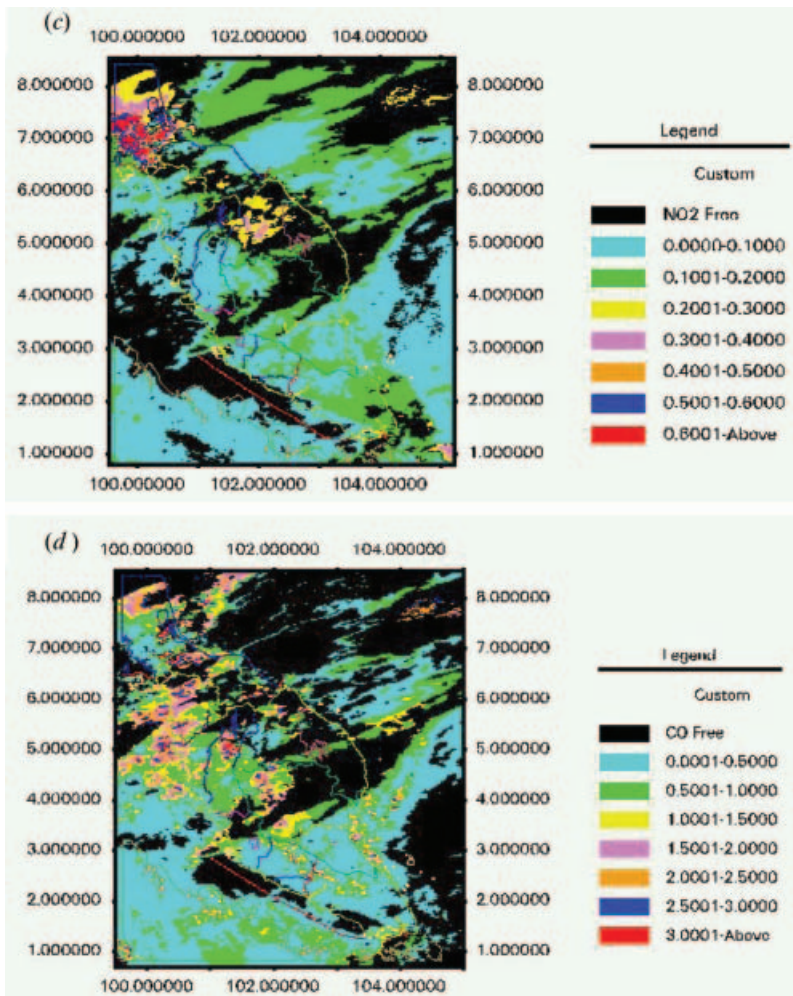

Figure 6. (*Continued*).

reason for the highest levels of this pollutant at the specified locations could also be contributed to by industries where nitric acid is used in chemical reactions, automobile exhausts, power plants and low heat burners in these areas.

Generally, the spatial distribution of ozone showed insignificant levels of the pollutants, whereas the distribution pattern for PM10 is more concentrated in the north parts of the Peninsula where small patches exhibited values more than $300 \,\mu g \, m^{-3}$. This value, indeed exceeds the unhealthy condition specified by the Malaysian Air Quality Index. SO_2 and O_3 seem to have been insignificant pollutants over Peninsular Malaysia during the fire period.

The reasons for the dispersion and transmission of these pollutants from Sumatra are the prevailing meteorological conditions in Southeast Asia in 1997. From August onwards, significant haze started accumulating in the lower atmosphere near the main fire locations, south-east Sumatra and south-west and central Kalimantan. Spreading and intensifying fire locations in the following months contributed to a further increase in the haze. Predominating south-west wind directions transported the haze to the north-east and caused subsequently high pollution levels in places far away from the fires.

4. Conclusions

Remote sensing can be used to map air pollutants over large areas with minimum cost and time. Satellite sensors typically provide coarse resolution smoke plume maps that 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 infrared channels of the AVHRR. By using data from several monitoring stations on the ground, we have been able to produce models for the distribution of CO, SO_2, NO_2, O_3 and PM10 over Peninsular Malaysia in September 1997. The regression analysis using air pollutant readings obtained from *in situ* observation stations and satellite reflectance shows good correlation for all the pollutants. The resulting maps of the distributions of these five pollutants showed that of all the five pollutants, PM10 was the only potentially hazardous
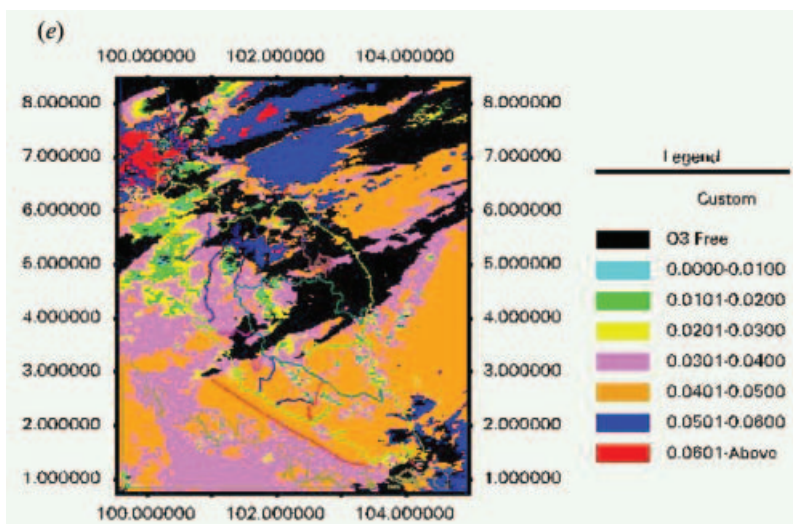

Figure 6.   (*Continued*).

pollutant present in the Malaysian atmosphere during the 1997 forest fire scenario in Southeast Asia.

References

CAHOON, D. R. JR, STOCKS, B. J., LEVINE, J. S., COFER, W. S., and PIERSON, J. M., 1994, Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia. *Journal of Geophysical Research*, **99**, 18627–18638.

CHRISTOPHER, S. A., VULCAN, D. V., and WELCH, R. M., 1995, Radiative impact of aerosols generated from biomass burning. *Proceedings of the International Geoscience and Remote Sensing Symposium*, *10–14 July 1995*, *Firenze, Italy* (Firenze: Italy), vol. 3, pp. 1850–1852.

COAKLEY, J. A., and BRETHERTON, F. P., 1982, Cloud cover from high-resolution scanner data: detecting and allowing for partially filled fields of view. *Journal of Geophysical Research*, **87**, 4917–4932.

FRANÇA, G. B., and CRACKNELL, A. P., 1995, A simple cloud masking approach using NOAA AVHRR daytime data for tropical areas. *International Journal of Remote Sensing*, **16**, 1697–1705.

HASHIM, M., and AHMAD, A., 1997, Determination of haze from remotely sensed data: some preliminary results. *Proceedings of the 18th Asian Conference on Remote Sensing*, *20–24 October 1997* (Kuala Lumpur: Asian Association of Remote Sensing), pp. R11-1–R11-6.

HEIL, A., 1998, Air pollution caused by large scale forest fires in Indonesia 1997, German Technical Cooperation (GTZ), http://www.icsea.or.id/sea-span/scipol2/STUDY4.htm, 21 May 2001.

JACOB, D. J., 1999, *Introduction to Atmospheric Chemistry* (Cambrdige, MA: Harvard University Press), http://www.as.harvard.edu/people/faculty/djj/book/bookchap8.html, 15 March, 2000.

JENSEN, J. R., 1996, *Introductory Digital Image Processing* (Englewood Cliffs, NJ: Prentice Hall).

JOHN, R. J., 1996, *Introductory Digital Image Processing: A remote sensing perspective*, 2nd edn (Englewood Cliffs, NJ: Prentice Hall).

KAUFMAN, Y. J., 1993, Aerosol optical thickness and atmospheric path radiance. *Journal of Geophysical Research*, **98**, 2677–2692.

KAUFMAN, Y. J., and TANRÉ, D., 1998, Algorithm for remote sensing of tropospheric aerosol from Modis. http://ltpwww.gsfc.nasa.gov/MODIS-Atmosphere/_docs/atbd_mod02.pdf (date of access: 21 May 2001).

KAUFMAN, Y. J., TUCKER, C. J., and FUNG, I., 1990, Remote sensing of biomass burning in the Tropics. *Journal of Geophysical Research*, **95**, 9927–9939.

RAO, N. C. R., and CHEN, J., 1998, Calibration updates for the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAA. NOAA/NESDIS Office of Research and Applications, Washington, D.C. 20233. http://noaasis.noaa.gov//NOAASIS/ml/n14update.html (date of access: 9 April 2001).

SAUNDERS, R. W., 1986, An automated scheme for the removal of cloud contamination from AVHRR radiances over western Europe. *International Journal of Remote Sensing*, **7**, 867–886.

SAUNDERS, R. W., and KRIEBEL, K. T., 1988, An improved method for detecting clear sky

and cloudy radiances from AVHRR data. *International Journal of Remote Sensing*, **9**, 123–150.

SIEGENTHALER, R., and BAUMGARTNER, M. F., 1995, Analysis of haze and mist situations over Swiss lowlands during summer smog-periods with NOAA-AVHRR data. *Proceedings of the International Geoscience and Remote Sensing Symposium, 10–14 July 1995, Firenze, Italy* (Firenze: Italy), vol. 3, pp. 1842–1846.

THEIRMAN, V., and RUPRECHT, E., 1992, A method for the detection of clouds using AVHRR infrared observations. *International Journal of Remote Sensing*, **13**, 1829–1841.

UNEP (The United Nations Environmental Protection Agency), 1999, Wildland Fires and the Environment: A global synthesis, edited by J. S. Levine, T. Bobbe, N. Ray, A. Singh and R. G. Witt, UNEP/DEIAEW/TR.99-1.

VADIVALE, M., 1997, Haze: are we hazy about the facts? http://www.geocities.com/HotSprings/2188/hazemma.html, 9 March 2000.