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Locating air quality monitoring station using wind impact area diagram

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Abstract In this study a new methodology is suggested to approximate the impact area downwind of an air pollution source, where air quality monitoring can be carried out to capture the maximum pollutant concentration. Hourly wind speed for a given month is grouped in to different wind speed ranges and the distance of pollutant travel is approximated from the average wind speed of that wind speed range. Since change in wind direction causes the impact distance to rotate, its rotation is approximated by the SD of wind direction change. Using this approach, area or region down wind of a source is determined and plotted. The pattern of monthly change of wind is better represented by the new type of diagram as compared to the wind rose diagram.

Keywords Air quality monitoring · Windrose · Wind impact area · Wind direction persistence · SD of wind direction

Introduction

Ambient air quality monitoring program is an integral part of air quality surveillance, environmental impact assessment (EIA) and source apportionment study. Each study is aimed at different objective requiring different type of air quality monitoring program. These monitoring programs differ in selection of pollutant to be monitored, duration and frequency of monitoring and site selection criteria. A ten step procedure is suggested and discussed by Noll and Miller (1977) for designing an air sampling network. In all the studies, the relative position of pollution source and wind velocity plays a vital role in fixing the sampling location. Usually a wind rose diagram, which is a graphical representation of wind data, showing the frequency of wind speed and direction on a polar scale, is used to determine the down wind side of the pollution source. This information is then used in identifying the sampling location.

Wind data was first presented graphically by Leon Lalanne of France in 1843 named windrose diagram (Fig. 1), and was considered as a milestone in the history of thematic cartography and data visualization. Subsequently the computing and graphics capability of computer have resulted in generating windrose diagram to be used by meteorologists. In this diagram, the length of the arm represents the duration for a specific wind speed and its position on polar coordinate shows the direction from where wind is blowing. A windrose diagram can have a maximum of 360 arms if a least count of 1° is considered. Conventional windrose diagram uses 4, 8 or 16 radial arms by grouping the wind directions in 90, 45 or 22.5°, respectively. Grouping of wind directions in four direction-windrose results in wind direction uncertainty of 90° and in 16

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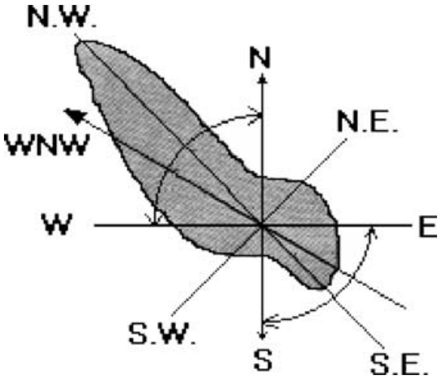

Fig. 1 Leon Lalanne's windrose diagram

radial arm windrose it is 22.5°. In a wind rose diagram, wind speed and wind direction are grouped and the frequency of these groups are shown graphically. In this paper, a methodology is suggested for graphically representing the impact area down wind of a source where pollutant is expected to occur under a given wind field. The new graphical representation would be called wind impact area diagram. This diagram can be used to identify the area down wind of a source that is impacted and can be used to locate the air quality monitoring station with relatively less uncertainty.

Methodology

In the first step, the wind data are grouped in to different category of wind speed, and for each wind speed category, the average distance traveled by the pollutant per unit time from the source will be represented by the mean wind speed (V_j) of that category. For example, wind speed category can be from 1 to 3, 3 to 5, 5 to 7, 7 to 9 km h^{-1} etc. The area of impact in the down wind for a wind speed class can be approximated using radius i.e., average wind speed (V_j) and the angle subtended at the center (SD of wind direction, σ_θ) in radians, in unit time. Figure 2a shows the windrose for a specific wind speed. Figure 2b shows the down wind impact area. The length of wind rose shown on the upwind side is in proportion to the frequency of wind data, whereas the radial distance of impact area on the down wind side is in length units. Figure 2c shows the parameters of the down wind impact area. The radial length of the impact area estimated as the mean wind speed of category '*j*' is V_j, the predominant wind direction estimated as the mode of wind direction distribution is denoted by A_θ and spread of wind about this predominant wind is denoted by σ_θ. This is considered applicable to wind speed more than 1 km h^{-1} and excludes calm wind conditions. In this method, estimate of mean wind speed is simple however SD of wind direction about predominant wind direction can not be estimated as a linear variable due to its cyclic/periodic nature.

The SD of wind direction can be estimated by several methods (Essenwanger 1964, Nelson 1984, Mardia 1975; Verrall and Williams 1982; Yamartino 1984, Ackermann 1983; Weber 1991. One of the simplest methods considered for estimating SD of wind direction is the use of an analytic estimate of predominance of wind direction also called wind direction persistence (P). Mori (1986), Yamartino (1984), Weber (1992) and Leung and Liu (1996) have used persistence for estimating the SD of wind direction. Wind direction persistence is measured on a scale of 0 to 1. A value of P=0 indicates wind direction distributed equally in all directions and P=1 indicates a persistent and constant wind direction. Essenwanger (1985) defined persistence as the ratio of vector mean (V_v) to scalar mean (V_s) of wind speed.

$$P = \frac{V_\mathrm{v}}{V_\mathrm{s}} \tag{1}$$

$$V_\mathrm{v} = \left[\left(\frac{1}{N}\sum_{i=1}^{N} u_i\right)^2 + \left(\frac{1}{N}\sum_{i=1}^{N} v_i\right)^2\right]^{\frac{1}{2}} \tag{2}$$

$$V_\mathrm{s} = \frac{1}{N}\sum_{1=1}^{N}\left(u_i^2 + v_i^2\right)^{\frac{1}{2}} \tag{3}$$

In this study, the model developed by Weber (1992) is used for estimating σ_θ.

$$\sigma_\theta = 105.8(1-P)^{0.534} \tag{4}$$

Similar to windrose diagram, a small circle at the center would represent percentage of calm duration. Wind speed less than 1 km h^{-1} can be drawn. For each wind speed category, the radius of the arc of the circle would be equal to the average wind speed of that category. Predominant wind direction can be determined based on frequency of the wind speed and direction. Care should be taken not to choose the resultant of the wind velocity. SD of wind direction

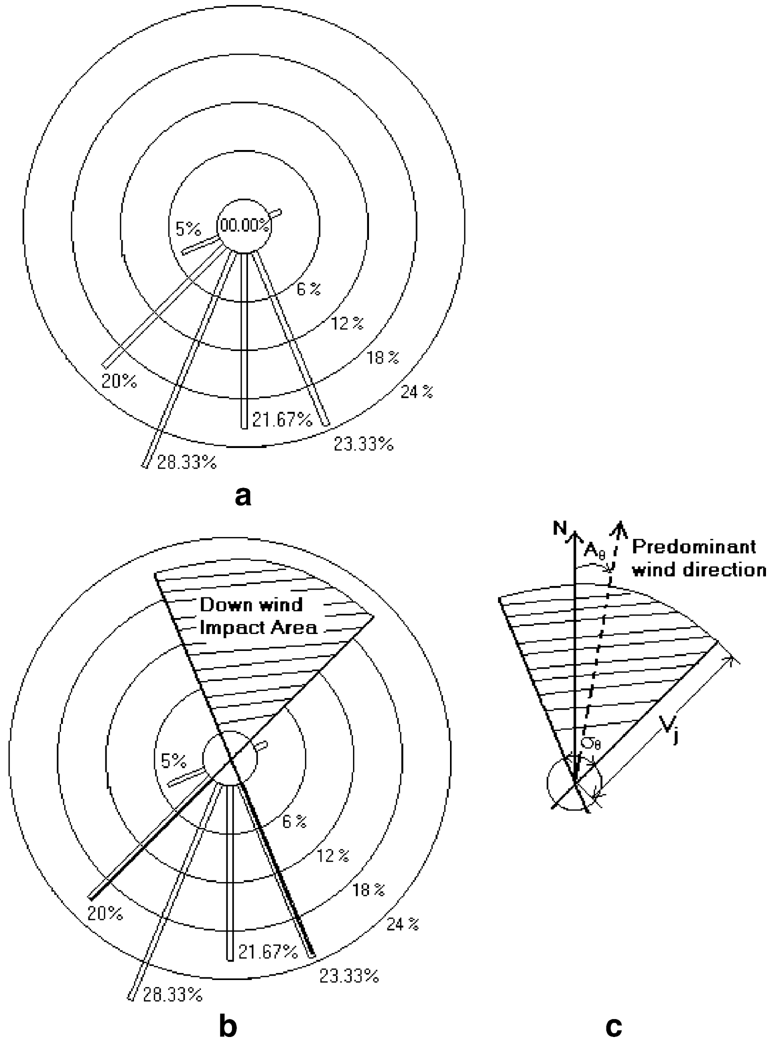

Fig. 2 Impact area down wind of windrose diagram. **a** Windrose for a specific wind speed. **b** Down wind impact area. **c** Parameters of the down wind impact area

for each wind speed category can be determined using Eqs. 1 to 4 and can be plotted on either side of the predominant wind direction ($A_\theta \pm \sigma_\theta/2$). Superimposing all the sector area over one center would create the wind impact area diagram.

Result and discussion

Hourly wind data collected at Vadodara, Gujarat, India for the year 2004 is analysed by the methodology discussed above. However detailed result of only 1 month's data is presented in this paper as a demonstration of the technique. For the month of December 2004, the wind speeds grouped in to seven categories and estimates like average wind speed (V_j), persistence (P_j), predominant wind direction ($A_{\theta j}$), and SD of wind direction ($\sigma_{\theta j}$) etc. determined and is presented in Table 1. Using these estimates, wind impact area diagram is plotted and is presented in Fig. 3a. For sake of comparison with the conventional wind rose diagram, the same is also plotted from the wind data and is presented in Fig. 3b. The windrose diagram shows the direction from where wind is blowing and is used for identifying the downwind area where a ground level pollutant source will cause potentially high concentration. This diagram does not give a pictorial view of the down wind distance up to which wind can cause pollutant to travel. However, if the center of wind impact area diagram is superimposed over a ground level pollution source, the downwind distance up to which pollution can travel can be

Table 1 Wind data analysis for December, Vadodara, Gujarat, 2004

Number	Wind speed category (V_j)	Data in category (N_j; %)	Average WS (V_{sj}) (km h^{-1})	Persistence of WD (P_j)	Predominant WD ($A_{\theta j}$; °)	SD of WD ($\sigma_{\theta j}$; °)
1.	$V_{calm}<1$	11.5				
2.	$1<V_1\leq 2$	16.18	1.43	0.86	225	36.38
3.	$2<V_2\leq 3$	16.91	2.50	0.83	202.5	41.42
4.	$3<V_3\leq 4$	18.14	3.44	0.80	180	44.61
5.	$4<V_4\leq 5$	16.67	4.44	0.85	157.5	37.98
6.	$5<V_5\leq 6$	11.52	5.43	0.76	225	49.88
7.	$6<V_6$	9.07	7.33	0.81	180	43.71

gauged and accordingly the sampling location can be fixed. From the windrose diagram, it can be seen that calm period is 11.52% of the time and the same is applicable for impact area diagram. Relatively low wind of 1.43 km h^{-1} prevailed along NE direction and therefore the pollutant will move and spread in the SW direction (225° measured from north) for 16.18% of the time (please refer Table 1 vis-à-vis Fig. 3a). Similarly, highest average wind speed of 7.33 km h^{-1} prevailed along north direction thereby pollutant will move towards south of the source for 9.07% of the time and so on. Almost for the whole month the pollutant will spread on the south of the source and therefore air monitoring sampler can be placed on the south of the source.

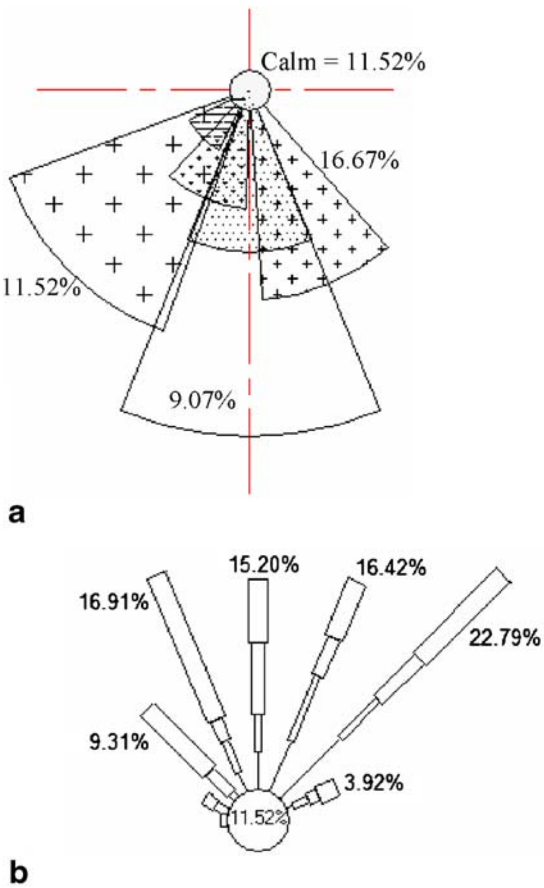

Fig. 3 **a** Wind impact area diagram for December 2004. **b** Windrose diagram for December 2004

Considering the one hour averaging as required in regulatory models (ISC, AERMOD), for 16.18% of the time pollutant can be captured along SW direction, downwind of the source, for 16.91% of the time along SWS direction and so on. These information is implicit in the windrose diagram, however wind impact area diagram shows these information explicitly and also provides additional information like pictorial view of the down wind area where impact of pollutant under the influence of wind may take place and the degree of spread of impact areas. It can be seen in Fig. 3a that there exist an area on the south of the source where all impact area overlaps and therefore this area can be chosen for setting up the air pollution monitoring station.

In order to show the monthly variation of wind direction change over a year, the wind data of all the months of year 2004 is analysed and corresponding windrose and wind impact area diagram is presented in Figs. 4 and 5, respectively. It can be inferred from Fig. 5 that there is a gradual variation in wind direction over a year. In January, the wind is from north resulting in impact area to be on the south to south-west direction. In the next month gradually the wind pattern changes resulting in wind impact area to be on SE to NE direction with high wind speed as seen from long sectors in May and June. In July and August, the impact area is on NE and is true as the SW monsoon sets during these months in Indian continent.

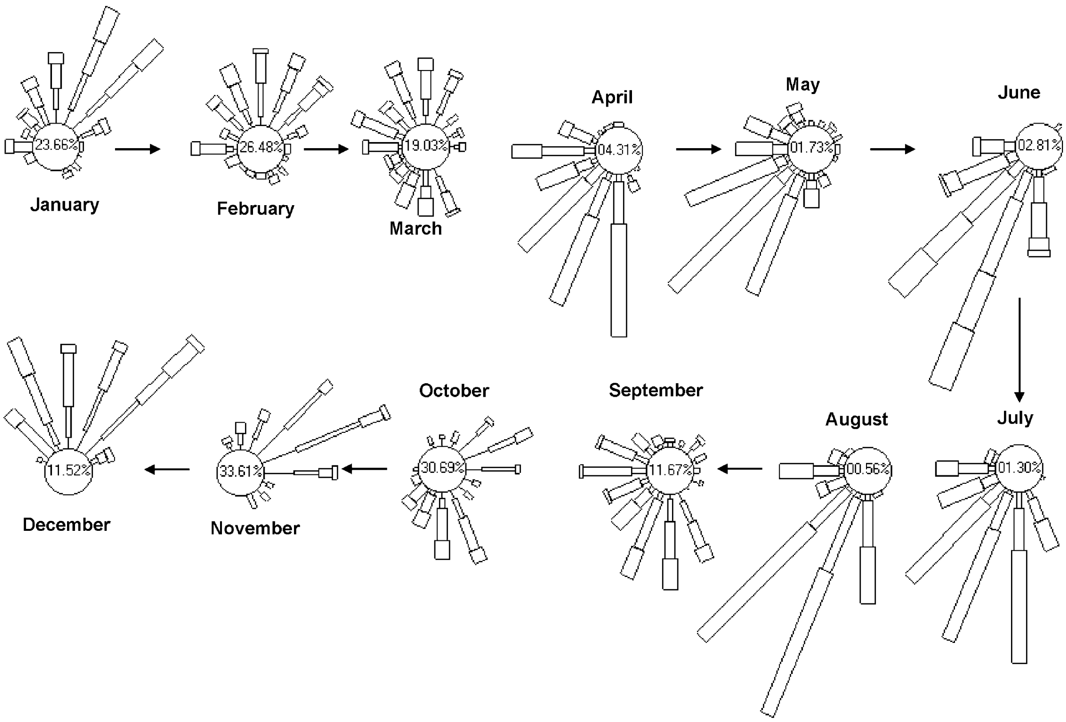

Fig. 4 Monthly windrose diagram for Vadodara, Gujarat, 2004

September is the end of rain period or SW monsoon and therefore the predominance of wind direction changes and is evident in the impact area of October, which is on the NE to NW. In the post monsoon period, the wind speed reduces to lower levels and calm period increases resulting in lower wind impact area and is clearly seen in the month of October and November.

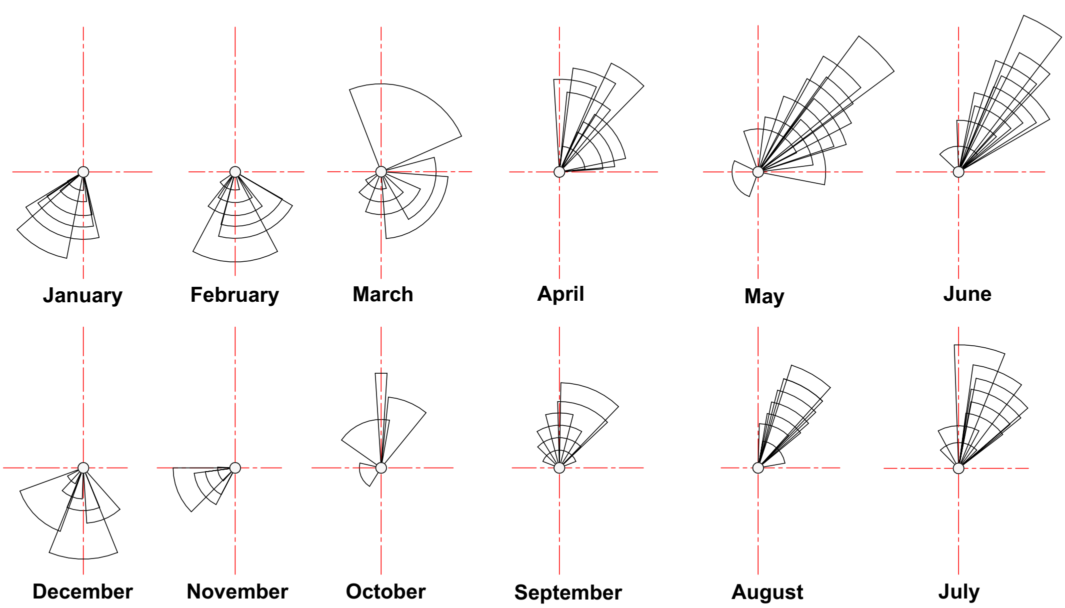

Fig. 5 Monthly Wind Impact Area Diagram for Vadodara, India, 2004

Conclusion

Conventionally wind data is represented using wind-rose diagram and is used by meteorologist as well as air pollution scientist. The meteorologist is interested in knowing the direction from where wind is blowing, however the interest of air pollution scientist is to know the direction where the pollutant would travel under the influence of this wind. Therefore a diagram that uses wind data and displays location where pollutant would spread is of more utility to environmental meteorologist. This objective is achieved in wind impact area diagram. An averaging time of one hour as applied in this study may seem to too long or too short for some of the applications, however USEPA approved dispersion models like ISCST and AERMOD makes use of hourly meteorological data and therefore one hour averaging time can be considered appropriate for similar applications. Sum total of impact area under different wind speed category can also be used as a measure of horizontal dilution potential of atmosphere and can be used to compare wind in space and time. Comparison of total impact area for different months may be useful in identifying periods of lower dilution thereby choosing periods of air pollutant sampling. Since this methodology provides horizontal extent of pollution spread, combined use along with vertical measure of atmosphere for pollutant spread like mixing height and vertical wind speed profile may yield volume of atmosphere and can be used as a box model for estimating the dilution potential of atmosphere.

Notation

- P_j Wind direction persistence of a specific wind speed category
- N Total number of wind data
- u_i Wind speed component along X axis
- v_i Wind speed component along Y axis
- σ_θ Angular SD
- A_θ Principle direction of wind impact area
- V_j Mean wind speed of wind speed category 'j' (km h^{-1})
- j Wind speed category
- N_j Number of wind data in a specific wind speed category
- θ Wind direction

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