Modeling the Effect of Wind Speed and Win Direction on RSPM Concentrations in Ambient Air: A Case Study at Urban Areas in Central India

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Abstract- **A statistical approach is used to study the impact of wind speed and direction on ambient RSPM concentration at three different urban sampling locations in Nagpur. Directional parameters play an important role in determining the RSPM levels in ambient air. The use of circular statistics in modeling the RSPM concentration using wind direction is suggested. The nonlinear model based on inverse relationship of RSPM concentration with wind speed and sine and cosine of wind direction is used to obtain one-step ahead forecast. The results are compared with benchmark persistence model.**

Keywords- ***Circular statistics; wind speed; wind direction; particulate matter; modeling***

I. INTRODUCTION

Respirable suspended particulate matter (RSPM or PM10 - particulate size less than 10 micron) can reach alveoli region of the lungs and impose serious threat to human health and environment. The high concentrations of RSPM can cause many significant health problems ranging from aggravated asthma to premature death [1]. The study of impact of meteorological parameters on particulate matter helps in understanding the role of meteorology in governing the concentration levels. There have been attempt to analyze the effect of wind speed and direction on suspended particulate matter (SPM) concentrations in Delhi [2]. Jones et al. [3] analyzed the wind speed dependence of concentrations of RSPM, chloride, sulphate, nitrate, organic carbon, elemental carbon, particle number and NOx in Marylebone, North Kensington and Harwell. Nair et al. [4] found a negative correlation of concentration with wind speed for ionic species of continental origin. Statistical association was observed between RSPM concentration and wind direction in London and Rochester [5]. The inverse relationship between wind speed and pollutant concentrations up to some threshold is established in the many studies ([6], [7]). As argued by [3], Gaussian plume models assume the inverse relationship between wind speed and pollutant concentrations. The dependence up to some threshold however cannot be modeled by using Gaussian Plume models. In addition to wind speed, wind direction also governs the levels of concentrations of pollutants. Wind direction is a circular variable and needs the application of directional or circular statistics in modeling the concentrations as a function of wind direction.

The study aims at analyzing the meteorological parameters mainly wind speed and wind direction with RSPM concentrations at three urban locations in Nagpur, located in the centre of India. Study of directional parameter needs the application of advance statistical techniques as traditional techniques do not provide adequate inference. Our focus is using circular statistics to assess the importance of wind speed and direction in RSPM variations and using the concept to develop a model to forecast RSPM concentrations in advance.

II. STUDY AREA AND DATA COLLECTION

Nagpur, situated in the geographical central part of India (210 9’N, 790 6’E 310m ASL), is the 13th largest urban conglomeration in India with a population of around 25 lacs. Recognized as the second green and clean city in India, it has witnessed rapid economic expansion and thereby ever-increasing environmental problems. The major air pollution sources are power plant and automobile exhausts. The area has a tropical wet and dry climate with dry conditions prevailing for most of the year. It receives an annual rainfall of 47.44” from monsoon rains during June to September. Summers are extremely hot lasting from March to June, with maximum temperatures occurring in May. Winter lasts from November to January, during which temperatures can drop below 10°C.

RSPM was monitored during January 2008-December 2009 at three urban sites, namely Urb1, Urb2 and Urb3 in Nagpur. Urb1 site is located on the western fringes of the city and made up of around 900 small and medium industrial units. The major ones among them are tractor-manufacturing plant, casting units, combustion units, automobile parts manufacturing unit, confectionery manufacturing plant, steel rolling units. Urb2 site is located in Itwari, which is the wholesale business center of Nagpur. It is having narrow lane with high traffic and congested building and various shops. Urb3 site is located at NEERI Nagpur, with an open and flat area approximately 150 meters away from the heavily trafficked area. There are no significant local sources of air pollution in the immediate vicinity of Urb3 site. The sampling sites can be classified as an urban location distanced from sources but representative of general population exposure. The location of sites is given in Fig. 1.

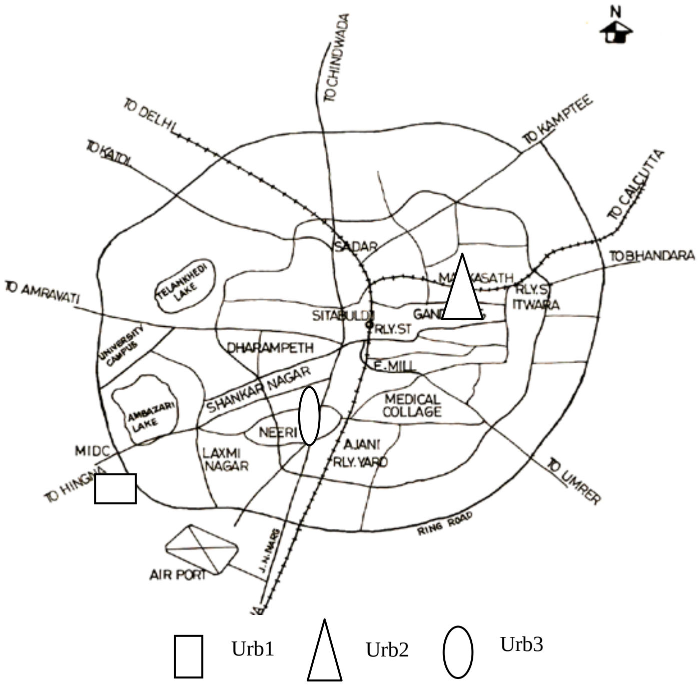


Fig. 1 Location of three sampling sites

The sampling inlets are located at about 25m above the ground level. The monitoring was carried out with a frequency of twice a week, thus giving 104 observations in a year. The air monitoring was carried out using high volume air samplers (Envirotech Model APM 415) equipped with a gaseous sampling attachment. The sampling inlet was located 25 ft above the ground level to collect the samples for particulate matter. Samples were taken at an interval of 8 hr as per standard methods described in APHA handbook [8]. For analysis of particulate matter, samples were collected on a 25-cm² Glass fiber filter (GFF) dried at 105° for an hour. The Weight of the GFFs was measured before and after sampling by using a 'SCALTEC SBC-22' standard electronic microbalance and the difference in weight gave the mass of particulate matter. The six missing values at Urb2 site were replaced by the average of the data. Meteorological data were collected from India Meteorological Departments (IMD). The statistical analysis was carried out using STATISTICA software.

III. METHODOLOGY

A simple linear-circular model is fitted to the data observed during 2008. The model involves linear and circular parameters as;

$$y = a + \sum_{i=1}^{k} a_i x_i + \sum_{j=1}^{l} a_j c_j \qquad (1)$$

Where y is the dependent variable, ai and aj are the coefficients to be determined using least squares or nonlinear estimation techniques, xi's are the linear independent variables and cj's are the circular independent variables. The choice of input variables is made based on the correlations of RSPM with wind speed and wind direction. As wind direction is a circular variable the circular correlation coefficient was computed [9] as;

$$r_c^2 = \frac{r_{xc}^2 + r_{xs}^2 - 2 r_{xc} r_{xs} r_{cs}}{1 - r_{cs}^2} \qquad (2)$$

Where rc is the correlation coefficient between linear and circular variables, rxc is the correlation between linear and cosine of circular variable, rxs is the correlation between linear and sine of circular variable and rcs is the correlation between sine and cosine of circular variable.

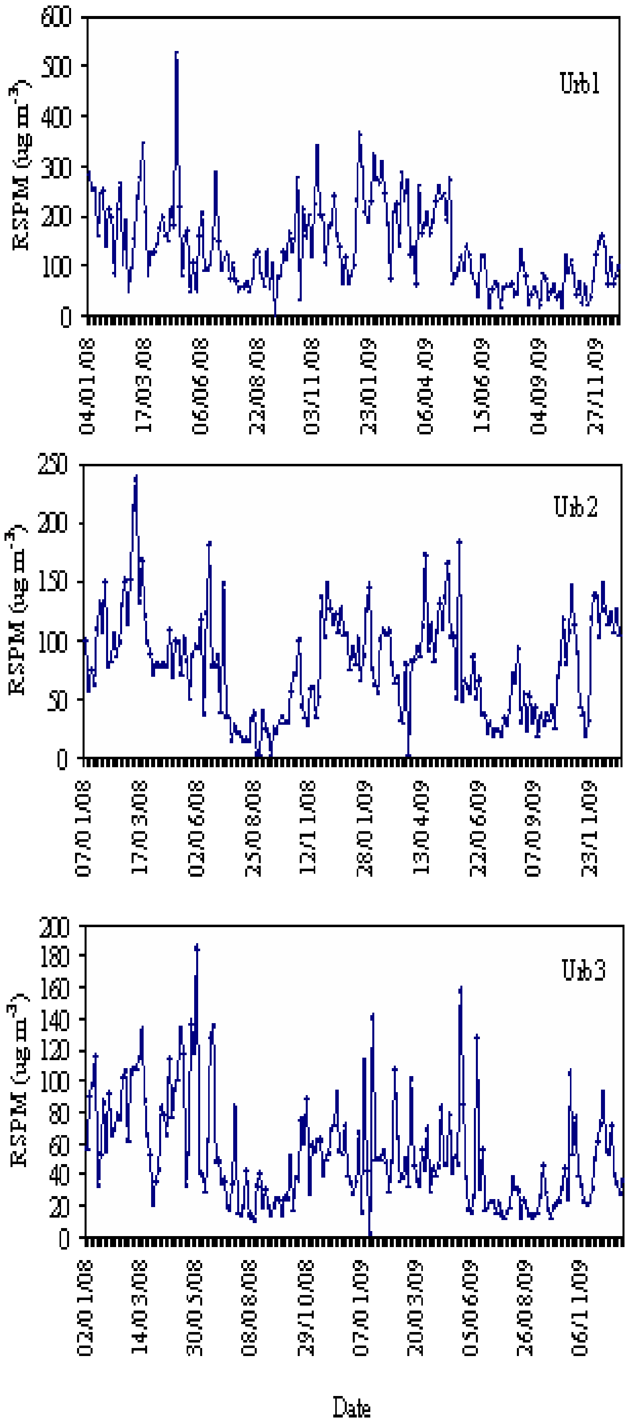
In order to include the temporal dependence in RSPM concentrations in the model, autocorrelation function is plotted. It is observed that RSPM time series has significant autocorrelations at lag1 and lag2. This suggests RSPM concentrations observed on a particular day depends on previous two-day's RSPM levels.

IV. RESULTS AND DISCUSSION

RSPM concentrations at three sampling sits observed during 2008-09 are given in Fig 2. The concentration varies from 10-527 μg m-3, 10-238 μg m-3 and 10-255 μg m-3 at Urb1, Urb2 and Urb3 sites, respectively. The standard limit of 100 μg m-3 provided by Central Pollution Control Board for RSPM concentration is exceeded most of time. Approximately 60%, 30% and 10% of the observations are above the standards at Urb1, Urb2 and Urb3 sites, respectively. The highest concentration at Urb1 is observed in April'2008, followed by March and November. For Urb2, highest concentrations are observed in March and June, whereas for Urb3, highest concentration is observed in May. The strong and medium winds during April to June create local disturbances in the environment which cause frequent dust storm, which build high RSPM levels in ambient air. Winter is observed to be most critical as compared to summer, monsoon and post monsoon period with reference to level of RSPM concentration. During monsoon, mostly winds from east prevail and frequent rains washes down the air borne particulates, therefore the period from July to September is cleaner period. The winter period is governed by calm wind conditions causing slow dispersion of pollutants which help in building high RSPM levels.

The statistical summary of the data is provided in Table I. It can be observed that Urb1 site is critical compared to other two sites with reference to RSPM concentrations. This site is in the vicinity of several industries along with traffic activities. The variability is however high at Urb3 site as evident by coefficient of variation (CV) in Table I.

For model development, the choice of input variables is important. For this, with the available data on wind speed, wind direction and RSPM concentrations, the correlation analysis was carried out. As wind direction is a circular variable, the circular correlation coefficient was therefore computed. The results of correlation analysis are given in Table II. It can be observed that the correlation between RSPM and wind velocity is not significant except at Urb1 site where significant correlation is observed between RSPM and wind speed. Weak negative correlation between PM10 and wind speed was also observed by [10].



Further analysis of wind direction and distribution of RSPM concentration is therefore carried out to gain more insight. Fig 3a shows the wind rose diagram at three sites. It can be observed that wind prevails mostly from E and ESE direction at three sites. In order to assess the prevailing wind direction for maximum RSPM concentration, 90th percentile is chosen as the threshold. RSPM concentration exceeding the 90th percentile and corresponding wind direction was noted down. The wind rose for RSPM>90th percentile is given in Fig 3b.

TABLE I. STATISTICAL SUMMARY OF RSPM CONCENTRATION (μg m^{-3}) IN NAGPUR DURING 2008-09

Parameter	**Urb1**	**Urb2**	**Urb3**
Average±SD	138.5±84.8	78.5±45.4	53.7±37.2
98th Percentile	326	177.3	139
CV	0.61	0.58	0.69
LoD	10	10	10

LoD- limit of detection, SD-standard deviation, CV-coefficient of variation

TABLE II. CORRELATION OF RSPM WITH WIND SPEED AND WIND DIRECTION

Variable	**Urb1**	**Urb2**	**Urb3**
WS	-0.23 (0.024)	-0.10 (0.34)	-0.01 (0.92)
WD	0.02 (0.84)	0.03 (0.77)	0.002 (0.98)

Significance level is given in brackets

It can be seen that the prevailing wind direction for maximum concentration is almost similar as for all the concentrations. Wind speed ranges from 4-16 km/hr for the maximum concentrations, whereas for the entire RSPM concentration data, it ranges from 1-16 km/hr. This suggests that RSPM concentrations at the three sites are not governed directly by wind velocity. Linear model hence may not be suitable for the present case to fit RSPM concentrations using wind velocity. Nonlinear model is therefore used to forecast the RSPM concentrations. As per the Box-Jenkins model selection criteria, parsimonious model selection is an important step.

The independent variables considered are wind speed(x1), RSPM concentrations at lag 1(x2) and lag 2(x3) and sine and cosine of wind direction (c1 and c2) to estimate response variable i.e. RSPM concentration (y). The model best fitted to the derive the RSPM concentrations is;

$$RSPM = a + a_1 WS^{-a_2} + a_3 RSPM_{-1} + a_4 RSPM_{-2} + a_5 \cos WD + a_6 \sin WD \quad (3)$$

Where a,a1-a6 are the coefficients to be determined using least squares estimation or nonlinear estimation techniques, RSPM-1 and RSPM-2 are concentrations observed at lag 1 and lag 2. The data observed during 2008 is used to develop the model and the data observed during 2009 is used to test the performance of the model to unseen data. The parameters were estimated based on Quasi-Newton algorithm. The algorithm is well known for finding the optimum of the nonlinear function. Newton's method is based on Taylor series expansion to find the stationary point of a function, where the gradient is 0. Quasi-Newton method approximates the Hessian matrix or its inverse to reduce the amount of computation per iteration. The Hessian matrix is updated by analyzing successive gradient vectors instead to find the root

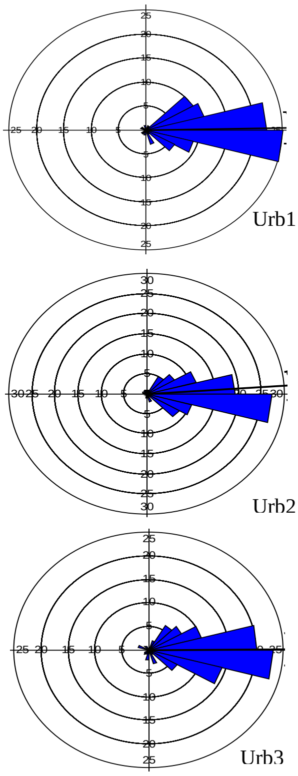


Fig. 3a Wind rose at three sites in Nagpur during 2008-09
x and y axis are the frequency of occurrences

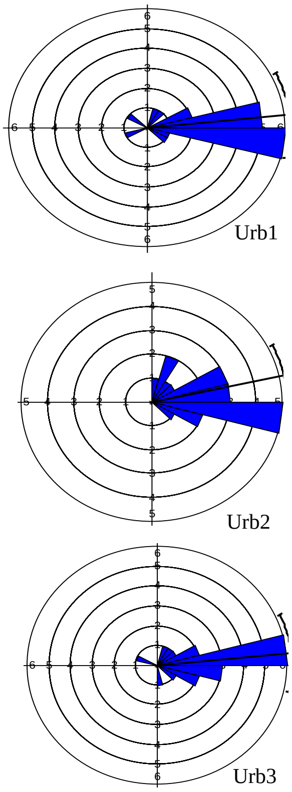


Fig. 3b Wind direction for RSPM>90th percentile at three sites in Nagpur
x and y axis are the frequency of occurrences

of the first derivative for multidimensional problems. The Hessian matrix is updated using the secant equation. The best fit equation is derived for the three sites, respectively as;

$$\begin{aligned}
\mathrm{RSPM} &= -0.821 + 0.85(\mathrm{WS})^{-0.891} + 0.41(\sin \mathrm{WD}) \\
&\quad -1.86(\cos \mathrm{WD}) + 0.534\mathrm{RSPM}_{-1} + 0.34\mathrm{RSPM}_{-2} \\
\mathrm{RSPM} &= 14.47 + 2.55(\mathrm{WS})^{-0.1} - 4.35(\sin \mathrm{WD}) \\
&\quad -0.038(\cos \mathrm{WD}) + 0.517\mathrm{RSPM}_{-1} + 0.284\mathrm{RSPM}_{-2} \\
\mathrm{RSPM} &= 7.53 + 0.638(\mathrm{WS})^{-0.1} + 2.399(\sin \mathrm{WD}) \\
&\quad +0.25(\cos \mathrm{WD}) + 0.622\mathrm{RSPM}_{-1} + 0.182\mathrm{RSPM}_{-2}
\end{aligned} \tag{4}$$

The coefficients were significant with $p<0.05$. The forecast results are summarized in Fig 4a. The goodness of model fit was assessed using diagnostic tools such as mean absolute percentage error (MAPE), normalized root mean square error (NMSE), index of agreement (IA) and coefficient of determination (R2) (for further details, refer [11]). Table III shows model performance results for observed and fitted concentration (data during 2008) and observed and predicted concentrations (data during 2009). MAPE and NMSE close to 0 suggests good agreement between observed and predicted values, whereas in case of IA, value close to 1 suggests the good agreement between observed and predicted concentration. It can be observed that for the prediction period, MAPE and NMSE are less than 0.5 for Urb1 and Urb2 and <0.6 for Urb3 site. IA is >0.6 for the three sites for prediction set. The prediction results are also compared with benchmark persistence model (yt=yt-1). Comparing the performance with persistence model shows better reliability of suggested model with reference to error statistics. The residuals were observed to be distributed normally using Q-Q plots (not shown here). The distribution of residuals is independent of predicted concentrations as can be seen from Fig 4b, which shows the reliability of the model predictions.

TABLE III.
GOODNESS OF FIT TEST RESULTS

Error statistic	Site	Model Fitting	Model Prediction	Persist
R^2	Urb1	0.85	0.72	0.56
MAPE		0.35	0.46	0.53
NMSE		0.25	0.33	0.45
IA		0.86	0.62	0.59
R^2	Urb2	0.92	0.88	0.47
MAPE		0.27	0.39	0.42
NMSE		0.16	0.17	0.32
IA		0.81	0.72	0.66
R^2	Urb3	0.95	0.93	0.58
MAPE		0.38	0.54	0.62
NMSE		0.27	0.40	0.70
IA		0.72	0.67	0.61

R^2-coeffcient of determination, MAPE-mean absolute percentage error, NMSE-normalized mean square error, IA-index of agreement, Persist – persistence model

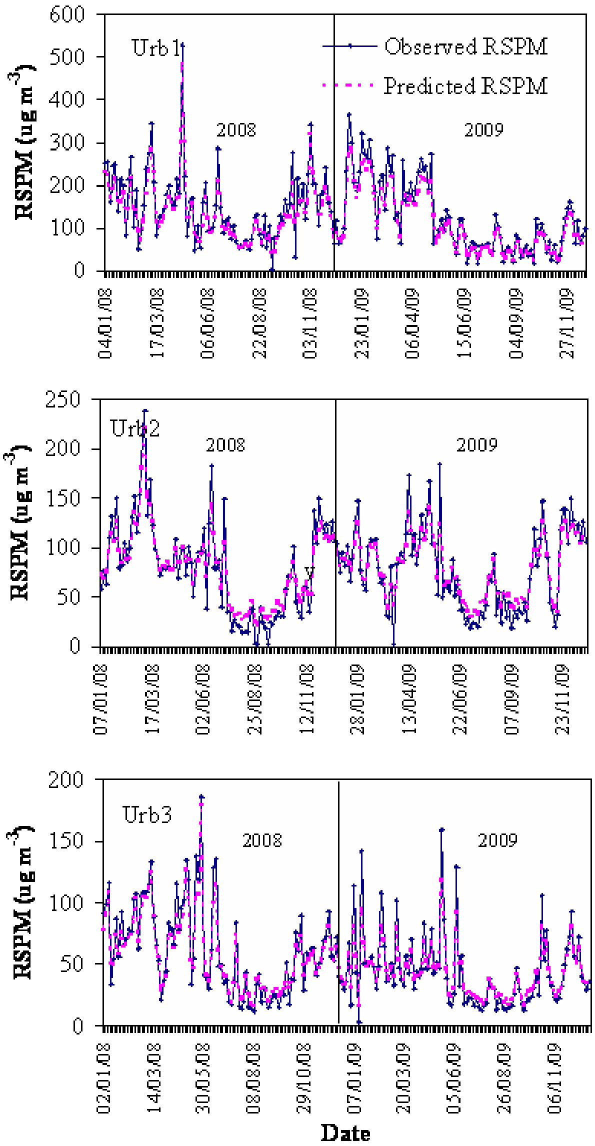


Fig. 4a Observed and predicted RSPM concentration during 2008 and 2009 2008 data are used for model development and 2009 data are used for prediction purpose
Vertical line is used to differentiate between fitting and prediction data

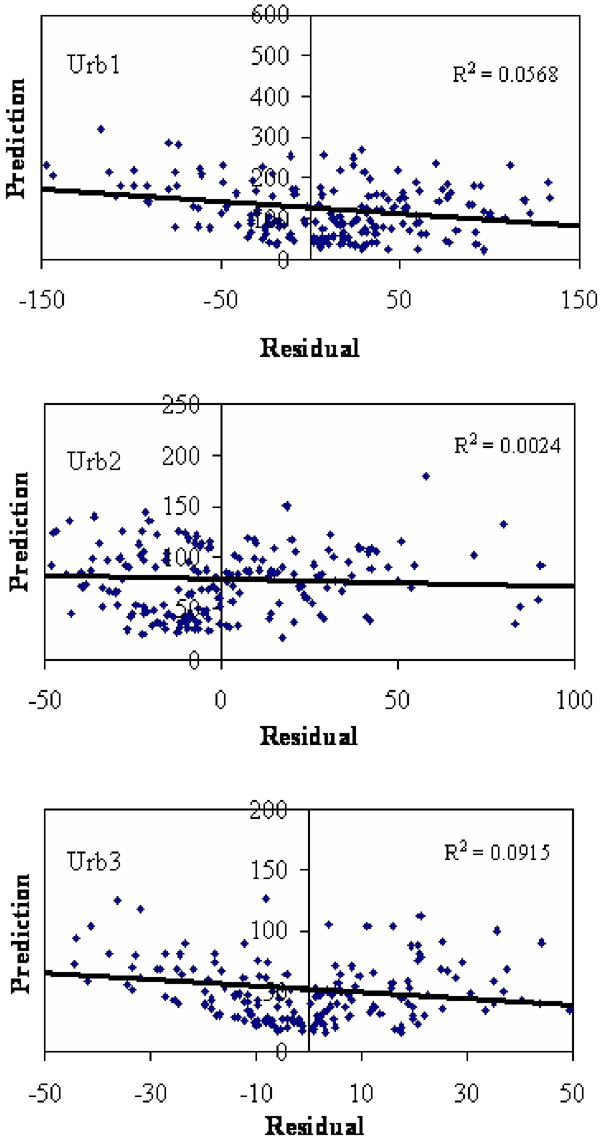


Fig. 4b Scatter plot of residuals with predicted concentration during 2009

V. CONCLUSIONS

The dependence of RSPM concentration on wind speed and wind direction is studied at three urban sites in Nagpur. The use of circular statistics in modeling the RSPM concentration using wind direction is suggested. The nonlinear model based on inverse relationship of RSPM concentration with wind speed and sine and cosine of wind direction is used to obtain one-step ahead forecast. The results are compared with benchmark persistence model, which showed better reliability of the suggested model in terms of statistical performance criterias.

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