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An investigation of roadside particles and carbon dioxide gas concentration in Gaborone, Botswana: A statistical study

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ABSTRACT

The present experimental study was conducted to monitor the aerosol particle concentration and carbon dioxide gas concentration in Gaborone, Botswana. The measurements of concentration of aerosol particles larger than 0.3 µm and carbon dioxide gas concentration in Gaborone, between September 2006 and August 2008 were made at 12 noon everyday. Particle measurements were made using a battery -powered hand held particle counter-model HHPC- 6 - Met One. Carbon dioxide gas concentration measurement was made using Horiba VIA-510 gas analyzer. The collected data was analyzed using graphical and traditional statistical techniques. A new classification criterion is introduced to identify severity states of airborne particles. Two new measures to assess the symmetry of counts of severity states and spread of severity states around the normal states are proposed. This study shows that the mean monthly particle concentration increases and becomes its maximum during winter [June-August]. Similar trend is also observed with the mean monthly carbon dioxide gas concentration. The new measures proposed reveal a strong correlation between the airborne particles, precipitation and biomass burning. The particles and carbon dioxide originate from vehicular emissions and biomass burning. In Botswana, during winter the biomass is by and large used in cooking and heating purposes. It is worthwhile to note that 47% of the world biomass is burnt in African continent.

Keywords: Atmospheric aerosols, Biomass, Multinomial model, Seasonal impact, Dispersion and volatility index.

INTRODUCTION

The road side particle concentrations in urban areas depend on vehicle characteristics, traffic and weather conditions and the geographic and built environment characteristics of the local site. Biomass burning has also been identified as a major source of particle concentration as it

releases a large amount of particulate matter. [1,2,3]. The composition of atmospheric particulate matter is an important factor in component deposition, cloud condensation nuclei, source apportionment and its origin. [4,5,6].

This type of study could reveal the effects of such particle concentrations in the environment. A study on thermal implication of oil spillage on select soil samples obtained from different locations of the Niger Delta shows that spills on soil samples reduce the density of the soil. This has effect on the use of land (soil) for agriculture and habitation in addition to the effect on the geologic controls [7]. The accumulation of heavy metals in aquatic biota also has become a major problem. This is because most humans consume fishes from these polluted water bodies and this can cause health problems [8].The high concentrations of Chromium, Cadmium, Copper, Lead and Zinc were found in the muscle tissues of commercially important fishes. This is due to the release of fertilizers and pesticides to rivers by metal processing industry and sugar mill industry as wastes [9]. Studies also showed that groundwater contamination by fluoride (F) can result from the natural dissolution of minerals from subterranean strata. These inorganic contaminant in drinking water is known to cause serious health problems when the maximum contaminant levels (MCL) exceed 1.5 mg/L [10].

Botswana is a land-locked country in southern Africa surrounded by Namibia to the west, South Africa to the east and south and Zambia and Zimbabwe to the north. It has a population of about 1.6 million, and a total area of about 581730 km^2. The Country lies between longitudes 20 and 30 degrees east of Greenwich and between the latitudes 18 and 27 degrees approximately south of the equator. It is approximately 500 km from the nearest coast line; to the south west [11]. There are approximately 125 motor vehicles for every 1000 people. The total number of registered vehicles has increased from 31684 in 1980 to just over 200000 in 2006 [12]. This increase in vehicle population also contributed to vary the particle concentration in the atmosphere of Gaborone. This country is hot and dry for much of the year. The rainy season is in summer, which brings high temperature and is in between November and March with the peak in January and February. Rain is unpredictable and regional, sometimes followed by sunshine. The mean annual rainfall is about 650 mm in the north, and 250 mm in extreme south [13]. Winter is in between May and August. Winter days are sunny and warm; but night temperature can drop below freezing point in some places. Biomass burning is common during winter and releases particulate matter in the sub micrometer size range as well as other gases such as carbon dioxide.

The objectives of this study are the following:

a) To define a notion of severity for airborne particles and propose a classification rule for identifying different severity states given a time series data of airborne particles.
b) To build a probabilistic model that best explains the uncertainty in the movements of monthly airborne particle measurements from one severity state to another.
c) To propose a new index of dispersion that will help to compare airborne concentration measurements over the entire study period and additionally across the seasons.
d) To propose a new index of volatility to measure the deviance between observed and assumed probability model of the severity states.
e) To examine if there is a correlation between road side particle concentration and carbon dioxide gas concentration measurements during the study period.

f) To see if there is any systematic trend in road side particle concentration and carbon dioxide concentration measurements.
g) To understand and interpret the monthly variations in airborne particles by accounting the presence of concomitant factors such as precipitation, biomass burning, vehicle emissions, etc.

MATERIALS AND METHODS

Methodology

2.1 Background of the data

The aim of the present study was to examine the aerosol particles and the carbon dioxide gas concentration in the atmosphere of Gaborone. Aerosol particles were taken from air which was sampled around the University of Botswana campus over two years. Particle measurements were made using a battery -powered hand held particle counter-model HHPC- 6 - Met One. This instrument counts particles larger than 0.3 µm, separating them into six size ranges ≥0.3µm, ≥ 0.5µm, ≥ 0.7µm, ≥1.0µm, ≥2.0 µm, and ≥5.0 µm. It also measures relative humidity and temperature. Carbon dioxide gas concentration measurement was made using Horiba VIA-510 gas analyzer. This analyzer uses an infra red absorption method which offers superior sensitivity, selectivity, and stability. Data were collected at 1200 local time every day. This time was chosen as the observations at other times were not stable with respect to traffic. More over air was relatively clean and calm during this time. The daily data collected is not reported here but can be obtained from the first author on request.

The study period was from September 2006 to August 2008. During this period, particle concentration and carbon dioxide concentration measurements were taken on suitable days in each month. The frequency of sampling in each month varied from six to twenty four days depending on the availability of experimental, human and capital resources.

The recorded measurements were grouped into two distinct non overlapping seasons namely Non-winter season (November, December, January, February, March April, September and October), and winter season (May, June, July and August). This classification of seasons is consistent with the practice followed by Botswana Meteorological Services. Thus, for the non-winter season, observations were obtained for 15 months and for winter season for 8 weeks. No observations were collected during the month of December 2006. Based on the daily data, the summary statistics, such as minimum, maximum, mean and variance of particle concentration and carbon dioxide concentration measurements for the two seasons were computed. The results are displayed in table 1.

Table1. Summary statistics –Average particle and CO_2 concentration in cm^{-3} units

Season	Variable	No. of Months	Minimum	Maximum	Mean	Variance
Winter	Particle Concentration	8	3.63	335.25	73.70	2978.67
	CO_2 Concentration	8	227.00	441.00	352.33	1272.36
Non-winter	Particle Concentration	15	5.57	192.32	73.24	1785.97
	CO_2 Concentration	15	291.00	472.00	350.03	1707.07

From Table 1, it is evident that both mean aerosol particle concentration and CO_2 concentration measurements for the winter season is more than those for the non-winter season. Further,

particle concentrations vary in between 3.63 particles cm^{-3} and 335.25 particles cm^{-3} during the non-winter season, while for the winter season the corresponding values are 5.57 and 192.32. As can be seen from the table, particle concentration measurements are subject to large magnitude of variations due to one or more factors and this variation is significantly more during the winter season than during the non-winter season. A similar trend is visible in respect of CO_2 concentration measurements across the two seasons.

2.2 The need for an alternative approach

From a practical point of interest one may be interested to see if the mean aerosol particle concentration and carbon dioxide concentration measurements are somehow related over the study period. The conventional correlation coefficient may not be an apt measure of this relation as it is hard to pinpoint a cause and affect relationship between these two variables of interest. However, both these variables owe their root to one or more pollution sources such as biomass burning, industrial emissions, automobile emissions etc. However, a simple trend analysis of the two variables may give the direction of movement as impacted by such extraneous factors.

As the atmospheric aerosol particles and CO_2 concentration measurements are known to influence climate adversely, it may be of interest to study the monthly variations in an objective way. The new approach used is based on recognition of the fact that it is not only the presence of airborne particles but also its magnitude need to be accounted for. This would naturally lead to a naïve approach of categorize monthly variations into certain classes based on percentage increase or decrease in the corresponding monthly mean with respect to a reference time. However, this categorization may appear subjective as percentage cut-off points may be arbitrarily defined and more over such categorization is not data driven. An objective way of categorizing monthly variations is to adopt a rule that is defined by the underlying parameters of the sampling distribution of the monthly averages; for example, the mean and standard deviation. The parameters mean and standard deviations are chosen for simplicity, as it is well known that mean measures the central tendency while the standard deviation, the spread of the underlying distribution of the data. Moreover, the interval (mean ± 3 standard deviation) covers almost all the data. For example, when the underlying sampling distribution is Gaussian, as may be the case in several atmospheric data, the intervals (mean ± 3 standard deviation), (mean ± 2 standard deviation), (mean ± standard deviation), are respectively known to cover approximately 97%, 95% and 68% of the observations in a given data. The notion of severity of concentration measurements is linked to these intervals. These intervals *inter alia* may be used to define the severity or criticality of concentration characterizing how far individual observations are spread from the centre of the data. This principle in used in this study to define classes that categorize monthly atmospheric aerosol and CO_2 concentration measurements.

2.3 Severity states for airborne particles

In the sequel, the variable ‘airborne particle’ will mean either aerosol particle concentration or CO_2 concentration measurements. Suppose that we have a time series data, say, of daily airborne particle concentration measurements, $P_t, t = 1,..., N,$ where $'N'$ is the length of the study period in days. Here $'t'$ refers to the day. We shall denote the total number of months during the study period by ‘n’ and the number of observations recorded in a month ‘m’ by ‘n_m’ (Usually n_m varies between 2 to 31, the number of days in a typical month during which airborne particle

concentration was monitored). Then the monthly mean and variance of airborne particle concentration are respectively given by

$$\bar{P}_m = \frac{1}{n_m}\sum_{t=1}^{n_m} P_t, m = 1,...,n \qquad (1)$$

and

$$s_m^2 = \frac{1}{(n_m - 1)}\sum_{t=1}^{n_m}\left(P_t - \bar{P}_m\right)^2 \qquad (2)$$

Assuming that the monthly mean concentration m airborne particle measurements can be classified into seven states depending on their severity, we may define the following seven states: S_1: Extremely Negligible State, S_2: Moderately Negligible State, S_3: Negligible State, S_4: Normal State, S_5: Critical State, S_6: Moderately Critical State, S_7: Extremely Critical State. Further, if we assume that $\bar{P}_m$'s come from a population with finite mean μ_m and finite variance σ_m^2, then we know that $E\left(\bar{P}_m\right) = \mu_m$ and Var $(\bar{P}_m) = \frac{\sigma^2}{n_m}$. Then one may use the standardized statistic $Z = \sqrt{n_m}\left(\frac{\bar{P}_m - \mu_m}{\sigma_m}\right)$ to construct appropriate classification rules for the severity of states. In Z, we replace the population mean μ_m by its unbiased estimator $\bar{P}_m$ and the population variance σ_m^2 by its unbiased estimator s_m^2, respectively, given by (1) and (2) above. Thus, we may classify the severity of airborne particle concentrations in monthly data into seven states $S_j, j = 1,...,7$ as follows. For the current month $(m+1), m = 1,...n-1$ the airborne particle concentration measurement is said to belong to

$$\left.\begin{array}{l}
\text{(i) State } S_1, \text{ if } \bar{P}_{m+1} < \bar{P}_m - 3\frac{s_m}{\sqrt{n_m}} \\
\text{(ii) State } S_2, \text{ if } \bar{P}_m - 3\frac{s_m}{\sqrt{n_m}} \le \bar{P}_{w+1} < \bar{P}_m - 2\frac{s_m}{\sqrt{n_m}} \\
\text{(iii) State } S_3, \text{ if } \bar{P}_m - 2\frac{s_m}{\sqrt{n_m}} \le \bar{P}_{m+1} < \bar{P}_m - \frac{s_m}{\sqrt{n_m}} \\
\text{(iv) State } S_4, \text{ if } \bar{P}_m - \frac{s_m}{\sqrt{n_m}} \le \bar{P}_{m+1} < \bar{P}_m + \frac{s_m}{\sqrt{n_m}} \\
\text{(v) State } S_5, \text{ if } \bar{P}_m + \frac{s_m}{\sqrt{n_m}} \le \bar{P}_{m+1} < \bar{P}_m + 2\frac{s_m}{\sqrt{n_m}} \\
\text{(vi) State } S_6, \text{ if } \bar{P}_m + 2\frac{s_m}{\sqrt{n_m}} \le \bar{P}_{m+1} < \bar{P}_m + 3\frac{s_m}{\sqrt{n_m}} \\
\text{(vii) State } S_7, \text{ if } \bar{P}_{m+1} \ge \bar{P}_m + 3\frac{s_m}{\sqrt{n_m}}
\end{array}\right\} \quad (3)$$

In the above stated classification rule, we compare the current month's mean airborne particle concentration with previous month's mean particle concentration plus or minus a multiplier of the standard error of that month's mean to decide the severity state of the current month's mean. The multipliers ± 3 and ± 2 of $\frac{s_w}{\sqrt{n_w}}$ suggested here is quite appropriate in the sense that the intervals formed with these multipliers can be shown to capture almost all variations that exist in the month's means. For example, when the underlying distribution of monthly mean is Gaussian, the interval $\left(\bar{P}_w - \frac{3}{\sqrt{n_w}}s_w, \bar{P}_w + \frac{3}{\sqrt{n_w}}s_w\right)$ is known to cover approximately 99.73% of the variations in the monthly means (See for example, [14] .

2.4 A multinomial probability model for severity of states

The volatility or wide swings that are prevalent in monthly mean airborne particle concentration measurements can be approached from the classical probability point of view in that one may model different states of severity based on a certain probability distribution. Here the volatility in means refers to the swings from one state to another over certain period of months. In general, suppose that there are k mutually exclusive and exhaustive states, say $S_1,...,S_k$ to which the weekly mean $\overline{P_w}$ can be assigned based on a certain classification rule, say for example, rule (3) with $k = 7$ and let $P_r\left(S_j\right) = \theta_j$ denote the probability that a typical monthly mean $\overline{P_w}$ belongs to the state j for $j = 1,...,k$.

Let $n_j, j = 1,...,k$ to denote the number of occurrences of the state S_j in an independent sequence of the phenomena observed say, for $n = \sum_{j=1}^{k} n_j$ months. Then the vector $\mathbf{n} = (n_1,...,n_k)$ follows a multinomial distribution (See for example, [14] with the joint probability mass function (p.m.f.) given by

$$p(n_1, n_2, ..., n_k) = \prod_{j=1}^{k} \frac{n!}{n_j!}\theta_j^{n_j} \qquad (4)$$

where, $0 < \theta_j < 1, \sum_{j=1}^{k}\theta_j = 1, n = \sum_{j=1}^{k} n_j$ .In general, the parameters θ_j's in the model given by (4) are unknown and can be estimated by their empirical estimates

$$\hat{\theta}_j = \frac{n_j}{n}, j = 1,...,k. \qquad (5)$$

It may be pointed out that $\hat{\theta}_j$'s are in fact the unrestricted maximum likelihood estimators of θ_j's, $j = 1,...,k$. For the airborne particle concentration data, the multinomial model that best describes different severity states is given by

$$p(n_1,...,n_7) = \frac{n!}{n_1!n_2!n_3!n_4!n_5!n_6!n_7!}\theta_1^{n_1}\theta_2^{n_2}\theta_3^{n_3}\theta_4^{n_4}\theta_5^{n_5}\theta_6^{n_6}\theta_7^{n_7}, \qquad (6)$$

$$\text{for } 0<\theta_j<1,\ j=1,...,7,\ \theta_7=1-(\theta_1+...+\theta_6),\ n=\sum_{j=1}^{7}n_j\ . \qquad (7)$$

Given the data on mean monthly aerosol particle concentration, using the classification rule (3), we can obtain n_j's, $j=1,...,7$ and then estimate the probabilities using (5). These probabilities may be used to interpret the likelihood of different states of severity in the long run.

2.5 Indices of volatility and dispersion for airborne particle severity states

Having defined the seven severity states as in equation (3), given an observed data, it is of considerable interest to see if counts of severity states are symmetric around the normal state. This can be examined by proposing a simple index of volatility. For instance, one may use the multinomial model given by (6) to propose an index of volatility for airborne particle concentrations. It is but natural to surmise that if airborne particle concentrations are subject to random chance fluctuations alone; then, one would expect a symmetric multinomial model with $\theta_1=\theta_7, \theta_2=\theta_6$ and $\theta_3=\theta_5$ in (6) above, given by

$$p(n_1,...,n_7) = \frac{n!}{n_1!n_2!n_3!n_4!n_5!n_6!n_7!}\theta_1^{n_1+n_7}\theta_2^{n_2+n_6}\theta_3^{n_3+n_5}\theta_4^{n_4}, \qquad (8)$$

for $0<\theta_j<1,\ j=1,...,4,\ \theta_4=1-2(\theta_1+...+\theta_3),\ n+n_4=\sum_{j=1}^{4}(n_j+n_{8-j})$. Ideally in the model (8), most of the monthly variations in airborne particle concentrations will be symmetrical around the state S_4; on the other hand if the airborne particle concentrations are subject to significant cause variations; like biomass burning, precipitation etc., then the counts of severity states may be uneven around the normal state. The notion of volatility is designed to capture this unevenness in the counts of severity states. As a measure of such a volatility, an index below is proposed.

As before, let $n_j, j=1,...,7$ denote the number of occurrences of the state S_j in an independent sequence of the phenomena observed say, for $n=\sum_{j=1}^{k}n_j$ months. Suppose $E(n_j)$ denotes the expected number of occurrences of the state S_j under the hypothesis of symmetric multinomial model (8). Then it can be shown that the maximum likelihood estimators of θ_j's in the model (8) are given by

$$\hat{\theta}_j = \frac{n_j+n_{8-j}}{2n},\ j=1,...,4. \qquad (9)$$

Thus an estimate of $E(n_j)=E(n_{j-8})$ can be obtained as

$$\hat{n}_j = n\hat{\theta}_j = \frac{(n_j+n_{j-8})}{2},\ j=1,...,4. \qquad (10)$$

It is reasonable to expect that under the hypothesis of symmetric multinomial model, the observed and the expected number of occurrences of the state S_j must be more or less the same, and therefore a suitable function of their difference would reflect the magnitude of volatility. Thus, an index of volatility can be taken to be

$$I_V = \sum_{j=1}^{7}\left(n_j - \hat{n}_j\right)^2$$

$$= \frac{1}{2}\sum_{j=1}^{4}\left(n_j - n_{j-8}\right)^2 . \qquad (11)$$

When the counts of severity states are symmetric, $I_V = 0$; otherwise non-zero. Large values of I_V suggest that severity states are highly volatile.

Finally, given the severity states of each month, one can propose a measure or an index of dispersion which may be used to compare severity of airborne particle concentrations across different years or seasons in one or more years. The index of dispersion measures the spread of the severity states around the modal or the normal state. Let T denote the number of months in a season and $t_m, m = 1,..,T$ be the value of the severity state corresponding to the month m. Note that t_m will take one of the values from 1 to 7. For example, if $t_1 = 2$; for the first month, then the severity state is '2', if $t_2 = 6$; for the second month, then the severity state is '6' and so on. Then an index of dispersion is given by

$$I_S = \frac{1}{T}\sum_{m=1}^{T}\left(t_m - 4\right)^2, \qquad (12)$$

It is seen that when monthly airborne particle concentration measurements are subject to chance causes alone, then S_4 will be the severity state for every month, in which case $t_m = 4$ for all w and therefore, $I_S = 0$. On the other hand if monthly means show swings on either side of the normal state S_4, I_S will be significantly different from 0. In the extreme case, it can be easily shown that the severity index I_S will be equal to 9. Thus, greater the value of dispersion index, more pronounced is the variations in the states of airborne particle concentrations. These considerations precisely constitute the rationale behind the measure I_S proposed here and in particular given different series of airborne particle concentration measurements one can compare them in terms of the index I_S.

RESULTS AND DISCUSSION

3.1 Preliminary Data Analysis

Table 2 gives the monthly mean and standard deviations of aerosol particle and CO_2 concentration measurements for the two seasons-winter and non-winter.

Table 2. Airborne particle measurements during the winter and non-winter seasons for the year 2006-07 and 2007-08

Winter Season: Aerosol Particle Measurements **CO_2 Measurements**

Year	Month	Mean	S.D	Mean	S.D
2007	May	73.58	68.77	330.50	14.58
2007	Jun	59.64	48.71	338.50	40.13
2007	Jul	74.97	88.85	359.19	27.34
2007	Aug	82.48	52.75	308.12	31.47
2008	May	47.52	19.82	387.94	15.10
2008	Jun	72.29	37.97	398.94	8.53
2008	Jul	78.15	53.53	347.00	10.04
2008	Aug	87.99	36.28	358.29	17.79

Non Winter Season: Aerosol Particle Measurements **CO_2 measurements**

Year	Month	Mean	S.D	Mean	S.D
2006	Sept	77.79	56.71	307.19	24.89
2006	Oct	78.356	47.79	315.60	18.99
2006	Nov	48.06	8.61	339.42	54.98
2007	Jan	51.65	21.95	314.92	24.68
2007	Feb	50.49	17.99	315.78	41.55
2007	Mar	55.17	23.50	326.80	36.17
2007	Apr	74.73	45.39	367.33	50.10
2007	Sept	112.96	39.97	382.23	49.77
2007	Oct	81.75	39.48	348.65	28.07
2007	Nov	61.56	36.79	347.08	41.24
2007	Dec	57.59	42.03	326.11	12.52
2008	Jan	59.70	35.64	351.54	22.00
2008	Feb	78.40	45.38	360.23	15.03
2008	Mar	70.01	32.44	390.50	10.21
2008	Apr	92.03	50.02	388.59	10.31

It can be noted that the mean particle concentrations during the non-winter season (September – April) had a minimum of about 48.06 particles per cm^3 and was recorded in November 2006. A steady increase was seen as the winter sets in and the biomass burning increases. The maximum concentration recorded was about 113 particles per cm^3 and was recorded in September 2007. The minimum monthly mean concentration of carbon dioxide for 2007-08 was about 326 ppm and was recorded in December 2007. The maximum mean concentration was about 399 ppm and was recorded in June 2008. The carbon dioxide concentration starts to increase from December 2007 and becomes its maximum in June 2008.

Based on the actual monthly mean measurements of airborne particle concentrations, it is evident that as the mean monthly carbon dioxide concentration increases, the mean monthly particle

concentration also increases. This is due to the fact that during winter biomass is burnt and this contributes to increase in the concentration of carbon dioxide gas particles as well as the concentration of particulate matter in the atmosphere.

Table 3. Rainfall in mms during September 2006 to August 2008

Year	2006-07											
Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Rainfall in mms	0	5.6	28.2	8.2	35.4	2.9	6.4	29.7	0	21.5	0	0

Year	2007-08											
Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Rainfall in mms	57.8	51.5	70.7	72.2	194.8	29.7	146.6	0.9	35.2	0	0	0

Table 3 provides the monthly rainfall data for the period September 2006 to August 2008. There were four dry months during the year 2006-07 and three in the year 2007-08 in the city of Gaborone. The quantum of rain even during the rainy season varies from year to year. Even during the winter season, June 2008 and May 2008 recorded good amount of rain in Gaborone. The table indicates uncertainty of rain over the months in terms of occurrence as well as quantity.

Figure 1 shows the trend lines of aerosol particle and CO_2 concentration measurements during the period September 2006 to August 2008.

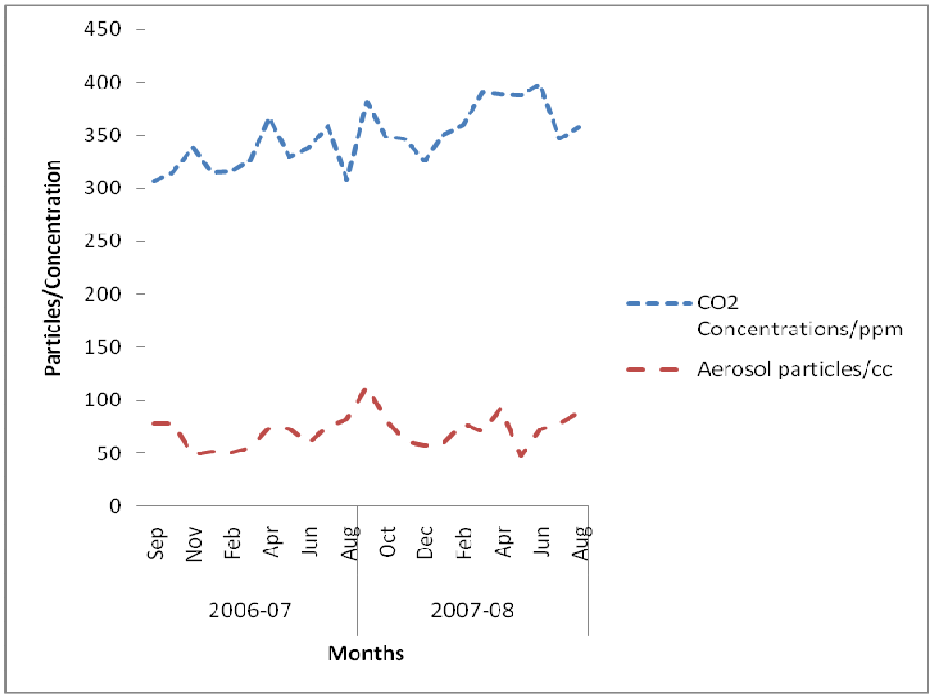

Figure 1. Trend lines for aerosol particles and CO_2 concentrations during September 2006-August 2008

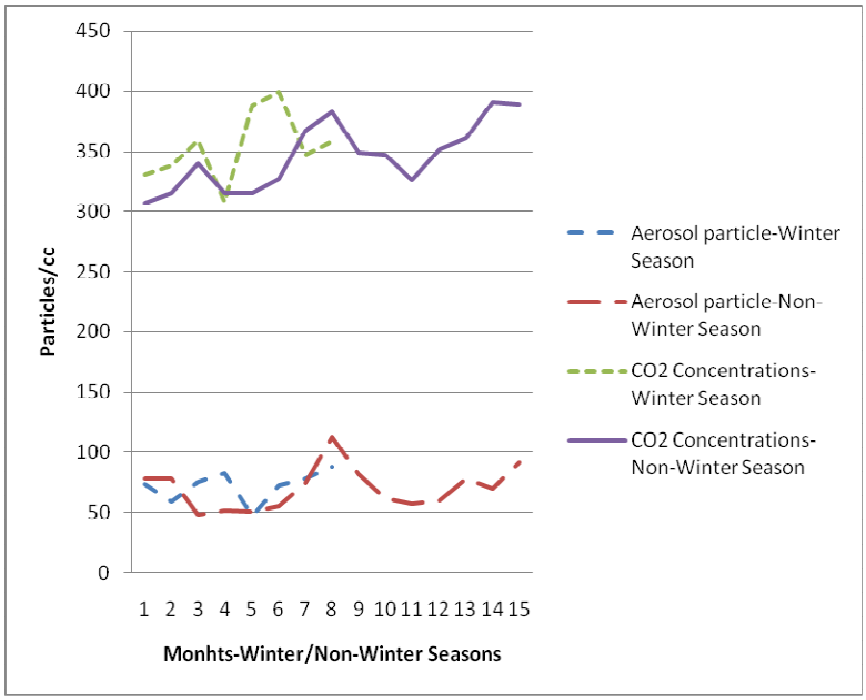

Figure 2. Seasonal variations in mean monthly concentration of airborne particles for the years 2006/07 and 2007/08

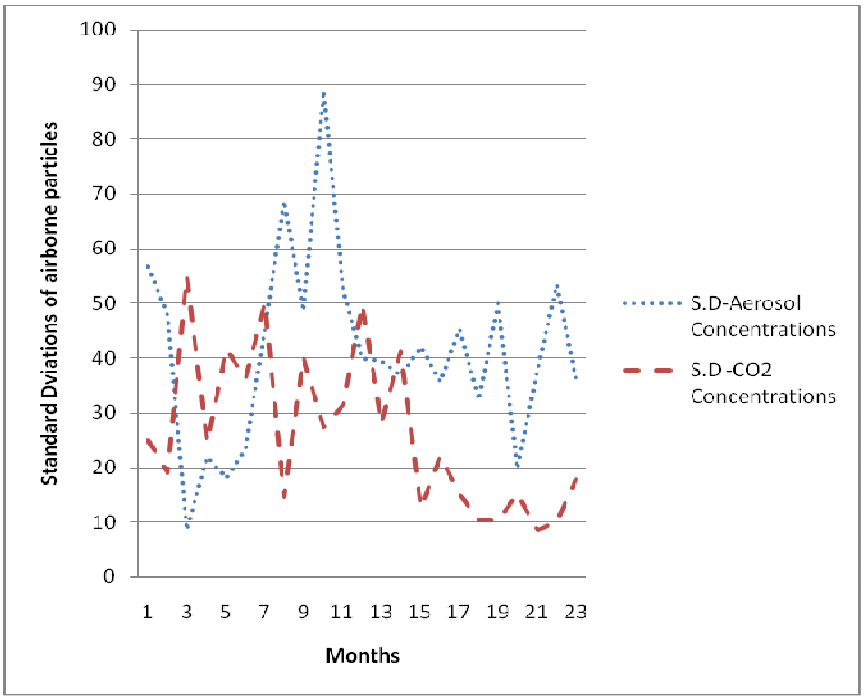

Figure 3. The monthly standard deviations of airborne particle concentration measurements during September 2006 to August 2008

It is clear from the graph that both the series of measurements show a marginal increasing trend for most of the months over the study period. However, the trend is very much visible if the

period of study is divided into winter and non-winter seasons as evident in the subsequent tables and figures.

Figure 2 shows the seasonal variations in mean midday concentration of aerosol particles larger than 0.3 µm and CO_2 concentrations measured in Gaborone between September 2006 and August 2008.

The trend lines in the lower part of the graph refer to the aerosol particle concentrations observed during the winter and non-winter seasons, while trend lines of mean monthly concentration of carbon dioxide for the same period are shown in the upper part. It is clear from the figures that mean airborne particle concentration measurements for the winter season are appreciably higher in winter than during the non-winter season.

Figure 3 shows the graph of monthly standard deviations of airborne particle concentrations during the study period.

It is clear that the data exhibits wide variations. The variation in aerosol concentration measurements is smallest for the month of November 2006 and largest for the month of September 2006. For the carbon dioxide concentration measurements, the monthly variation is smallest during March 2008 and highest in April2007.

Table 4. Severity states of airborne particles during the years 2006-08

Year	2006			2007											
Months	Sep	Oct	Nov	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Severity States															
Aerosol	4	4	2	5	4	5	7	4	4	5	4	6	1	2	4
CO_2	3	5	7	3	4	5	7	2	5	6	1	7	1	4	2

Table 5. Severity states of airborne particles during the winter season of the years 2006-08

Year	2008							
Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Aerosol	4	6	4	7	1	7	4	4
CO_2	7	5	7	4	4	7	1	7

Year	2007				2008			
Months	May	Jun	Jul	Aug	May	Jun	Jul	Aug
	Severity States							
Aerosol	4	4	5	4	1	7	4	4
CO_2	2	5	6	1	4	7	1	7

Table 6. Severity states of airborne particles during the non-winter season of the years 2006-08

Year	2006			2007								2008			
Months	Sep	Oct	Nov	Jan	Feb	Mar	Apr	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Severity States															
Aerosol	4	4	2	5	4	5	7	6	1	2	4	4	6	4	7
CO_2	3	5	7	3	4	5	7	7	1	4	2	7	5	7	4

Next, a calculation of Pearson's correlation coefficient between mean monthly aerosol concentration and CO_2 concentration measurements were made. The calculation yields a correlation value r = 0.297; which is insignificant (n = 23, p-value = 0.168). As pointed out earlier, this insignificant relationship is not surprising as there is any cause and effect relationship between them. However, calculated separately for the two seasons, it turns out that for the winter season r = -0.411 and for the non-winter season r = 0.569. The first of these is statistically insignificant (n = 8, p- value = 0.311) while the second is significant at 5% level of significance (n = 15, p- value = 0.027).

3.2 Data analysis based on indices of volatility and dispersion for severity states

Finally, the data is analyzed based on the new methodology developed here and discussed in section 2.

In Table 4, 5 and 6 we report the severity states of aerosol particle and CO_2 concentrations respectively for the years 2006-08; winter seasons and non-winter seasons of the years 2006-08.

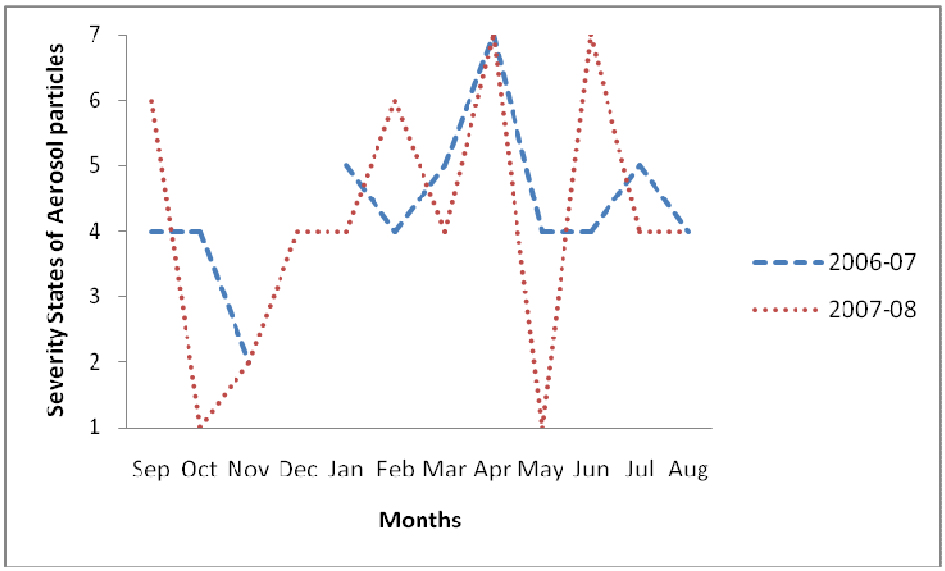

Figure 4. The severity states of monthly mean of aerosol concentration measurements for the years 2006-07 and 2007-08

Figure 4 and 5 show the graphs of severity states for airborne particle measurements during the two study periods 2006-07 and 2007-08. It is apparent that in Figure 4, aerosol particle states for the year 2006-07are more often found above the normal state (S_4) rather than on either side of it. On the other hand for the year 2007-08, at least on three occasions (October, November and May) the states are found below the normal state. Thus the year 2006-07 exhibited more volatility than the year 2007-08 in respect of aerosol particles. Turning to the CO_2 measurements, by similar argument it is seen that year 2007-08 is more volatile than the year 2006-07. As will be seen, these findings are confirmed by the index of volatility to be discussed subsequently.

The frequency of occurrences of severity of states in the whole study period 2006-08 and the two seasons are reported in the Table 7.

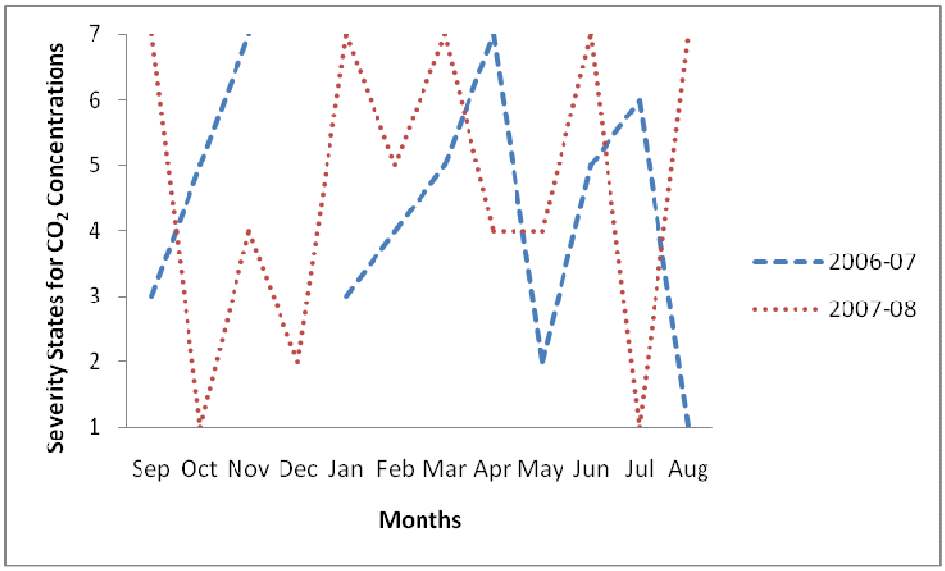

Figure 5. The severity states of monthly mean of CO_2 concentration measurements for the years 2006-07 and 2007-08

Table 7 Severity states of airborne particles during study period 2006-08and the two seasons

Period	Study Variable	Severity States							
		1	2	3	4	5	6	7	Total
2006-08	Aerosol	2	2	0	11	3	2	3	23
	CO_2	3	2	2	4	4	1	7	23
Winter Season	Aerosol	1	0	0	5	1	0	1	8
	CO_2	2	1	0	1	1	1	2	8
Non-winter Season	Aerosol	1	2	0	6	2	2	2	15
	CO_2	1	1	2	3	3	0	5	15

Following the discussions in section 2 and using the equations (5) and (6), one may construct the multinominal probability model for the three peroids under consideration, namely the entire period of study, the winter season and the non winter season. These computations are reported in Table 8.

Table 8 Empirical estimates of probabilities of severity of states

Study Period	States Variable	1	2	3	4	5	6	7	Total
2006-08	Aerosol	0.0870	0.0870	0.0000	0.4783	0.1304	0.0870	0.1304	1.00
	CO_2	0.1304	0.0870	0.0870	0.1739	0.1739	0.0435	0.3043	1.00
Winter	Aerosol	0.1250	0.0000	0.0000	0.6250	0.1250	0.0000	0.1250	1.00
	CO_2	0.2500	0.1250	0.0000	0.1250	0.1250	0.1250	0.2500	1.00
Non-winter	Aerosol	0.0667	0.1333	0.0000	0.4000	0.1333	0.1333	0.1333	1.00
	CO_2	0.0667	0.0667	0.1333	0.2000	0.2000	0.0000	0.3333	1.00

It can be seen that during the years 2006-08, in Gaborone, approximately 35% and 52% of the times the aerosol particle and CO_2 gas concentrations were above the threshold of normal state. Turning into seasons, it is seen that for the winter season the corresponding incidents were 25%

and 50 %, while 40% and 53% for the non-winter season. It is worthwhile to note that the extremely critical state had one of the highest probabilities of occurrences in all the three periods.

Finally, using the equation (11) and (12) we proceed to compute volatility and dispersion indices for year 2006-07and 2007-08, the winter and non-winter seasons. These indices are computed for both the study variables and are displayed in Table 9.

Table 9. Indices of volatility and severity for aerosol particles and CO_2 concentration measurement

Period/Season of study	Volatility Index		Dispersion Index	
	Aerosol	CO_2	Aerosol	CO_2
2006-07	5.50	1.00	1.45	3.64
2007-08	0.50	5.5	4.00	5.67
Winter Season	0.50	0.5	2.38	5.63
Non-winter Season	2.50	9.00	3.00	4.20

The two indices reported in the table indicate that
i) The aerosol particle concentrations showed more vaolatility during the year 2006-07 than 2007-08. The smaller volatility index for the year 2007-08 could be possibly due to the impact of precipitation. It has been well established by earlier researchers that precipitation scavenges aerosol particles. In the present case, according to the Botswana Meteorological Services records, the total rain fall during 2006-07 and 2007-08 were respectively 137.9 mms and 659.4 mms. Further, in 2006-07 it rained for a total of 28 days while in 2007-08 for 50 days.

ii) The scavenging effect seems to have pushed severity states to be different than the normal state more often during the year 2007-08 resulting in a larger dispersion index for that year.

iii) The volatility and severity indices for aerosol particles and CO_2 gas concentration are higher for the year 2007-08 than 2006-07. This is certainly indicative of atmospheric degradation in the Gaborone area of Botswana.

iv) The severity index for aerosol particles during the non-winter season is slightly more than that of winter season. In general, the latter is expected to reflect a larger index because of biomass burning, automobile emissions and so on. However, for Gaborone, it may be once again due to the scavenging factor as corroborated by the weather data. For instance, according to the Botswana Meteorological Services records, in Gaborone (see Table 3) the months of June 2007 and May 2008 falling in the winter season recorded a total rain fall of 21.5 mms and 35.2 mms respectively.

v) The dispersion index for CO_2 gas during the winter season is more than that of non-winter season suggesting that increased biomass burning may be one of the reasons.

vi) The volatility index for CO_2 gas during the non-winter season is appreciably larger than that of winter season suggesting lack of symmetry of severity states around the normal state.

CONCLUSION

In this study the mean monthly aerosol particle and carbon dioxide gas concentration measurements collected from Gaborone, Botswana were analyzed. The period of study was from September 2006 to August 2008. The data was analyzed for three periods of interest, namely, the entire study period, winter season and non-winter season. Besides elementary statistical techniques such as graphs and tables, correlation, a new methodology is introduced to analyze daily atmospheric data collected over a period of time. The new methodology defines states of severity of atmospheric data and also proposes measures of assessing volatility and dispersion among the defined states.

This study shows that the mean monthly particle concentration increases and becomes its maximum during winter. Similar trend is also observed with the mean monthly carbon dioxide gas concentration. There is a perceptible trend in mean monthly carbon dioxide concentration and the mean monthly aerosol particle concentration over the study period. This is due to the burning of the fire wood during winter which is common in Botswana during winter. It should also be noted that in southern Africa, during winter, photosynthesis in plants is reduced due to the reduction in sunlight and this could cause a rise in carbon dioxide level in the atmosphere.

An investigation into the monthly mean concentration of aerosol particles and carbon dioxide gas concentration over the winter and non-winter season has been made in terms of two new indices proposed here. Both these indices prove that precipitation scavenges aerosol particles.

Finally, the approach suggested here to analyze atmospheric time series data will be of interest to experimental physicist and atmospheric researchers. The new indices of volatility and dispersion are shown to reflect the symmetry of defined severity states and deviation from the normal state respectively. Because of paucity of data, in this study the new methods have been illustrated with a time series data with just two years. It is expected that these indices will be more accurate when applied to large time series data.

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