The use of Gaussian model for the final concentration computation, though used under present data constraints, may not give precisely close to the actual concentration values. It is still the best screening approach when only wind speed, directions are known. Inadequacies creep in due to the following reasons.

(1) **Non inclusion of a Plume Inversion Trap**

The presence of an elevated inversion can have a devastating effect on the ground level concentration downwind from a stack, since the inversion acts as a giant lid on the upward dispersion of pollutant gasses. This situation is often modeled as a gas passing downwind between the reflecting surfaces, the ground and the bottom of the elevated inversion layer. The ground reflection can be modeled by a virtual image at \(-H\) below the earth’s surface, with the additional reflections considered at height \(L\) and \(-L\), where \(L\) is the distance to the bottom of the inversion layer. An accounting of all the stable layer and ground reflections can be made through summation of terms. The end result is a centerline expression of the form:

\[
C = \frac{Q}{2\pi \sigma_y \sigma_z u} \sum \left\{ \exp \left[ -\frac{(Z-H+2jL)^2}{2\sigma_z^2} \right] + \exp \left[ -\frac{(Z+H+2jL)^2}{2\sigma_z^2} \right] \right\}
\]
Where the summation is carried out from $j = -\infty$ to $+\infty$. This series usually converges rapidly, requiring only the first few terms, for example, values of $j$ up to $\pm 2$ or $\pm 3$.

A good approximation to this equation may be made by assuming that the inversion layer has no effect on the vertical dispersion until a downwind distance $x_L$ for which $\sigma_z = 0.47 (L-H)$. If we know the height of the inversion layer, we can use this relation to estimate $x_L$. The effect of reflections from the stable layer and the ground beyond the distance $x_L$ is such that uniform vertical mixing has taken place by the downwind distance $2x_L$. Beyond $2x_L$, the appropriate equation is.

$$C ( > 2x_L, y, z) = \frac{Q}{(2\pi)^{1/2}\sigma_y \sigma_z} \exp \left[ - \frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right]$$

This expression contains only $x$ and $y$ variables. For distances between $x_L$ and $2x_L$, Turner (1969) suggests that ground level, centerline concentrations be read from a straight line drawn between the concentrations for points $x_L$ and $2x_L$ on a log-log plot of ground level, centerline concentrations versus distances.

(2) Gaseous Deposition from Stacks

Gaseous concentration with reflection is

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \left[ \exp \left( - \frac{y^2}{2\sigma_y^2} \right) \right] \left[ \exp \left( - \frac{(Z-H)^2}{2\sigma_z^2} \right) + \exp \left( - \frac{(Z+H)^2}{2\sigma_z^2} \right) \right]$$

and without reflection it is

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp \left( - \frac{1}{2} \left[ \frac{y^2}{\sigma_y^2} + \frac{(Z-H)^2}{\sigma_z^2} \right] \right)$$
Assumption of 100% reflection is against the 2nd law of thermodynamics and the assumption of no reflection (i.e. treating ground as a sink) is also unrealistic. The actual situation lies somewhere in between these two extremes which can be assessed if we consider partial absorption of SO₂ in the surface taking into account the ground humidity. This should be properly taken care of by taking into account different moisture conditions.

(3) The Gaussian equation is valid if diffusion in downwind direction may be neglected. If the duration of release is equal to or greater than the travel time from the source to the location of interest, downwind diffusion may be assumed absent; but, when the wind speed is small σₓ becomes significant.

(3.1) Estimation of Wind Speed

For mean wind speed U, the value measured at 10-meter height (surface wind) should be used for distance up to about 1 km for surface sources or short stacks. For greater distances or elevated sources a mean speed through the vertical extent of the plume about (2σ₂) should be used. A speed midway between the surface and geostrophic speeds should be reasonable.

(4) Effect of Aerodynamic Downwash

The influence of the mechanical turbulence around a building or stack may, significantly, alter the effective stack height. This is especially true under high wind conditions when the beneficial effect of high stack gas velocity is at minimum and the
plume is emitted nearly horizontally. The region of disturbed flow surrounds a building (an obstacle) generally to twice its height and 5 to 10 times its height downwind. By using models of obstacle shapes and stacks, the wind speeds required to cause downwash for various wind directions may be determined.

By determining the critical wind speeds that will cause downwash from various directions for a given set of plant factors, the average no. of downwash annually can be calculated by determining the frequency of wind speeds greater than the critical speeds for each direction.

(5) In the present model hourly wind speed and direction data have been used. As a general rule, the higher the wind speed, the more persistent the wind direction will remain. But, for low speed winds there may be remarkable deviation in the direction. To minimize this discrepancy, 15-min. or even smaller period wind data should be used instead.

(6) Chemical transformation, Gravitational settling, rain-out and washout should be taken into consideration for improving the predictive ability of the model.

(7) Model Uncertainty

Air pollution models vary from simple models, which possess only a few parameters, to complex ones characterized by a large no. of parameters. Larger the no. of parameters, the lower the natural (or "stochastic") uncertainty associated with the model and the smaller the errors in the models representation of the physical reality.
Unfortunately, however, the larger the no. of output parameters to be specified, the larger the input data error. There is an optimum no. of parameters that minimizes the total model uncertainty.

(8) In a complex terrain the meteorological data at one place cannot be applied to different places because of the rapid change in these variables in such topographies. On site meteorological data is required for better assessment of air quality.

(9) Non inclusion of Shear Effects of the Wind

Change in wind direction with height affects diffusion rates. Csanady (1969); and Egan and Mahony, (1972) have estimated that even moderate wind direction shear results in effective increases of plume dispersion which are some orders of magnitude larger than those expected in the absence of shear. In the case of complex terrain the situation is further complicated due to the topographic effects.

(10) Wind flow is a function of the shape and size of the hill. This could not be considered presently.

(11) Flow systems of the terrain are not available. These are to be considered. Under near neutral conditions the appearance of the flow approaching the terrain object is expected to behave like conventional flow past one obstruction. Flow which approaches the peak would get accelerated and the inner streamline distance is reduced. The fluid on the side of the obstacle may experience hydraulic jump, cavitation, separation or lee wave
formation depending on the wind speed, and obstacle characteristics. These should be properly taken care of. Potential flow theory may provide one step more towards better prediction. Other phenomenon which is to be considered is channeling which results in flow accelerations and distortions. All these need to be considered for better prediction.

(12) Non inclusion of viscous effects and stratifications effects resulting from density variations.

(13) In the derivation of Gaussian equation, the diffusion in the orthogonal directions is considered independent, but the distribution is jointly as well as separately Gaussian.

Suggestions

(1) Improved data from remote sensors such as acoustic sounders, lidars for mixed depth, plume height and range resolved turbulence intensity and wind and wind shear will improve the model prediction greatly.

(2) Inclusion of potential flow theory.

(3) Use of on-site meteorological data

(4) Improvement of transport wind data with the requirement for on-site mean vector wind profiles. The local transport, wind direction.

(13a) The most common formula for the PBL height, \( h_e \), first suggested by ZilitinKevich (Businger and Arya, 1974) is
\[ h_e = a \sqrt{\frac{u_* L}{f}} \]  

where \( a \) is the constant of proportionality and \( L \) is the Monin-Obukhov length.

According to the above eqn. \( h_e \) approaches infinity in neutral air, becomes small in stable air and depends directly on the square root of \( U^* \). This simple interpretation explains why the performance of complex models is often equal or inferior to that of simpler methodologies. Complex models work well only when their extensive data input requirements are satisfied, which rarely occurs.

Attention must be paid to model evaluation efforts, whose results, because of the considerations above, can be misleading. Complex models can, in fact, because of their high no. of parameters, be easily "tuned" or "calibrated" to well fit available measurements than simpler techniques, when applied on an "independent" data base. (i.e, a data base different from the one used for model calibration) In other words, complex models can fit the data better than simpler techniques, but this does not necessarily indicate that complex models can forecast better than simpler ones.

\[ L = - \frac{u^3 \rho C_p T}{K \rho H} \]  

Where symbols have their usual meanings.

Attempts to test the above eqn(1) by measurement, however, have been disappointing; there has been little correlation between measured values of \( h \) and those estimated by the equation (Mahrt et al, 1979). Garret (1982) suggests that the unsatisfactory results with eqn (1) are due to the difficulties in obtaining accurate
measurements of $U_*$ and $L$ rather than to the inadequacies of the equation. He suggests that in middle latitudes the value of $a$ in the above equation (4) is 0.4.

Since estimates of $U_*$ and $L$ are unreliable during the relatively weak turbulence in stable satisfaction, it may be better for practical purposes to estimate $h$ directly from measurements by acoustic radar (sodar). Sodar measures the distribution of high frequency temperature fluctuations. Above $h$, such fluctuations become intermittent; thus $h$ can be inferred from the record.

However, at night over land, the mixing depth sometimes is so small that echoes from turbulence are masked from the thin turbulent layers above $Z_i$ (inversion base). Thus, sometimes the height of the true $h$ is much lower. However, this ambiguity can be avoided by separating echoes from turbulent and laminar layers which are different in appearance.

(14) The Roughness Length $Z_o$

The parameter $Z_o$ is generally, function of surface roughness only, though it may be affected by the wind speed (when the roughness elements bend with the wind) and the wind direction (when different terrain features surround the region). It has also been suggested that the effective value of $Z_o$ should increase with height (Wilczak, J. M. & Philips, M.S., 1986). The value of $Z_o$ can be approximated as $Z_o = \epsilon/30$, where $\epsilon$ is the average height of the obstacles in the study area. The roughness length can also be computed from wind profile measurements. In fact, in purely mechanical turbulence (i.e. with logarithmic wind profile for $Z > Z_o$) which is given by
\[ U(z) = \frac{U_*}{k} \ln \left( \frac{Z}{Z_o} \right) \]

when the roughness elements are small. When the roughness elements are not small, a displacement length \( d \) can be defined (Panofsky & Dutton, 1984), which is typically 70% of the height of the large roughness elements. The wind profile for \( Z > d \)

\[ U(z) = \frac{U_*}{k} \ln \left( \frac{Z-d}{Z_o} \right) \]

Finally, the optional application of a deterministic model for control strategy analysis should incorporate its calibration and evaluation with local quality monitoring data, in order to determine its applicability and minimize forecasting errors. It becomes a difficulty when sufficient air quality and meteorological data are not available. Since, ideal model application conditions are seldom found air quality models are used beyond their theoretical and practical limits of applicability.

(15) **Power Law For Wind**

The wind speed at the height \( z \) is given by

\[ U(z) = U_r \left( \frac{Z}{Z_r} \right)^p \]

Where \( U(z) \) is the adjusted wind speed at stack height \( z \); \( U_r \) is the wind speed measured at a reference height \( Z_r \), \( p \) is the wind profile exponent.

Several observers (Arya, 1982; Kaimal et al., 1976; Pennell and Le Mone, 1974; Clarke, 1970; Izumi and Barad, 1963) have noted that the wind speed doesn’t obey power law throughout the entire boundary layer, whose height is defined by the mixing lid.
Instead, the increase of wind speed with height is found to level off or even slightly decrease above a certain height, depending upon the mixing height in unstable conditions or the surface layer friction velocity, \( U_* \), in neutral and stable conditions.

In unstable conditions, the height limit is 0.1 times the mixing height. Arya (1981) shows that in neutral and stable conditions, the approximate height of the wind speed maximum (\( H_{\text{max}} \)), is given by

\[
H_{\text{max}} = 0.142 \frac{U_*}{f}
\]

Where, \( U_* \) is the friction velocity, and \( f \) is the coriolis parameter.

For general application, \( H_{\text{max}} \), can be specified approximately using a 10-m wind speed. With assumptions for typical values of surface roughness length in complex terrain (meter) and the coriolis parameter \( (10^{-4} \text{ sec}^{-1}) \). The resulting values of \( H_{\text{max}} \) as a function of stability are.

\[
H_{\text{max}} = 0.1 \text{ mixing height for unstable conditions}
\]

\[
H_{\text{max}} = 200.10.\text{m wind speed (m/sec) for neutral and stable conditions.}
\]

The above equation is therefore modified as follows:

\[
U(z) = U_r \left( \frac{Z_{\text{max}}}{Z_r} \right)^p
\]

where \( Z_r = Z \) if \( Z < Z_r \),

\( Z_{\text{max}} = \min(Z, H_{\text{max}}) \) if \( Z > Z_r \).

Pollutant concentrations estimated by the Gaussian plume equation used in the model are inversely proportional to average wind speed. This implies that concentrations would approach infinity as the wind speed approaches zero, which is clearly not the case. To simulate the effects of very low wind speed cases, hourly wind speeds that are below
1m/sec are set at 1m/sec. This precludes an invalid application of the model. For calm conditions, where there is no measured wind direction, the wind direction from the previous non-calm hour persists. This assumption can cause the model to overestimate pollutant concentrations for multiple hour averaging times if calm persists for several hours.

(16) Wind Profiles Over Hills

When air ascends a hill, streamlines converge rapidly, and the air accelerates. The theory of this behaviour has been treated by many investigators (Taylor, 1977; Jackson & Hunt, 1975), but only for neutral conditions. Also, the slope has generally been assumed small. The results of the theories agree well with each other and with the observations, even when the slopes are significantly larger than the required by theory.

The limitation to neutral conditions (more exactly, mechanical turbulence) is not serious in most of the engineering applications because the interest is generally in strong winds. The Parameters used in these theories are: h, the height of the hilltop above the place, L, the horizontal upstream distance from the hilltop to the point where the height above initial terrain is h/2 and Z₀, the roughness length. Thus, h/L is a measure of the slope. Jackson and Hunt separate the layer of air influenced by the hill into two layers. The inner layer is of thickness l and is influenced by the hill through the turbulent exchange. It is a region with large wind shear. In the outer layer the turbulent exchange can be neglected, and potential flow prevails. The wind shear in this region is small, and the wind at the top of the layer approaches the undisturbed profile.
The thickness 1 of the inner layer is given by

$$\frac{1}{L} \log \frac{1}{Z_o} = 2K_a^2$$  \hspace{1cm} (1)

where $K_a = \text{Von Karman constant}$. Typically, 1 is of the order of 0.1L. Below $Z-d = 1$, the profile is logarithmic, given by

$$u = \frac{u_0}{k_a} \log \frac{Z-d}{Z_o}$$  \hspace{1cm} (2)

Where $u_0$ represents only the surface stress the actual stress decreases upward.

It is common to define a speed up factor, $\Delta S$, which measures $\Delta U/U_0$, the ratio of the wind change at a fixed height above local terrain to the original wind. This according to Jackson and Hunt (1975), is given by

$$\Delta S = \frac{\Delta u}{u_o} = \frac{h}{L} \frac{\ln^2 \left( \frac{L}{Z_o} \right)}{\ln^2 \left( \frac{1}{Z_o} \right)}$$  \hspace{1cm} (3)

In practice, this is typically of the order of 2h/L, and, hence, proportional to the slope. The speed up factor is very nearly constant below 1; and, so the originally logarithmic profile remains logarithmic as the air flows up the slope. Also, the surface friction velocity grows up by about the same factor as the wind. That is why the slope on the hill profile remains a measure of the surface stress. Below $Z = 1$, the vertical wind shear exceeds its upstream value by $\Delta S$; above $Z = 1$, shear is less than upstream.

So far, we have assumed that the roughness lengths are the same upstream and on the hill. If a hill is smooth and the upstream region enough, there are two speed up
factors. Taylor (1977) has shown that the combined speed up factor is, very approximately, the product of individual factors. Quite commonly, the slope causes acceleration, but the roughness change, declaration. But the acceleration due to increased roughness is mostly confined to the air close to the surface; the acceleration due to the slope influences the wind at relatively higher levels.

(17) Treatment of the Wind Velocities less than 1m/sec

In the data from meteorological (IMD sources), the directions have been mentioned for calm conditions. Hence, the wind speeds which are less than 1m/sec have been taken as 1m/sec because the use of the wind speed as 0 would give the concentration as infinite which is unrealistic.

The use of the Gaussian plume model in conditions of very low wind speeds is questionable because the wind speed and direction are very variable in these conditions, so that a well defined plume is unlikely to exist and the assumption that along wind dispersion can be neglected is no longer valid. Smith & Readings have considered the error in estimating the wind speed at a point away from a meteorological station. They estimated errors of above 2m/s in speed and upto 20° in the direction of the wind at a height of 10 m, arising from instrument error and from the extrapolation to other locations within a few tens of kms. of the measuring point over rolling terrain. The absolute error in wind speed increases with increase in wind speed while that in direction is greatest for low wind speed.
(18) Model Use in the Complex Terrain

The lack of detailed descriptive data bases and basic knowledge concerning the behaviour of atmospheric variables in the vicinity of complex terrain presents a considerable obstacle to the solution of the problem and the development of refined models. Several major complex terrain problems are:

1. Valley stagnation
2. Valley fumigation
3. Downwash on the lee side of terrain obstacles,
4. Identification of conditions under which plume impaction can occur.

In addition, insight into the lee side effects problem is also anticipated.

Fluid modeling can give an insight into these problems.

(19) Non Inclusion of Inversion break-up

Due to non-availability of such data. This drawback can be done away with if surface based inversion data are available and we proceed conceptually as:

Concentration in an Inversion Break-up condition

A surface-based inversion may be eliminated by the upward transfer of sensible heat from the ground surface when that surface is warmer than the overlying air. This situation occurs when the ground is being warmed by solar radiations or when the air flows from a cold to relatively warm surface. In either situation pollutants previously emitted into the stable layer will be mixed vertically when they are reached by the thermal eddies, the ground level concentrations can increase. (This process is called
Fumigation

A difficulty is encountered in estimating a reasonable value for the horizontal dispersion since in mixing the stable plume through a vertical depth some additional spreading occurs. If this spreading is ignored and \( \sigma_y \) for stable condition is used, the probable result would be estimated concentration would be higher than actual concentrations.

To estimate ground level concentrations under inversion break up fumigations, one assumes that plume was initially emitted into a stable layer. Therefore, \( \sigma_y \) & \( \sigma_z \) characteristic of stable conditions must be selected for the particular distance of concern. An equation for the ground-level concentration when the inversion has been eliminated to a height \( h_i \) is

\[
\chi_r(x, y, 0, H) = \frac{Q \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-0.5p^2\right) dp \cdot \exp\left(-\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right)}{\sqrt{2\pi} \sigma_y uh_i}
\]

Values for the integral in brackets can be found in most statistical tables. This factor accounts for the portion of the plume that is mixed downward. If the inversion is eliminated up to the effective stack height, half of the plume is presumed to be mixed downward, the other half remaining in the stable air above. The above equation can be approximated when the fumigation concentration is near its maximum by

\[
\chi(x, y, 0, H) = \frac{Q \exp\left(-\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right)}{\sqrt{2\pi} \sigma_y uh_i}
\]

using an approximation suggested by Birely & Hewson (1972)
\[ \sigma_{yr} = \frac{2.15 \sigma_{y(\text{stable})} + H \tan 15^\circ}{2.15} \]

\[ = \sigma_{y(\text{stable})} + \frac{H}{8} \]  

(3)

A Gaussian distribution in the horizontal is assumed. The above equation (3) should not be applied near the stack, for if the inversion has been eliminated to a height sufficient to include the entire plume, the emission is taking place under unstable and not stable conditions. Therefore, the nearest downwind distance to be considered for an estimate of fumigation concentrations must be great enough, based on the time required to eliminate the inversion, that this portion of the plume was initially emitted into stable air. This distance \( X = U \cdot t_m \), where \( U \) is the mean wind to eliminate the inversion from \( h \), the physical height of the stack \( h_i \).

\( t_m \) is dependent upon both the strength of the inversion and the rate of heating at the surface. Poolder, (1965) has derived an expression for this time:

\[ t_m = \frac{\rho_s C_p}{R} \frac{\delta \theta}{\delta z} (h_i - h) \left( \frac{h + h_i}{2} \right) \]

(4)

where,

\( t_m = \) time required for the mixing layer to develop from the top of the stack to the top of the plume; sec.

\( \rho_s = \) Ambient air density, g m\(^{-3}\)

\( C_p = \) Specific heat at constant pressure, cal g\(^{-1}\)K\(^{-1}\)

\( R = \) net rate of sensible heating of an air column by solar radiation, cal m\(^2\)sec\(^{-1}\)
\[ \frac{\delta \theta}{\delta z} = \text{vertical potential temperature gradient } \circ \text{Km}^{-1} \]

\[ \frac{\delta T}{\delta z} + \Gamma \text{ (the adiabatic lapse rate)} \]

\[ h_i = \text{height of the base of the inversion sufficient to be above the plume.} \]

Note that \( h_i-h \) is the thickness of the layer to be heated and \( (h+h_i)/2 \) is the average height of the layer. Although \( R \) depends on season, and cloud cover and varies continuously with time, Pooler has used a value of 67 calm\(^2\)sec\(^{-1}\) as an average for fumigation.

In the case of complex topography the prediction of inversion break-up concentration values is further complicated because of complexity of meteorological conditions and topographic features. This needs further research.

(20) Advanced Plume Rise Formulas

The semi empirical formulation have shown a great degree of uncertainty. Additional methods have been proposed that provide, at least in theory, a better physical representation of the two basic phenomena related to the plume rise.

(1) The vertical increase of the plume centerline.

(2) The entrainment of ambient air into the plume and its consequent horizontal and vertical spreading.

The integral plume rise method of Schatzmann,(1979) allows a numerical solution of the equations of the conservation of mass, momentum, concentration of thermal energy. This method seems particularly effective (at least close to the source). Since, it does not use common Boussinesq approximation and, therefore, allows the treatment of jet flow with density greatly different from that of ambient air. This model, however,
fails to account for the inertia of "effective mass" outside the plume, seems to contains an unrealistic drag term, and shows problems in the mass conservation equation. Golay (1982) has proposed an even more complex approach, a differential entertainment model. It is able to simulate bent-over plumes in complicated vertical atmospheric structure by numerically integrating the conservation equations of mass, momentum, heat, water vapour, liquid water and the two equations for the turbulent kinetic energy and eddy viscosity in the form presented by Stuhmiller, 1974. The major limitation of Golay's approach is the detailed meteorological information that is required, i.e. the vertical profiles of wind speed, virtual potential temperature, relative humidity, turbulence kinetic energy, and turbulent viscosity.

Gladening et al., (1984) proposed a simpler approach, which numerically integrates the conservation equations using, however, several simplifying assumptions (the plume is axisymmetric and the three dimensionality of the plume is ignored.

Henderson-Sellers (1987) has developed a comprehensive model that encompasses both plume rise and pollutant dispersion within a single numerical model formulation. Results are expressed in terms of centerline trajectory, entertainment velocities, rates of speed and ground level concentrations. The model is also applicable to cases of non-uniform wind and temperature fields as well as to urban terrains.

Probably the most promising technique for the simulation of buoyant plumes in unstable conditions was performed by Van Heren and Nieuwstadt (1989), who obtained reasonable agreement between the output of the large eddy simulation model and field experiments of Carras and Williams (1984). Their large eddy simulation results allow differentiation between the fraction of plume motion caused by convective turbulence and
the that caused by plume buoyancy.

Another advanced and computational intensive procedure is the stack Exhaust Model (SEM) developed by Skyes et al.,(1989). the SEM model is the most detailed member of a hierarchy of atmospheric models developed for the Electric Power Research Institute. This model uses state-of-the-art turbulent simulation techniques in an effort to simulate the initial phase of the plume, including its buoyant rise and bending over phase. SEM uses the Reynolds averaged Navier-Stokes equations, under the assumption of an incompressible, Bossinesq fluid. These equations are solved numerically using second order finite diffusion techniques. The model generally provides steady state solutions, although it is capable of simulating time-dependent flows.

Inclusion of these concepts can further improve the predictive ability of future models.