ELSEVIER

Ecological Modelling 127 (2000) 235–244

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

Modelling PM_{10} aerosol data from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa

Johann P. Engelbrecht [a], Leon Swanepoel [a], Mark Zunckel [b], Judith C. Chow [c,*], John G. Watson [c], Richard T. Egami [c]

[a] *Mintek, Private Bag X3015, 2125 Randburg, South Africa*
[b] *CSIR, P.O. Box 17001, 4013 Congella, South Africa*
[c] *Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA*

Accepted 5 October 1999

Abstract

D-grade (i.e. poor quality) coal is widely used for household cooking and heating purposes by lower-income urban communities in South Africa. The smoke from the combustion of coal has had a severe impact on the health of society in the townships and cities. To alleviate this escalating problem, the Department of Minerals and Energy of South Africa evaluated low-smoke fuels as an alternative source of energy. The technical and social implications of such fuels were investigated in the course of the Qalabotjha Low-Smoke Fuels Macro-Scale Experiment. Three low-smoke fuels (Chartech, African Fine Carbon [AFC], and Flame Africa) were tested in Qalabotjha during the winter of 1997. This paper examines diurnal variations of PM_{10} (particles with aerodynamic diameters less than 10 μm) concentrations at the clinic site in Qalabotjha. Both the fuel type and the wind were found to have an effect on the air particulate concentrations. This paper demonstrates how continuous PM_{10} data together with wind measurements can be modelled. Pronounced dual-peak diurnal variations of PM_{10} concentrations were found in winter's stable atmosphere with 30-min PM_{10} levels often exceeding 1000 μg/m^3 around 07:00–08:00 h in the morning and around 18:00 h in the evening. PM_{10} diurnal variations coincided with surface radiation inversions and residential cooking activity, suggesting that human exposure is confined to a very localized environment. On windy days, very low PM_{10} concentrations with very little to no diurnal variations were found. Much of the locally generated cooking emissions may have been diluted by dispersion and transport. An exponential model that allowed for all measured particulate concentrations to be re-calculated to 'zero wind' values was created to estimate the impact of D-grade coal combustion. From analysis of variance (ANOVA) calculations on the 'zero wind' concentrations, it is concluded that the combustion of low-smoke fuels would make a significant improvement to the air quality in Qalabotjha. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: PM_{10} modelling; Qalabotjha; Low-smoke fuels

* Corresponding author. Tel.: +1-775-674-7050; fax: +1-775-674-7009.
E-mail address: judyc@dri.edu (J.C. Chow)

PII: S0304-3800(99)00212-4

1. Introduction

D-grade (i.e. poor quality) coal has been widely used by lower-income urban communities in South Africa for cooking and space heating owing to its abundance, availability, and associated low cost. The smoke from the combustion of this coal in the townships was found to be contributing to as much as 30% of the particulate pollution in the industrialized areas of this country (Engelbrecht et al., 1998a). Although electricity has been available in most of these townships for some time, it is envisaged that coal stoves and braziers will be used for cooking and heating purposes for at least the next few decades.

Alternative sources of fuel for combustion in cooking and heating appliances are being considered to mitigate human exposure to D-grade coal combustion emissions. In 1997, South Africa's Department of Minerals and Energy conducted a macro-scale experiment to test three brands of low-smoke fuels (Chartech, African Fine Carbon [AFC], and Flame Africa) in the black township of Qalabotjha. Technical, health, and social benefits of using low-smoke fuels versus regular D-grade residential coal were compared. This paper demonstrates how continuous PM_{10} data, together with wind measurements can be modelled to produce normalized 'zero wind' pollution levels. These are compared over three consecutive 10-day periods, so as to quantify the improvement to the air quality from the burning of low-smoke fuels.

Engelbrecht et al. (1999a) compare PM_{10} concentrations between the Rupprecht and Patashnick tapered element oscillating microbalance (TEOM) continuous monitor and integrated filter samplers, and characterize PM mass and chemical compositions during the study period. Results from chemical mass balance (CMB) receptor modelling are presented by Engelbrecht et al. (1999b). This paper examines diurnal variations of PM_{10} concentrations at the clinic site in Qalabotjha and proposes a quantitative model for normalizing the pollution levels.

2. Monitoring

Qalabotjha lies in the Free State province on the southern bank of the Vaal River, close to the N3 route from Johannesburg to Durban, approximately 150 km to the south-east of Johannesburg (Fig. 1a). This residential township was selected for the low-smoke macro-scale experiment because of its size and general upwind position in relation to the heavily populated and industrialized Vaal Triangle and Mpumulanga Highveld regions. Qalabotjha, a black township, has an estimated population of 15 000 inhabitants and 2500 households, and lies to the north-east of the predominantly white residential area of Villiers. The dwellings in Qalabotjha are of variable construction, ranging from informal galvanized iron shanties to formal brick houses.

Four ambient monitoring sites were selected, three in Qalabotjha (police station, crèche and clinic) and one gradient site in Villiers (bowling club), all within a radius of approximately 1.2 km (Fig. 1b). All samplers were installed on roofs of single storied buildings with their inlets between 4 and 6.5 m above ground level. A TEOM continuous sampler equipped with a PM_{10} size-selective inlet was also installed at the clinic site to acquire 30-min average PM_{10} concentrations.

Wind and temperature profile data from a tethered weather balloon and three fixed meteorological sites in Qalabotjha and Villiers were recorded by the Council for Scientific and Industrial Research (CSIR) in the course of the 30-day sampling campaign between 21 June and 20 July of 1997.

3. Diurnal variations of PM_{10} concentrations

Fig. 2(a and b) show that diurnal variations of PM_{10} were more pronounced on stable, low-wind days as compared to windy days. In winter's stagnant atmosphere, PM_{10} concentrations are low (approximately 90 μg/m^3) between 12:00 to approximately 16:00 h (Fig. 2a). PM_{10} increases as fires for cooking are lit, and the smoke intensity rises sharply, reaching a maximum (often exceeding 1000 μg/m^3) at approximately 18:00 h in the

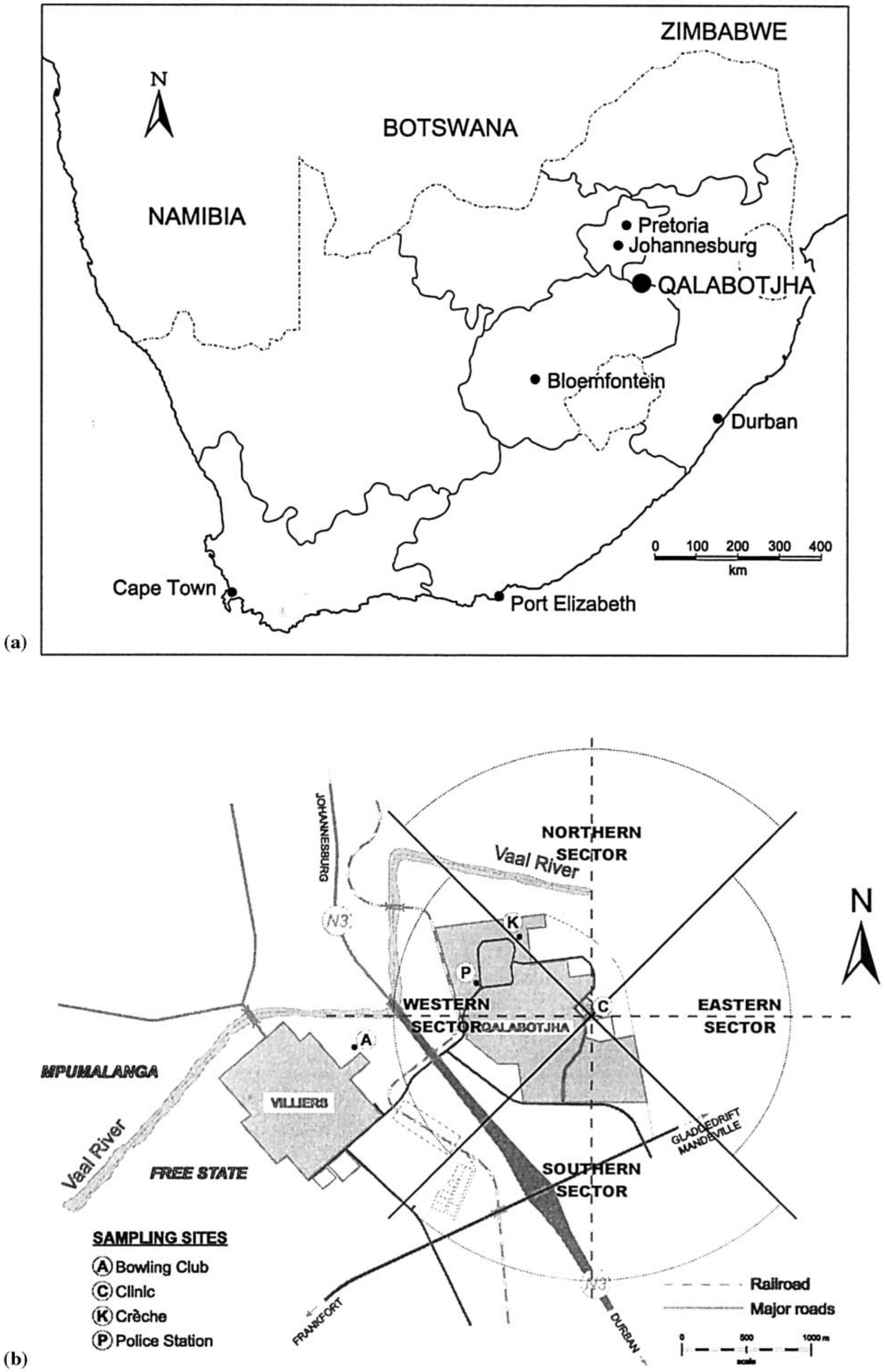

Fig. 1. (a) Map of South Africa showing the Qalabotjha study area in relation to other geographical features. (b) Locality map showing the Qalabotjha and Villiers sampling sites.

evening. As the atmosphere stabilizes, PM_{10} levels decrease beginning around 20:00 to 21:00 h, to approximately 70 μg/m^3. On cold winter nights, PM_{10} concentrations remain low until 06:00 h the following morning when fresh emissions (mainly from cooking) are injected into the atmosphere, causing PM_{10} levels to rise sharply once more to above 1000 μg/m^3. Morning peak PM_{10} concentrations occur at 06:30 h on weekdays and at 08:00 h on weekends. Elevated PM_{10} concentrations gradually decrease as the surface radiation inversion starts to break up during mid-morning. These dual-peak diurnal variations coincide with surface radiation inversions and residential cooking, suggesting that human exposure is confined to a very localized environment.

In contrast to stagnant atmospheric conditions, very little diurnal variation was found on windy days, as shown in Fig. 2(b). Much of the locally generated cooking emissions may have been diluted by dispersion and transport. During the study period, 30-min average PM_{10} concentrations exceeded 1000 μg/m^3 on eight of 30 sampled days.

Day-to-day PM_{10} variations at the clinic site are shown in Fig. 3. Average daily PM_{10} concentrations varied by 10-fold during the 30-day study

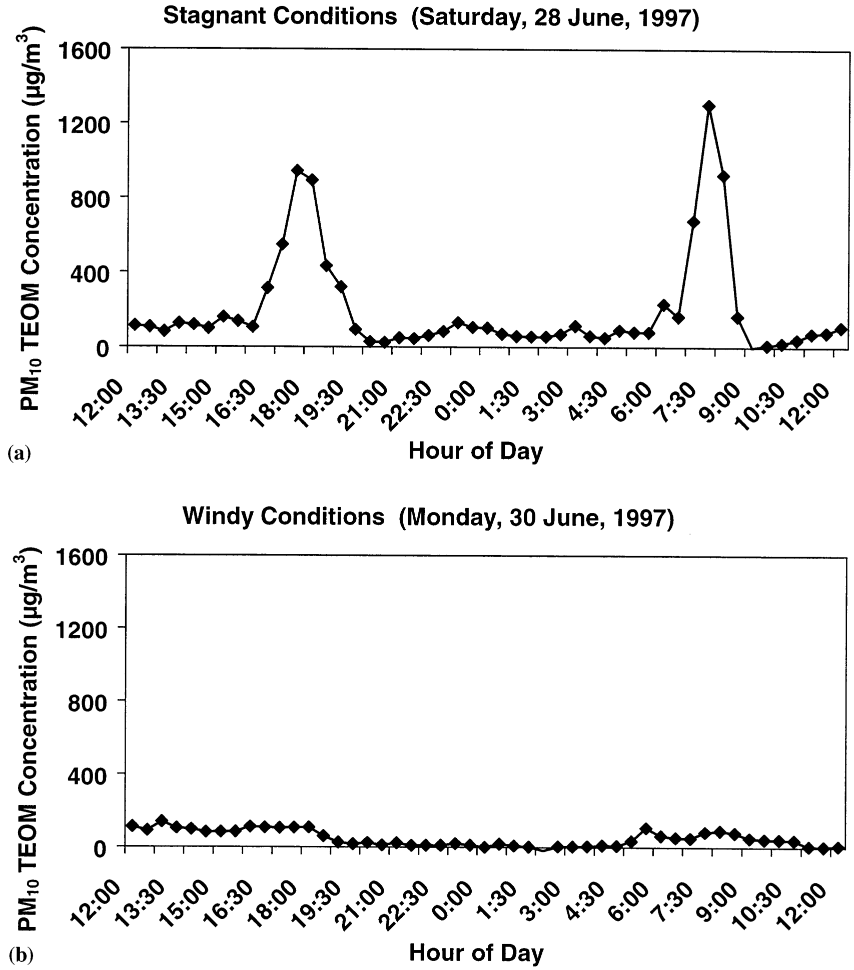

Fig. 2. (a) Diurnal variations of 30-min PM_{10} concentrations during stagnant atmospheric conditions. (b) Diurnal variations of 30-min PM_{10} concentrations during windy atmospheric conditions.

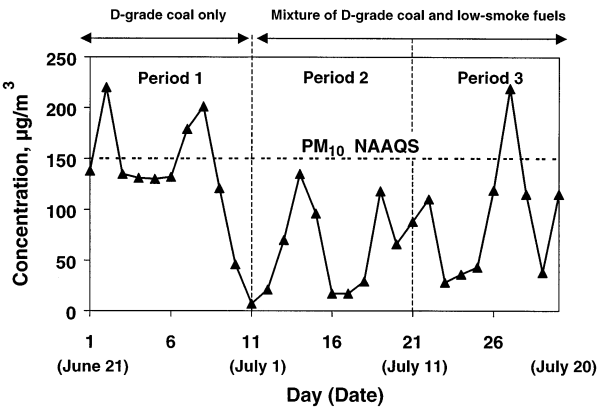

Fig. 3. Twenty-four hour PM_{10} concentrations acquired with a tapered element oscillating microbalance (TEOM) continuous monitor at the clinic site between 21 June and 20 July, 1997.

period. The highest particulate loadings were encountered during the first 10-day period (21–30 June 1997), when exclusively D-grade coal was used. Low-smoke fuels were provided to residents free of charge for use during the second 10-day period (1–10 July 1997). Some residents continued to use D-grade coal until their stocks were depleted, so that the use of the low-smoke fuels was only gradually phased in. As the use of the low-smoke fuels increased, significant decreases in PM_{10} concentrations were found. When supplies of low-smoke fuels ran out during the third 10-day period (11–20 July 1997) and residents resumed using D-grade coal, PM_{10} concentrations started to rise once more. Fig. 3 suggests that fuel sources may have a profound effect on PM_{10} concentrations, at least on a neighborhood scale.

4. Effect of wind

Wind sectors are superimposed in Fig. 1(b), to further augment the provenance of air pollution under different wind directions. Prevailing winds from the northern sector may pass over the north-eastern corner of Qalabotjha, and are mostly representative of distal or background sources. The eastern sector is representative of low-polluting sources, and easterly winds often import clean polar air. In some instances, the south-eastern corner of Qalabotjha may have been skimmed by winds from this direction. The southern wind sector represents winds passing over the southern dwellings in Qalabotjha, while the western wind sector encompasses the largest part of the township.

As could be expected, moderate winds from the southern and western wind sectors were more heavily laden with particulates than those from the other two sectors. Wind directions fluctuated during the course of the day. Southerly and westerly winds prevailed in the late afternoons, as PM_{10} concentrations are high, while northerly and easterly winds with very low PM_{10} concentrations commonly occurred during the early mornings. Wind speeds were generally light and variable, ranging from 1.6 m/s in the mornings to 2.6 m/s in the evenings.

The clinic site is situated on the eastern perimeter of Qalabotjha (Fig. 1b), and is exposed to relatively unpolluted easterly winds. As the wind direction shifts to westerly or southerly, pollution from Qalabotjha (from coal combustion in open braziers at many of the dwellings located south of the site) starts to impact the site. Under high wind conditions (>15 m/s), however, dispersion and dilution of smoke emissions often reduce PM_{10} concentrations to below 20 $\mu g/m^3$, irrespective of wind direction.

5. Empirical model for PM_{10}

The prime objective of this study was to assess if, and to what extent, the combustion of low-smoke fuels improved the ambient air quality in Qalabotjha over the second 10-day period of the sampling campaign, when such fuels were used. The results show that moderate to high winds, as well as the combustion of low-smoke fuels, improved the ambient air quality. These variables should be considered when developing an empirical model for PM_{10} concentration levels.

The particulate concentration (C) measured at any sampling site such as the one at the clinic, is a function of the smoke emission factor of the fuel (F), the wind speed (W_S), wind direction (W_D) as well as the proximity, size and dispersion properties (P) of the provenance:

$$C \propto F \cdot W_S \cdot W_D \cdot P \quad (1)$$

It is expected that the same amount of fuel would have been combusted over the 30-day period, and that D-grade coal would emit more smoke than low-smoke fuels. The smoke emission factor of the fuel (F) was therefore expected to be smaller during the second and third 10-day periods, when low-smoke fuels were consumed. Assuming that the wind direction (W_D) and provenance (P) factors would remain constant throughout the sampling campaign, an exponential relationship between wind speed and PM_{10} concentration can be derived, and 'zero wind' pollution levels can be calculated (Watson et al., 1996). By determining the 'zero wind' pollution levels for each day during the three 10-day periods, the smoke emission factors (F) can be compared:

$$C_{12}/C_{11} = \{F_2(W_S \cdot W_D \cdot P)\}/\{F_1(W_S \cdot W_D \cdot P)\} = \{F_2\}/\{F_1\} \quad (2)$$

where C_{11} = 'zero wind' pollution level during the first 10-day period (exclusively D-grade coal); C_{12} = 'zero wind' pollution level during the second 10-day period (low-smoke fuels and D-grade coal); F_2 = smoke emission factor for the low-smoke fuels (mixed with each other and with some D-grade coal); F_1 = smoke emission factor for the D-grade coal.

To develop an empirical model to estimate PM_{10} concentrations as a function of wind speed, the highest 30-min PM_{10} concentrations and the corresponding wind data for each of the late afternoon and early morning intervals during the first 10-day period were selected for modelling. It was assumed that the amount of smoke emitted on each day was constant, irrespective of cooking device or fire lighting method.

For the southerly wind sector, this produced five sets of input data (Fig. 4a). The best fitting mathematical equations for three of the five sets of input data are exponential expressions with the general formula:

$$y = C_1 \exp(C_2 \cdot x) \quad (3)$$

where y = measured particulate concentration (μg/m^3); x = measured wind speed (m/s); C_1 = constant for that specific exponential function = intercept on y-axis = 'zero wind' pollution level (μg/m^3); C_2 = constant for that specific exponential function = curvature of exponential curve (s/m).

Each pair of experimentally measured x (wind speed), $-y$ (particulate concentration) values, furthermore, fits an exponential curve with specific C_1 and C_2 constants, i.e.:

$$(x, y) \in \{(x_i, y_i), y_i = C_1 \exp(C_2 \cdot x_i)\}, \quad C_1, C_2 \text{ constants.} \quad (4)$$

The functions derived from the experimental data are shown in Fig. 4(a) for the southern wind sector, with an extrapolation shown in Fig. 4(b). This model shows that three exponential curves intersect at a wind speed of approximately 14.7 m/s, resulting in a PM_{10} level of 12 μg/m^3. This implies that, as wind speed exceeds a threshold of 14.7 m/s from the southern wind sector, the pollution from the township becomes totally diluted, is transported from the area, and PM_{10} concentrations simultaneously decrease to a background value of 12 μg/m^3.

The logarithmic function describing the relationship between the constants C_1 and C_2 for the given set of four exponential curves, as shown in Fig. 4(b), is expressed as:

$$C_2 = -0.0682 \ln(C_1) + 0.1695 \quad (5)$$

from which the values of C_1 ('zero wind' pollution level) and C_2 (curvature) could be calculated. Fig. 5 depicts the experimental relationship between C_1 and C_2 for the southern wind sector. The 'zero wind' pollution levels could thus be calculated from Eqs. (3) and (5), for each of the three 10 day sampling periods. A statistical summary of PM_{10} concentrations during the three periods is presented in Table 1. Under calm southerly wind conditions, PM_{10} concentrations would have decreased significantly from the first (days 1–10) to second periods (days 11–20), and increased again during the third period (days 21–30). A less dramatic change in pollution levels was found between the first and third sampling periods. Furthermore, for each of the three periods, the median values are less than the mean values, pointing to positively skewed distributions for each of the sampling periods.

The cumulative frequency distribution of 'zero wind' PM_{10} concentrations for the southerly wind sector over the three sampling periods is shown in Fig. 6. A sharp decrease in PM_{10} levels between the first and second periods is apparent, with a lesser difference between the first and third sampling period. The same empirical model was applied to the PM_{10} and wind data sets acquired from the other wind sectors (Engelbrecht and Swanepoel, 1998b). The exponential curve for the western wind sector was found to be similar to that of the southern wind sector. However, the data from the eastern and northern wind sectors are not as clearly delineated.

For each of the four wind sectors, there is a decrease in 'zero wind' corrected pollution levels from the first to the second sampling period. There is, in most instances, also an increase in pollution level from the second to the third measuring period.

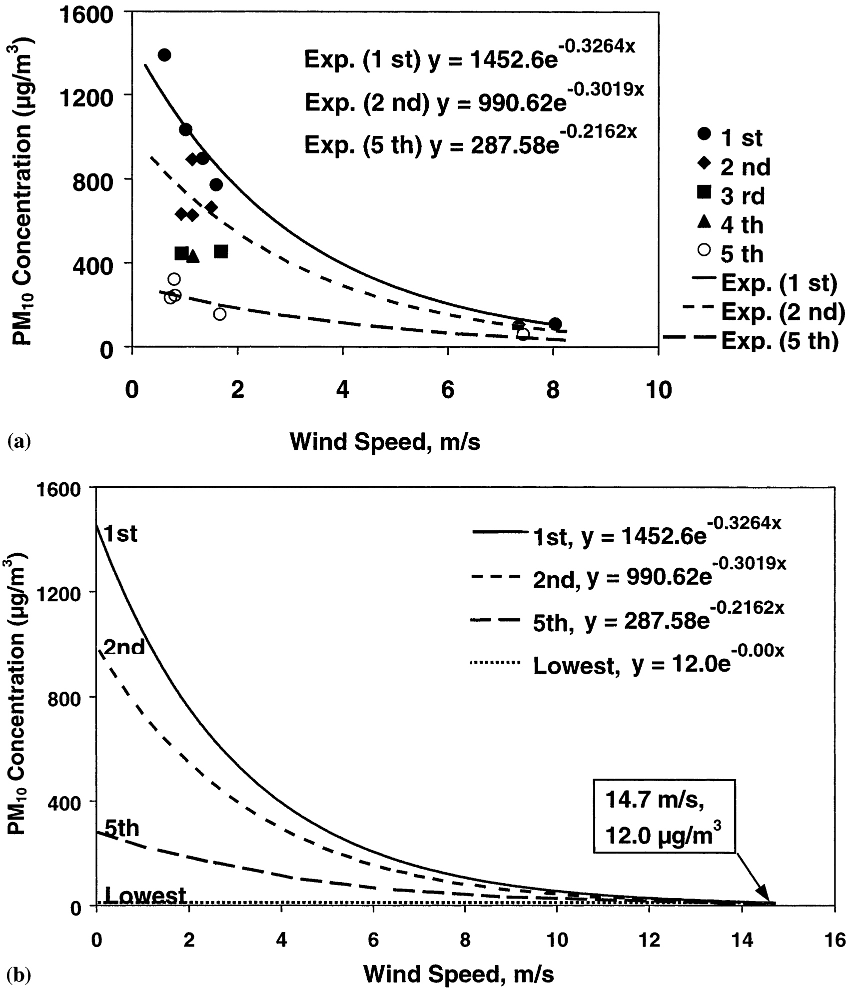

Fig. 4. (a) Relationships between PM_{10} concentration and wind speed for the southern wind sector (late afternoon). The exponential trend curves for the highest, second highest and fifth highest loadings are shown. (b) Set of four exponential curves describing the variation in particulate levels at the clinic site with wind speed, for the southern wind sector.

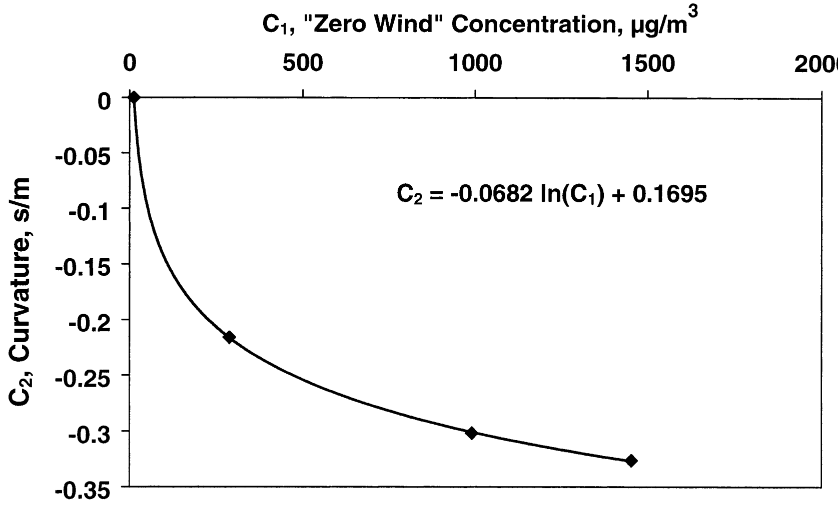

Fig. 5. Experimentally established relationship between the constants C_1 and C_2, for the southern wind sector.

Table 1
Statistics of the 'zero wind' pollution levels for the southern wind sector

	Period		
	1 (days 1–10)	2 (days 11–20)	3 (days 21–30)
Number of observations	32	23	27
Mean (µg/m^3)	521	186	362
S.D. (µg/m^3)	540	252	248
Median (µg/m^3)	280	90	250
80th percentile (µg/m^3)	1152	320	598
Maximum (µg/m^3)	1707	972	869

6. Analysis of variance (ANOVA)

The means of the three sampling periods for each of the four wind sectors was tested against the following hypothesis (Walpole and Myers, 1988; Watson et al., 1997):

H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_1$

H_1: the population means are not equal

where H_0 = the null hypothesis; H_1 = the alternative hypothesis; μ_x = the mean population 'zero wind' corrected pollution levels.

The assumptions are that the population means for each period are normally distributed with

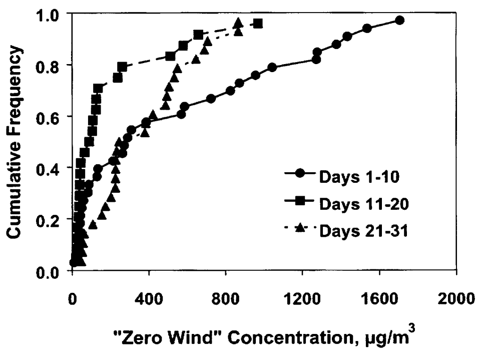

Fig. 6. A cumulative frequency plot of the 'zero wind' pollution levels for each of the three sampling periods, for the southern wind sector.

Table 2
Estimated daily combustion of D-grade coal and low-smoke fuels in Qalabotjha, as well as calculated average pollution indices for all four wind sectors

	Period		
	1 (days 1–10)	2 (days 11–20)	3 (days 21–30)
D-grade coal (tonnes)	20	8	16
Low-smoke fuels (tonnes)	0	12	4
Relative pollution index	100	37	75

common but unknown variances. Actual plots of the PM_{10} data collected during this campaign were found to be approximately normally or lognormally distributed. No transformation of these data was considered necessary.

The analyses of variance results prove that for the southern sector, the concentration means are not equal at a 95% confidence level. Comparing the pairs of data sets of the three periods from this sector confirm that the air pollution level for the first period is significantly greater than that for the second period, which in turn is significantly less than the mean pollution level for the third period. There is no significant difference between the mean pollution levels of the first and third periods for this wind sector.

By comparing the mean particulate concentrations among the three periods for this southern wind sector (Table 1), it was found that the mean 'zero wind' air pollution levels decreased to approximately 36% during the second 10-day period and increased again to approximately 69% during the third 10-day period, as compared to the mean level of the first 10-day period. This significant improvement in air quality during the second 10-day period is attributed to the combustion of low-smoke fuels.

The significance of the difference in means was tested by conducting a single factor analysis of variance on the 'zero wind'-corrected pollution levels, for each of the four wind sectors, giving the following statistical results:

- southern wind sector $\mu_1 \neq \mu_2 = \mu_3 \neq \mu_1$,
- western wind sector $\mu_1 \neq \mu_2 = \mu_3 \neq \mu_1$,
- northern wind sector $\mu_1 = \mu_2 = \mu_3 = \mu_1$, and
- eastern wind sector $\mu_1 \neq \mu_2 = \mu_3 \neq \mu_1$.

The null hypothesis (H_0) was therefore rejected for three of the four wind sectors, pointing to a significant decrease in PM_{10} pollution levels during the second 10-day period. This is ascribed to less smoke and a lower emission factor (F) from the combustion of low-smoke fuels during the second 10-day (1–10 July) as well as the third 10-day (11–20 July) periods.

Table 2 shows estimated daily coal consumption as well as its estimated pollution index. This estimate is based on the combustion by 2000 households of 10 kg of fuel each per day, the known distribution of low-smoke fuels to the community, and the mean 'zero wind' pollution levels calculated for all four wind sectors. The decrease in 'zero wind' pollution levels follows approximately the estimated combustion of D-grade coal and low-smoke fuels during the three periods. The contribution by distal background sources is considered to be negligible, and the elevated pollution levels are ascribed to the combustion of the D-grade coal alone. The pollution index decreased by 63% during the second 10-day period, when a majority of the low-smoke fuel was phased in, and by 25% during the third 10-day period. On average for the last 20 days of the campaign, the air quality in Qalabotjha improved by an estimated 44%. It is furthermore assessed that the contribution to PM_{10} by low-smoke fuels is negligibly small.

7. Summary and conclusions

Pronounced diurnal variations of PM_{10} concentrations were found in winter's stagnant atmosphere, with 30-min PM_{10} levels exceeding 1000 $\mu g/m^3$ around 18:00 h in the evening. Similar peak PM_{10} concentrations occurred at 06:30 h on weekdays and at 08:00 h on weekends. Elevated PM_{10} concentrations gradually decreased as the surface radiation inversion started to break up during mid-morning. On windy days, very low PM_{10} concentrations with very little to no diurnal variations were found. Much of the locally generated cooking emissions may have been diluted by dispersion and transport.

An empirical model was developed to estimate the atmospheric impact of D-grade coal combustion. From ANOVA calculations on the 'zero wind' concentrations, it is concluded that the combustion of low-smoke fuels made a significant improvement to the air quality in Qalabotjha. This experiment shows that low-smoke fuels, together with electricity and other fuels, may be considered as alternative sources of energy in the townships of South Africa.

Acknowledgements

The Qalabotjha low-smoke fuels macro-scale experiment was sponsored by South Africa's Department of Minerals and Energy (DME). The cooperation by the Qalabotjha community during the sampling campaign is sincerely appreciated. The Department of Environmental Affairs and Tourism is thanked for the loan of their TEOM continuous monitor. This paper is published by permission of Mintek and the DME.

References

Engelbrecht, J.P., Reddy, V.S., Swanepoel, L., Mostert, J.C., 1998a. Aerosol Monitoring and Source Apportionment in the Vaal Triangle. Special Publication no. 17. Mintek, Randburg, South Africa, pp. 135.

Engelbrecht, J.P., Swanepoel, L., 1998b. Aerosol Monitoring and Source Apportionment in Qalabotjha, Free State, South Africa. Communication MC5. Mintek, Randburg, South Africa, pp. 331.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G., Egami, R.T., 1999a. $PM_{2.5}$ and PM_{10} concentrations from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa. Environ. Monitor. Assess. (submitted).

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G., Egami, R.T., 1999b. A source apportionment study in Qalabotjha, South Africa. Environ. Sci. Policy (submitted).

Walpole, R.E., Myers, R.H., 1988. Probability and Statistics for Engineers and Scientists, 2nd edition. Macmillan, New York, p. 580.

Watson, J.G., Chow, J.C., Gillies, J.A., Moosmuller, H., Rogers, C.F., DuBois, D., Derby, J., 1996. Effectiveness demonstration of fugitive dust control methods for public unpaved roads and unpaved shoulders on paved roads. DRI Document No. 685-5200.1F1. Prepared for the California Regional Particulate Air Quality Study, California Air Resources Board, Sacramento, CA, by the Desert Research Institute, Reno, NV.

Watson, J.G., Chow, J.C., DuBois, D., Green, M., Frank, N., Pitchford, M., 1997. Guidance for network design and optimum site exposure for $PM_{2.5}$ and PM_{10} — Draft report. Prepared for the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park NC, by the Desert Research Institute, Reno, NV.