Sodar in Dispersion Modeling

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ABSTRACT
Usefulness of sodar data for dispersion modeling has been highlighted. A case study of using sodar data in a simple Gaussian dispersion model to calculate ground-level concentration of particulate matter emitted from a cement plant has been examined in the light of actual measurements of particulate matter using a high-volume air sampler.

1. Introduction

Boundary layer thermal structures characterizing atmospheric stability play a significant role in determining the dispersion of pollutant plumes. For instance in a free atmosphere, other factors being equal, the vertical spread of plume increases with more unstability. However, in some cases, the presence of an elevated barrier to vertical dispersion, such as a temperature inversion, may inhibit the vertical extent to which pollutants may become mixed, and in the case of an emission above, penetrating the inversion from above may prevent the plume from reaching the ground level for large distances beyond the source. Quantitative information on the height of such layers and their frequency of occurrence is, therefore, very important, particularly in assessing the possible contribution to ground-level pollutant concentration from elevated sources. Such information is also important as an input to dispersion models that simulate pollutant patterns or, perhaps more importantly, assess the air quality impact of new developments.

In this context, acoustic sounder (sodar) is a useful tool to provide (with real-time advantage) information on quantities such as the atmospheric boundary layer (ABL) mixing height, the presence of capping inversion with its thickness and strength and eroding ground inversion associated with fumigation. A knowledge of these parameters, especially when used as model inputs, can provide fairly reliable results where an ordinary model calculation would not work well as certain synoptic processes bring about a singular variation of the structure of boundary layer Xiao et al. (1985). In fact, usefulness of sodar data to derive air pollution concerned meteorological parameters was demonstrated two decades ago by Beran and Hall (1974), and several later papers have followed in pursuit of the same cause (Best et al. 1981; Asimakopoulos et al. 1990; Neff and King 1990; Beyrich 1992). However, only a few papers have considered sodar data for the real aim of dispersion modeling to calculate ground-level concentration of pollutants (Jensen and Petersen 1979; Xiao et al. 1985). In pursuit of similar efforts, a case study to calculate ground level concentration of particulate matter emitted from a cement plant at Nimbahe (Chittorgarh, Rajasthan) is presented and compared with actual measurements of particulate matter using a high-volume sampler.

2. Sodar data and the model input parameters

Real dispersion model calculations require meteorological inputs of mixing height, stability class, and the dispersion coefficients in addition to the given stack parameters and emission characteristics. In this context, determination of the stability class, which is a qualitative indicator of the atmospheric dispersive capabilities and which plays an important role as a further determination of quantitative turbulence parameters or dispersion coefficients, is based on the determined stability class. Stability classification schemes based on the measurements of standard deviation of the wind direction fluctuations in the horizontal ($\sigma_\theta$) and vertical direction ($\sigma_v$), vertical temperature gradient, and the Richardson number have been put forward by different researchers (Smith 1951; Cramer 1957; Carpenter et
<table>
<thead>
<tr>
<th>Period of day</th>
<th>Forenoon 0730–1030 LT</th>
<th>Broad daylight 1030–1630 LT</th>
<th>Evening 1630–1930 LT</th>
<th>Night 1930–0730 LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasquill stability class</td>
<td>A B C D E F</td>
<td>A B C D E F</td>
<td>A B C D E F</td>
<td>A B C D E F</td>
</tr>
<tr>
<td>Occurrence (%) of stability class</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Turner’s table (TT) (Turner 1967)</td>
<td>— 34 47 19 —</td>
<td>42 46 12 — — — 06 80 14</td>
<td>— — — — 05 47 48</td>
<td></td>
</tr>
<tr>
<td>2) Sodar (Singal et al. 1985)</td>
<td>— 38 40 14 08 —</td>
<td>68 15 09 08 — — — 08 10 56 26</td>
<td>— — — — 24 76</td>
<td></td>
</tr>
<tr>
<td>3) Bulk Richardson number $Ri_b$ (McElroy 1969)</td>
<td>14 28 24 13 10 11</td>
<td>74 07 09 07 02 01</td>
<td>39 11 05 26 16 03</td>
<td>04 03 03 08 53 29</td>
</tr>
<tr>
<td>4) Wind direction fluctuations $\sigma_d$ (IS* 1978)</td>
<td>36 34 22 02 03 03</td>
<td>56 18 12 06 06 02</td>
<td>42 22 14 06 13 03</td>
<td>48 18 12 08 08 06</td>
</tr>
</tbody>
</table>

*Indian Standard Institution.

al. 1971). However, the scheme proposed by Pasquill (1961) and slightly modified by Turner (1967) based on the surface wind speed classification, insolation, and cloudiness is most widely used because it could produce satisfactory results in most cases and is also easy to use.

Keeping in mind the limitations of using this scheme for complex terrain, distances more than 10 km, effective stack heights more than 100 m, and many other problems, attempts are being made to have some alternate simple and inexpensive technique to derive the atmospheric stability in real time. In this context, sodar echograms are known to be the manifestations of the dynamics of the prevailing thermal structures in atmospheric boundary layer and portray, qualitatively, the prevailing atmospheric stability and, quantitatively, the mixing height in real time. Therefore, attempts have been made in the past to exploit sodar potential to deliver meteorological inputs for dispersion modeling. Singal et al. (1985) made an attempt to parameterize the sodar structural details in relation to the Pasquill stability classes, which were derived from the measurement of wind direction fluctuations at a height of 10 m. Subsequently, sodar data were used to estimate the crosswind dispersion coefficient, $\sigma_d$ (Gera and Singal 1990).

Assuming the results of sodar structural parameterization (Singal et al. 1985) to be valid for the present site (which may not be strictly true) and using the same as the reference to derive stabilities from sodar echograms, the present simultaneous observations of sodar structural details and 10-m tower observations of wind and temperature have been used to compare (Table 1) the statistics of the occurrence frequency of stabilities as determined through sodar, Turner’s table (TT), bulk Richardson number ($Ri_b$), and the standard deviation of wind direction fluctuation ($\sigma_d$). The results shown in Table 1 reveal a fairly good compromising correlation, indicating thereby that the sodar-derived stabilities can be used at least as an exercise for dispersion model calculations.

![Diagram](Fig. 1. Schematic representation for sodar detection of effective stack height $h_e$ and vertical dispersion coefficient $\sigma_e$.)

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Further, as the hot stack plume produces thermal turbulence along its trajectories, it offers thereby regions for acoustic scattering and thus the sodar echoes. If we assume that the vertical spread of the thermal turbulent plume and the particulate plume are nearly equal, then under certain favorable wind conditions when the plume is passing through the sodar probing ranges, a direct measurement of the vertical dispersion coefficient $\sigma_z$, and the effective stack height $h_e$ is mapped on the sodar records (Fig. 1).

However, such measurements are limited to favorable wind directions and the times when the stack plume is passing through the regions where there is no sodar echo in the background or the effective plume height is more than the height of the underlying sodar echoes due the ground-based thermal structures (Fig. 1). Otherwise, it is not possible to distinguish the stack plume echo from the background sodar echoes as the two merge together.

As per above, the sodar-derived values of the effective stack height $h_e$ and vertical dispersion coefficient $\sigma_z$ have been compared, respectively, with the values of $h_e$ derived using the plume rise equations given by Briggs (1975) and values coming from the PG curves (Pasquill 1961).

As per Briggs approach, the increase in height $\Delta h$ above the stack height $h$ is given by the following relationship:

$$\Delta h = \begin{cases} 11.6 F^{1/3} \mu^{-1} \rho^{2/3}, & \rho < 3.5X^* \\ 1.6 F^{1/3} \mu^{-1} (3.5X^*)^{2/3}, & \rho > 3.5X^* \end{cases}$$

where

$$X^* = \begin{cases} 14F^{5/8}, & F < 55 \\ 34F^{2/3}, & F > 55 \end{cases}$$

$F = gV_sR_s^2(T_s - T_a/T_s)$ is the vertical flux of the buoyant plume, $V_s$ is average exit velocity (m s$^{-1}$) at the stack top, $g$ is acceleration due to gravity (m s$^{-2}$), $R_s$ is average temperature (K) of gases in plume, $T_a$ is ambient air temperature (K), $\mu$ is wind speed (m s$^{-1}$) at stack height, $\rho$ is distance (m) from source to receptor, and $3.5X^*$ is distance to the point downwind of the stack where the plume is no longer rising.

The results (Figs. 2 and 3) reveal that the sodar-derived values are higher and the range of difference between the two values varies from 10% to 20%. The higher sodar values of $h_e$ are probably due to the fact that the sodar maps the turbulent plume and not the particulate plume.

Further, as the results are referenced with no sodar echo in the background and since such a situation is known to be the characteristic of neutral stability, these results would be perhaps more valid for neutral stability class. However, since the sodar stability scheme depends more on the structural details of the ground-based echoes, we have assumed the same degree of difference to prevail for all other stability classes. Under this hypothesis we have used the sodar-derived values of $h_e$ and $\sigma_z$ whenever available and otherwise accordingly modified the values by an average factor of 15%, if they are computed through conventional means so as to keep the sodar-derived values as the base for the present work.
3. Dispersion modeling—A case study

As a case study, the above approach to use sodar data for dispersion calculation has been applied to compute ground-level concentration of particulate matter from a cement plant located at Nimbahera.

The site is a vast valley surrounded by medium range hills, a part of the Aravali mountains. The nearest hills are at a distance of around 10 km from the site. Sodar was placed at a distance of 500 m from the stacks. Simultaneous measurements of sodar observation and ground-level concentration of particulate matter using a high-volume sampler at a few selected locations were made for a period of 1 week during December 1991.

The Gaussian dispersion model described by following Eq. (1) has been used to determine the downwind ground-level concentration of the particulate matter due to emission from a point source:

\[
C = \frac{C_s}{\pi \sigma_x \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{Y^2}{\sigma_y^2} + \frac{h^2}{\sigma_z^2} \right) \right],
\]

where \( C \) is the ground-level concentration, \( C_s \) is the source emission, \( \sigma_y \) and \( \sigma_z \) are the dispersion coefficient, \( Y \) is the distance on the \( Y \) coordinate, and \( U \) is the wind speed at the stack level.

The calculations have been made for the two locations [Nimbahera (1) and Gambhiri (2)] as shown in the layout map (Fig. 4). Results of the experimentally measured values and those calculated values for these two sites for the various sampling periods are given in Table 2. It may be noted that continuous sampling was made for the duration 1700–0900 LT on the following day. From the results it may be seen that the model values are comparable with the observed values. The mismatch is considered to be due to the possibility of

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Sampling period (hours)</th>
<th>Observed</th>
<th>Sodar model calculated</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nimbahera</td>
<td>12 Feb 91</td>
<td>0900–1700</td>
<td>610</td>
<td>462</td>
<td>Possibility of local dust concentration</td>
</tr>
<tr>
<td>Gambhiri</td>
<td>30 Nov 91</td>
<td>1700–0000</td>
<td>94*</td>
<td>79</td>
<td>-do-</td>
</tr>
<tr>
<td></td>
<td>1 Dec 91</td>
<td>0000–0900</td>
<td>94*</td>
<td>67</td>
<td>-do-</td>
</tr>
<tr>
<td></td>
<td>1 Dec 91</td>
<td>1700–0000</td>
<td>114*</td>
<td>121</td>
<td>Sampler not in operation for part of the time</td>
</tr>
<tr>
<td></td>
<td>2 Dec 91</td>
<td>0000–0900</td>
<td>111*</td>
<td>183</td>
<td>-do-</td>
</tr>
</tbody>
</table>

* Continuous sampling from 1700 LT on one day to 0900 LT on the next day.
local dust contribution to the measured high-volume sampler values at Nimbahera, since the site of measurement was close to the road side and nonoperation of the high-volume sampler at Gambhiri due to the local power failure.

4. Conclusions

A fairly good correlation has been observed between the direct measurement of particulate matter and simple Gaussian plume model calculations using sodar-derived air pollution concerned meteorological data of stability class, modified values of dispersion coefficient, and effective stack height. Studies reveal a promising sodar potential for air quality studies and stress upon the need for more case studies. Special experiments using multitechniques may be designed to revalidate the conventional and other techniques of determination of stability class, dispersion coefficients, and plume rise calculations.

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REFERENCES


