FURTHER DEVELOPMENT, VALIDATION AND APPLICATION OF A *HY*BRID *WIN*D TUNNEL/NUMERICAL *MOD*EL, HYWINMOD, FOR COMPLEX PERMITTING APPLICATIONS

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ABSTRACT

At the 2009 and 2013 Guideline on Air Quality Models Conferences, the theory behind a hybrid wind tunnel/numerical modeling approach, ***HYWINMOD,*** and results of testing against the two field data bases were presented. Basically, ***HYWINMOD*** is a theoretical merging of wind tunnel model predictions and AERMOD plume rise and dispersion algorithms to allow for accurate concentration estimates for any averaging time for direct comparison with health limits, odor thresholds and/or NAAQS. The method is ideally suited for complex building or terrain configurations where AERMOD is not appropriate (i.e., urban area, very complex building configuration, upwind terrain wakes, etc.). Currently, AERMOD is used for these complicated modeling situations regardless of the fact that it was only developed to handle simple solid buildings and elevated downwind terrain. ***HYWINMOD*** it is not an approved EPA model, even though it would be more appropriate for many applications. Therefore, its use for permitting applications would be delayed until such approval is obtained. The challenges to using the ***HYWINMOD*** approach for regulatory applications are discussed along with a suggested path forward.

This paper discusses the new theoretical enhancements to ***HYWINMOD*** which include: better plume rise fit relationship, improved method for obtaining best fits to wind tunnel data, plume buoyant dispersion adjustment, and improved atmospheric stability correction method. Updated comparisons against the Bowline Point field data are presented along with a comparison against an SO_2 monitor downwind of an exhaust stack located near a tall structure. The results of the evaluation show that HYWINMOD agree as well with field observations as AERMOD, and in some case better than AERMOD. The results confirmed that HYWINMOD should be considered an alternate approach for situations where AERMOD is clearly not appropriate.

INTRODUCTION

At the 2009 and 2013 Guideline on Air Quality Models Conferences, the theory behind a hybrid wind tunnel/numerical dispersion modeling approach and results of testing against two field data bases were presented[1,2]. The approach has been named ***HYWINMOD*** (**HY**brid **WIN**d Tunnel/Numerical **MOD**el) and additional theoretical enhancements have been included.

HYWINMOD is a theoretical merging of wind tunnel model predictions and AERMOD[3] plume rise and dispersion algorithms to allow for accurate concentration estimates for any averaging time for direct comparison with the NAAQS, health limits and/or odor limits. The method is ideally suited for complex building or terrain configurations where AERMOD is unsuitable, such as urban areas, unusual or complex building shapes, cylindrical or lattice type structures and upwind terrain wakes. Currently, AERMOD is used for these complex situations even when it may not be theoretically sound. Regardless of the fact that ***HYWINMOD*** would be more appropriate for many applications, it is not an approved EPA model and its use for permitting applications would be delayed until such approval is obtained. The approval process for alternate models is very lengthy and as a result ***HYWINMOD*** would likely not be used by anyone seeking a permit, even though it may provide more accurate concentration estimates.

This papers summarizes the 2009 and 2013 papers and discusses the added theoretical enhancements to ***HYWINMOD*** which include: better plume rise fit relationship, improved method for obtaining best fits to wind tunnel data, plume buoyant dispersion adjustment, and improved atmospheric stability correction method. An updated comparison against the Bowline Point field data base[4] is presented along with comparisons against an SO_2 monitor downwind of an exhaust stack located near a tall structure in an industrial facility.

Future plans for the ***HYWINMOD*** and its use for Regulatory type applications are also discussed.

VALIDITY OF WIND TUNNEL MODELING

There are several reasons why wind tunnel modeling is a valid tool, and often superior to other models, to evaluate atmospheric dispersion. The first and most important reason is theoretical. A wind tunnel simulation is, in effect, a solution to the basic equations of motion. The basic equations are solved by simulating the flow at a reduced scale and the desired quantity (for example: concentration) is measured. Solving the basic equations (i.e., the wind tunnel simulation) provides a steady-state solution with a complete record of the time varying velocity and concentration fields. It should be noted that the Gaussian dispersion model also predicts steady-state average concentrations. The wind tunnel model, in effect, can be described as an analog computer with near infinitesimal resolution and near infinite memory. More information on the theoretical aspects and validity of wind tunnel modeling can be found in Snyder[5] and Cermak.[6]

Wind tunnel modeling is further validated by comparisons with field measurements in this paper and by other evaluations, which showed a high degree of consistency and accuracy.[7,8,9,10]

DETERMINING WIND TUNNEL OPERATING CONDITIONS

An accurate simulation of the boundary-layer winds and stack gas flow or source release conditions is an essential prerequisite to any wind tunnel study of diffusion. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. Based on the dimensional analysis and the requirements in the EPA fluid modeling guidelines[5], the criteria that are frequently used are summarized in previous papers[1,2]

DESRIPTION OF HYWINMOD APPROACH

The ***HYWINMOD*** (**HY**brid **WIN**d Tunnel/Numerical **MOD**el) approach is shown schematically in Figure 1. Each element of the approach is listed below.

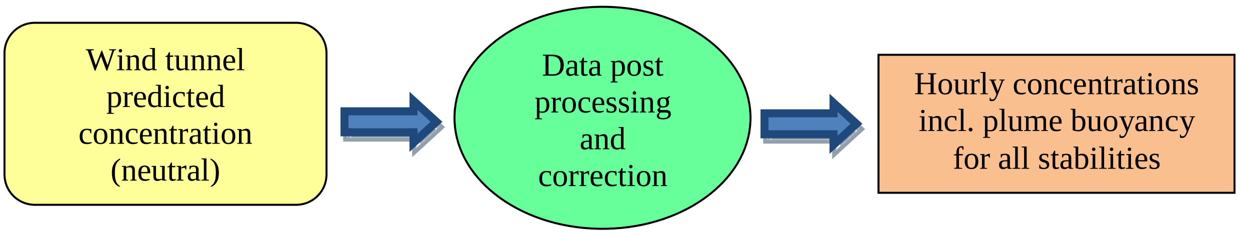


Figure 1. Schematic illustrating the HYWINMOD approach

HYWINMOD uses the following basic approach:

- Construct scale model of facility to be evaluated.
- Define the approach surface roughness using AERSURFACE[11].
- Specify model operating conditions assuming a neutral atmosphere and neutrally buoyant plume.
- Install model in the wind tunnel and establish the appropriate approach mean wind speed and turbulence profiles.
- Define the concentration as a function of wind speed and wind direction at each receptor location of interest.
- Using the concentration data, define a fit function at each receptor location.
- Obtain hourly meteorological data that is appropriate for the site (hourly wind speed, wind direction, temperature, etc. for ground-level and upper air).
- Obtain hourly source data (emission rate, temperature, flow rate, exit velocity).
- Process hourly meteorological data to obtain hourly wind speed, wind direction and temperature close to or at stack height, as well as Monin-Obukhov length.
- At each receptor predict the hourly concentrations using the fit function with stability and plume rise adjustments, the hourly meteorological data and the hourly source data.
- Post-process the hourly concentration predictions to obtain maximum concentration at each receptor for the averaging times of interest.

The following sub-sections will discuss the new aspects of this process; namely, the updated fit function and plume rise and stability adjustments

Development of the Fit Function

The fit function was developed from the basic Gaussian dispersion equation given below:

$$\frac{C}{m} = \frac{10^6}{2\pi\sigma_y\sigma_z U_h} \cdot \exp\left[-\frac{1}{2}\left(\frac{y-\bar{y}}{\sigma_y}\right)^2\right] \cdot \left\{\exp\left[-\frac{1}{2}\left(\frac{(h_s+h_r)+z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{(h_s+h_r)-z}{\sigma_z}\right)^2\right]\right\} \quad (1)$$

The ground-level concentration C [μg/m^3], normalized by the emission rate m [g/s], at each receptor is a function of the distance from the plume center line $(y-\bar{y})$, the stack height h_s the plume rise h_r, the wind speed at the stack top U_h and the dispersion coefficients, σ_y and σ_z, which are functions of atmospheric stability and distance from the stack.

Starting from the Gaussian dispersion equation (1), an equation was developed to fit the wind tunnel data:

$$\frac{C}{m} = \frac{A \cdot 10^6}{2\pi\sigma_{y,WT}\sigma_{z,WT}U_h} \cdot \exp\left[-\frac{1}{2}\left(\frac{x \cdot \tan(WD - WDc)}{\sigma_{y,WT}}\right)^2\right] \cdot \left\{ \begin{array}{l} \exp\left[-\frac{1}{2}\left(\frac{\left(h_s + \frac{K}{U_h\beta_j}\right) + z}{\sigma_{z,WT}}\right)^2\right] \\ + \exp\left[-\frac{1}{2}\left(\frac{\left(h_s + \frac{K}{U_h\beta_j}\right) - z}{\sigma_{z,WT}}\right)^2\right] \end{array} \right\} \quad (2)$$

where A is a curve fit constant, h_s is the stack height, WD is the wind direction (in degrees), WDc is the critical wind direction (in degrees) where the peak concentration occurs. Since the wind tunnel data at each receptor is collected as a function of wind direction (WD) rather than y, the $y-\bar{y}$ term in equation (1) is replaced by $x \cdot \tan(WD-WDc)$. The curve fit parameters (A, WDc, K, $\sigma_{y,WT}$ and $\sigma_{z,WT}$) are determined using a step-wise iteration to minimize the mean-square-error (*MSE*) between the predicted normalized concentration and the measured value.

The plume rise h_r was parameterized by assuming that the plume rise in the wind tunnel equals the final momentum rise h_f[12] as given below:

$$h_f = \frac{0.9\left(F_m \frac{U_h}{U^*}\right)^{1/2}}{U_h\beta_j} \quad (3)$$

Based on this equation, the final plume rise equation can be simplified to: $h_r = \frac{K}{U\beta_j}$ where

$\beta_j = 0.4 + 1.2\, U_h/U_s$ and K is a constant.

This equation represents one of ***HYWINMOD's*** enhancements. The previous version used $h_r = \frac{K}{U^2}$.

Another ***HYWINMOD*** enhancement includes a scheme to reach a solution faster by using the following initial guesses and constraints:
Minimum sigma values:

$$\sigma_{y,\min} = 0.75 * TI * x$$
$$\sigma_{z,\min} = 0.5 * TI * x \qquad (4)$$

Based on the turbulence intensity TI at stack height: $TI = n \dfrac{\ln\left(\dfrac{30}{z_0}\right)}{\ln\left(\dfrac{h_s}{z_0}\right)}$ (5)

The final enhancement was the development of a theoretical relationship between K and h_s, z, σ_z, V_e, U_{crit} and β_j. The relationship was developed by differentiating equation (2) with respect to U_h and setting that differential equal to zero, thereby solving for the critical wind speed. The resulting equation is provided below.

$$K = \frac{-B + (B^2 - 4C)^{0.5}}{2} \qquad (6)$$

Where $B = \beta_j U_{crit}(h_s - z)$, $C = -\dfrac{\beta_j \sigma_z{}^2}{\alpha}$ and $\alpha = \dfrac{\beta_j V_e + 1.2U_{crit}}{U_{crit}{}^2 \beta_j{}^2 U_s}$.

The concentration for any pollutant at each receptor where wind tunnel measurements are obtained can then be computed as long as hourly emission rate, wind speed and wind direction data are available. It should be noted that these concentration predictions will not have atmospheric stability or plume buoyancy effects included. The use of these predictions directly would tend to overestimate expected ground-level concentration levels, since plume rise is underestimated for buoyant plumes. For elevated receptors, the model could over or underestimate depending upon the receptor height.

Buoyant Plume Rise Correction

Since plume buoyancy cannot be fully simulated when conducting a wind tunnel study, a method for correcting for this deficiency was developed.[1]

The previous version of ***HYWINMOD***[1] did not include buoyancy induced dispersion which is now incorporated in the latest version. The dispersion coefficients are taken as a combination of dispersion due to ambient turbulence (as measured in the wind tunnel) and the increased dispersion due to plume buoyancy[2] via increased travel distance.

$$\frac{C}{m} = \frac{A \cdot 10^6}{2\pi(\sigma_{y,WT}{}^2 + \sigma_b{}^2)^{1/2}(\sigma_{z,WT}{}^2 + \sigma_b{}^2)^{1/2} U_h} \cdot \exp\left[-\frac{1}{2}\left(\frac{x \cdot \tan(WD - WDc)}{(\sigma_{y,WT}{}^2 + \sigma_b{}^2)^{1/2}} \right)^2 \right]$$

$$\cdot \left\{ \exp\left[-\frac{1}{2}\left(\frac{\left(h_s + \frac{K}{U_h \beta_j} \right) P_r + z}{(\sigma_{z,WT}{}^2 + \sigma_b{}^2)^{1/2}} \right)^2 \right] + \exp\left[-\frac{1}{2}\left(\frac{\left(h_s + \frac{K}{U_h \beta_j} \right) P_r - z}{(\sigma_{z,WT}{}^2 + \sigma_b{}^2)^{1/2}} \right)^2 \right] \right\} \qquad (7)$$

P_r is the plume rise correction coefficient. [1] The buoyancy induced dispersion coefficient is defined as follows:

$$\sigma_b = \frac{0.4 h_r}{\sqrt{2}} \qquad (8)$$

Stable and Unstable Dispersion Coefficient Corrections

The effects of atmospheric stability are included by adjusting the horizontal and vertical dispersion coefficients as described in Petersen and Beyer-Lout[1]. This paper evaluates a continuous stability correction based on the computed Monin-Obukhov length (L) values versus a single correction factor for each Pasquill-Gifford stability class[12] based on Figure 1.

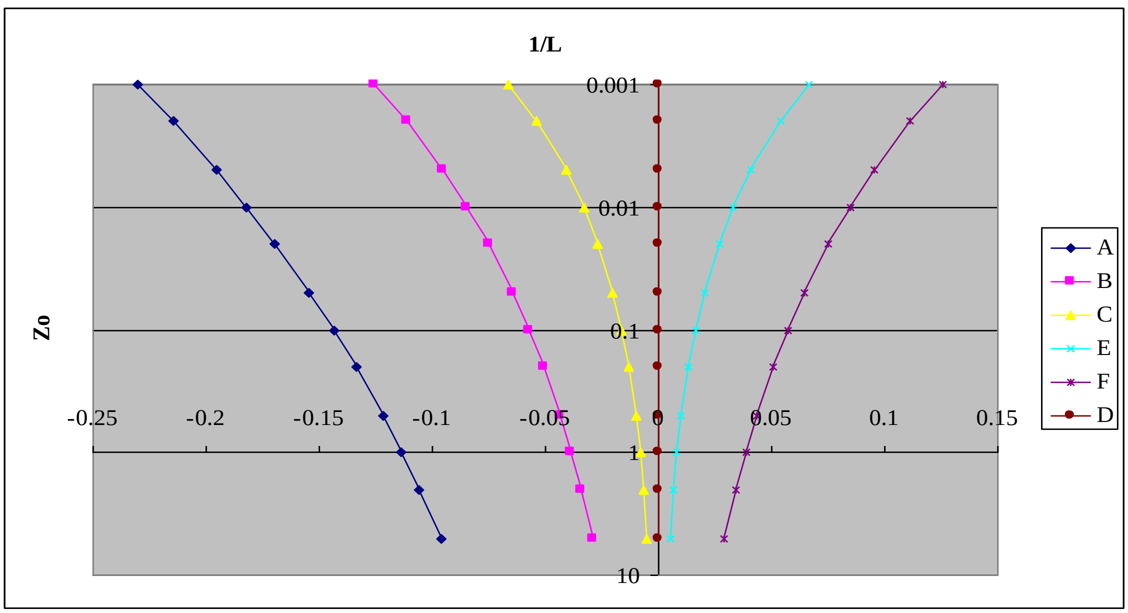


Figure 1. Relation between 1/L, surface roughness and stability class

Figure 1 is used with the following logic:

- Use C and E lines as cutoff for stability class D (everything in between is stability class D) and set the correction factor S to a value of 1 for stability class D.
- For 1/L values that fall between the B and C lines, the C line is used.
- For 1/L values that fall between the A and B lines, the B line is used.
- For 1/L values that fall to the left of the A line, the A line is used.
- For 1/L values that fall between the E and F lines, the E line is used.
- For 1/L values that fall to the right of the F line, the F line is used.

DATA BASES USED FOR TESTING AND VALIDATION

HYWINMOD was initially evaluated using the USEPA Bowline Point data base[1]. The data base and data collection methods are discussed in that paper[1] and will not be repeated here. A second data base subsequently used to evaluate ***HYWINMOD*** consisted of hourly SO_2 measurements taken 600 m downwind of stack S09 which is located near a tall boiler building. This data based is described elsewhere[2].

HYWINMOD VERSUS AERMOD MODEL EVALUATION METHOD

The model evaluation was designed to be the same as outlined by EPA[5]. Specifically, the procedures were designed to address the following questions:

1. Does ***HYWINMOD*** provide good predictions for the right reasons (a model physics evaluation)?
2. How well does ***HYWINMOD*** predict the maximum ground-level concentrations that are used to assess compliance with air quality regulations (operational performance evaluation)?
3. Is ***HYWINMOD*** performance significantly better than AERMOD?

Regarding evaluation criterion 1, ***HYWINMOD*** is based on sound physics as discussed in the previous sections. Evaluation criterion 2 was assessed using quantile-quantile (Q-Q) plots. Q-Q plots are created by sorting by rank the predicted and observed concentrations from a set of predictions initially paired in time and space. The sorted list of predicted concentrations is then plotted by rank against the observed concentrations also sorted by rank. The Q-Q plot is good method for demonstrating how well the model will perform for assessing compliance with air quality standards (i.e., predicting maximum concentrations).

In addition to the Q-Q plots, the difference between ***HYWINMOD*** and AERMOD was assessed using the robust highest concentration, or RHC[4]. The 26th highest concentration values were used to characterize the upper end of the concentration distribution for use in determining RHC.

MODEL EVALUATION RESULTS

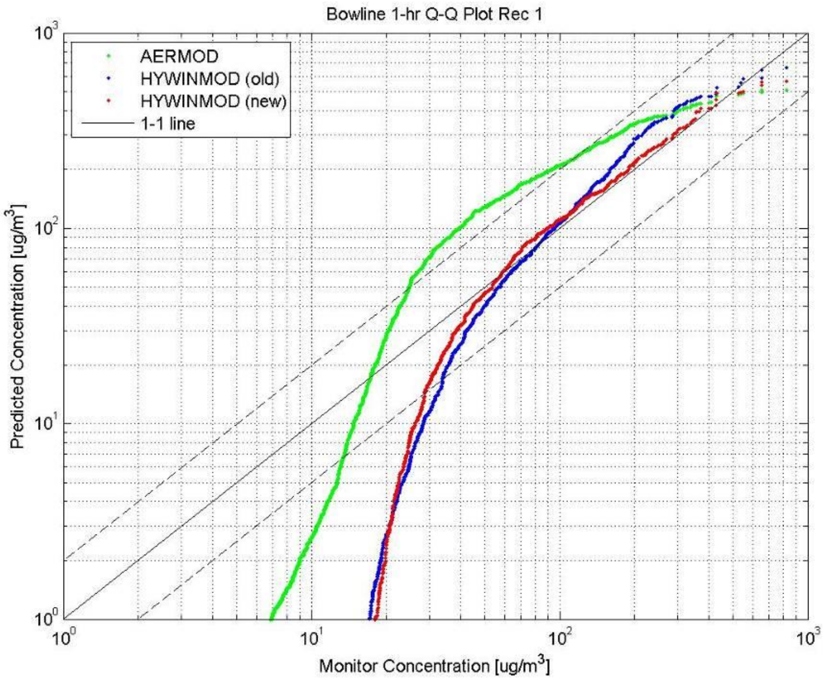
A summary of the robust highest concentration prediction results is provided in Table 1 for AERMOD, ***HYWINMOD*** (old) and ***HYWINMOD*** (new) for the two data bases evaluated.

Table 1. Summary of HYWINMOD Evaluation Results for Two Field Data Bases with Downwash									
Receptor/Scenario	Ratio of Modeled/Observed Robust Highest Concentrations								
	AERMOD			HYWINMOD(old)			HYWINMOD(new)		
	1-hr	3-hr	24-hr	1-hr	3-hr	24-hr	1-hr	3-hr	24-hr
Bowline Point									
1	0.76	1.14	1.47	0.91	1.05	0.94	0.88	0.83	0.61
3	0.85	1.12	1.62	1.03	0.83	0.55	1.44	1.26	0.58
Industrial Facility									
2009 average sulfur	0.40	0.52	0.53	0.77	0.61	0.71	0.80	0.63	0.70
2009 high sulfur	0.47	0.62	0.63	0.94	0.72	0.83	0.96	0.74	0.81

Bowline Point

Table 1 shows that ***HYWINMOD*** (old) tends to provide the best estimates of the RHC for all averaging times at Receptor 1. At Receptor 2, ***HYWINMOD*** (old) provides the best RHC estimate for the 1-hr averaging time but AERMOD provides the best estimates for 3 and 24- hour averaging times. ***HYWINMOD*** (new) provides better estimates of the 1-hr RHC than AERMOD at Receptor 1; otherwise ***HYWINMOD*** (new) does not agree as well as AERMOD or ***HYWINMOD*** (old). In general all methods are providing reasonable estimates of the RHC with ***HYWINMOD*** (old and new) tending to underestimate for the 24-hour averaging time.

Figures 2-4 show the Q-Q plots for Receptors 1 and 3 for the 1, 3 and 24-hour averaging times. These figures generally show that ***HYWINMOD*** (old) and ***HYWINMOD*** (new) agree well with observations, and for high concentration values, fall within the factor of two error bar. ***HYWINMOD*** (new) appears to agree better with observations for some averaging times while ***HYWINMOD*** (old) agrees better with observations for other averaging times.



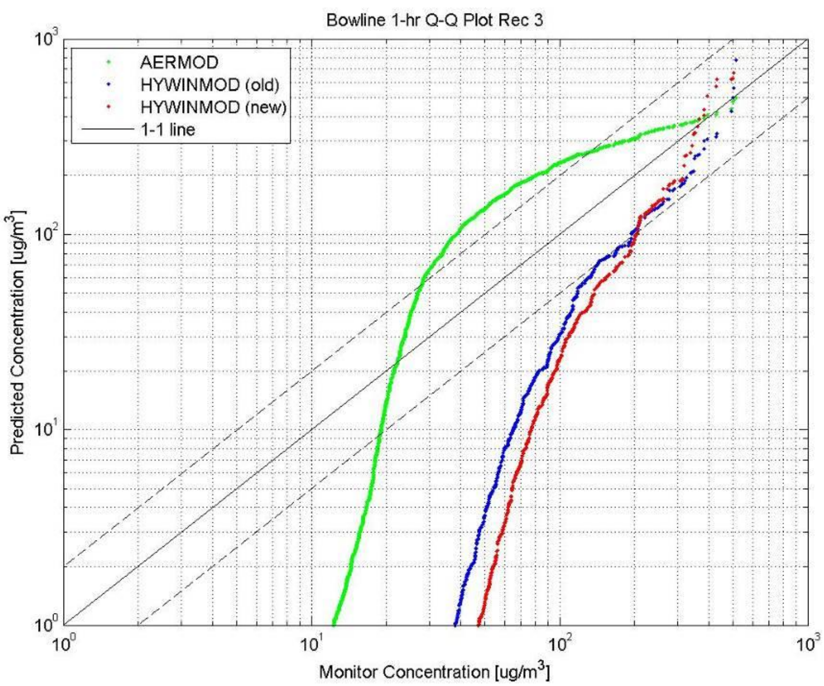
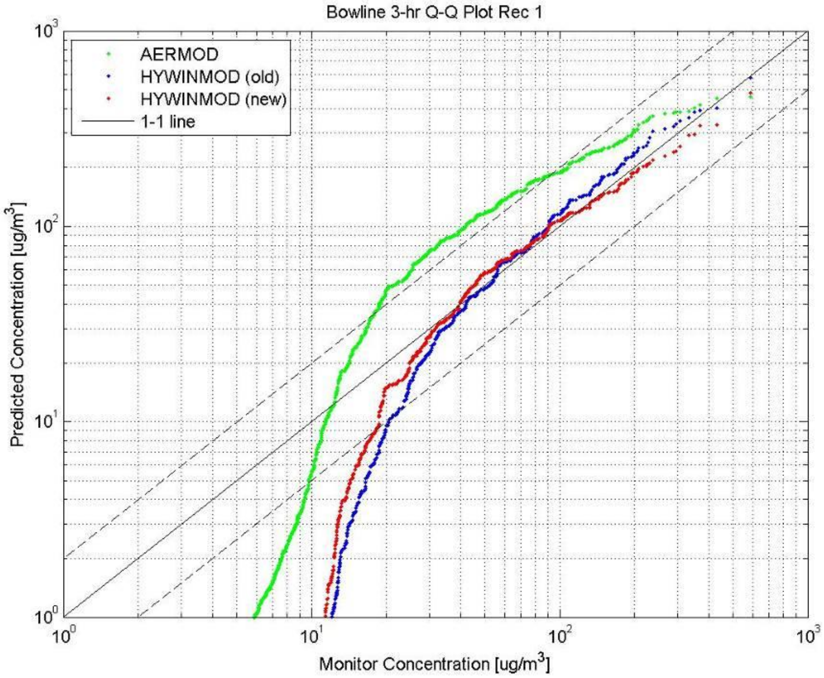


Figure 2. Q-Q plots for Receptors 1 and 3: 1-hr averaging time; green – AERMOD; Blue – HYWINMOD (old); Red – HYWINMOD (new).



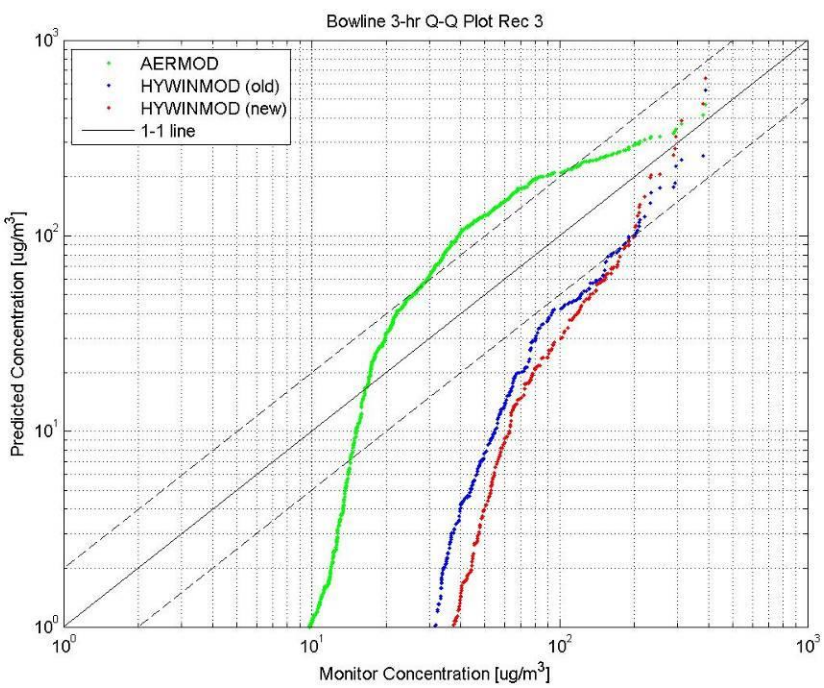


Figure 3. Q-Q plots for Receptors 1 and 3: 3-hr averaging time; green – AERMOD; Blue – HYWINMOD (old); Red – HYWINMOD (new).

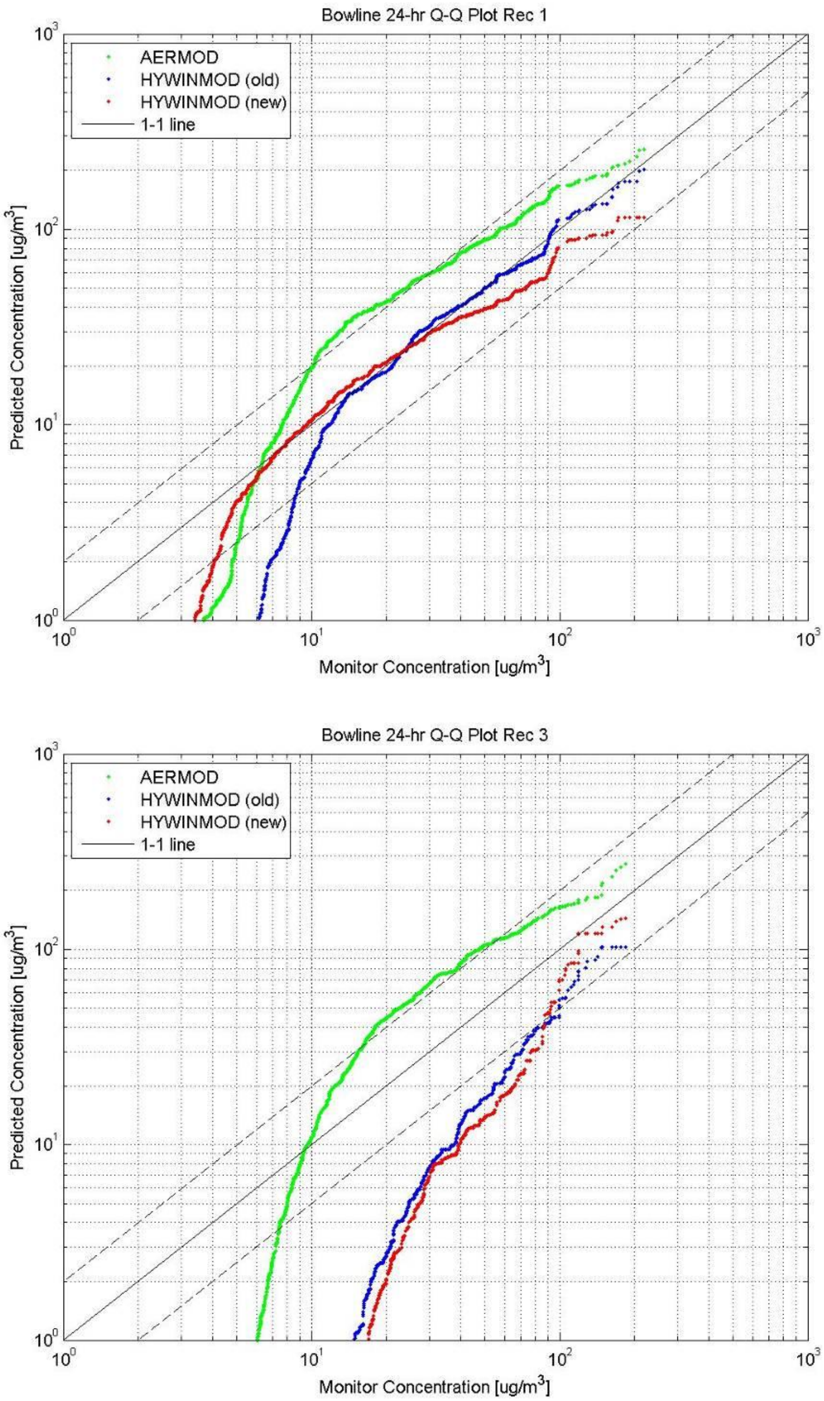


Figure 4. Q-Q plots for Receptors 1 and 3: 24-hr averaging time; green – AERMOD; Blue – HYWINMOD (old); Red – HYWINMOD (new).

Industrial Facility

A summary of the robust highest concentration prediction results is provided in Table 1 for AERMOD, ***HYWINMOD*** (old) and ***HYWINMOD*** (new). The table shows that ***HYWINMOD*** (new) tends to provide slightly better estimates of the RHC for all averaging times compared to ***HYWINMOD*** (old). Both ***HYWINMOD*** versions agree better with observations than AERMOD which tends to significantly underpredict observations. This is likely due to the fact that the critical wind direction is oriented such that an upwind corner vortex is generated. AERMOD does not include downwash due to corner vortices. This mechanism is included in the wind tunnel simulation.

Figures 5-7 show the Q-Q plots for 1, 3 and 24-hour averaging times. These figures generally show that ***HYWINMOD*** (old) and ***HYWINMOD*** (new) agree very well with observations for high values. The consistent underprediction performance for AERMOD is also evident.

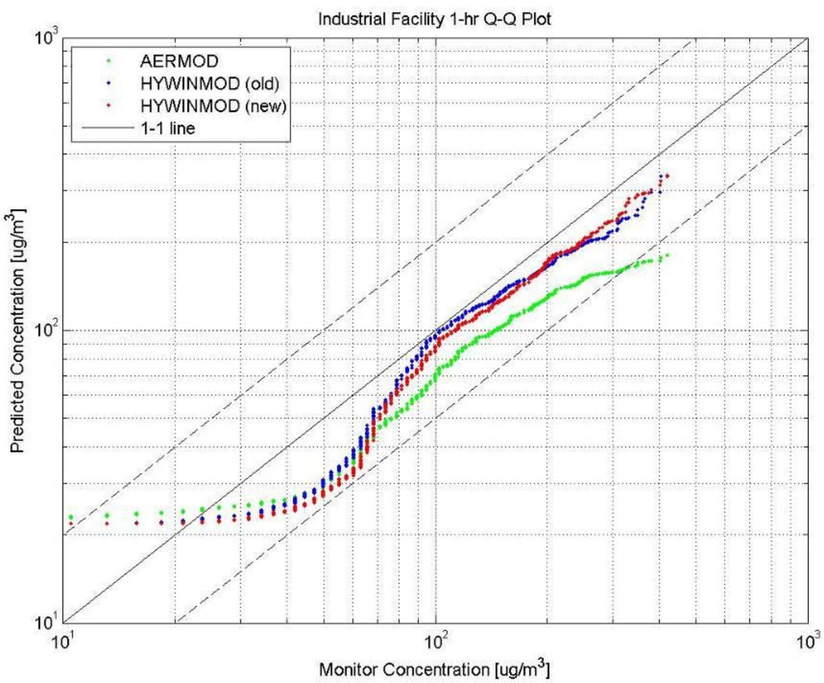


Figure 5. Q-Q plots for Industrial Facility SO_2 Monitor: 1-hr averaging time; green – AERMOD; Blue – HYWINMOD (old); Red – HYWINMOD (new). Hourly background value of 21.8 μg/m^3 was assumed.

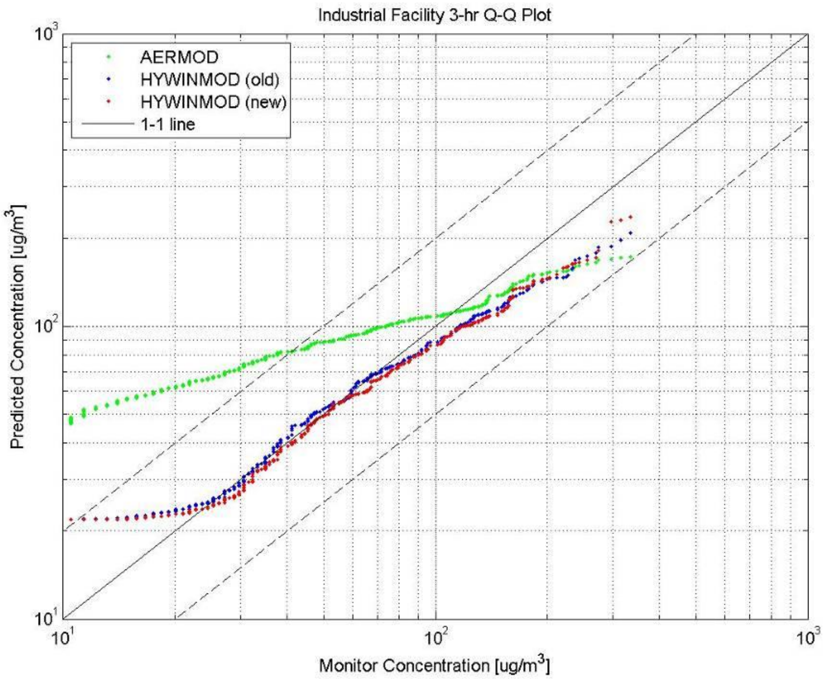


Figure 6. Q-Q plots for Industrial Facility SO_2 Monitor: 3-hr averaging time; green – AERMOD; Blue – HYWINMOD (old); Red – HYWINMOD (new). Hourly background value of 21.8 µg/m^3 was assumed.

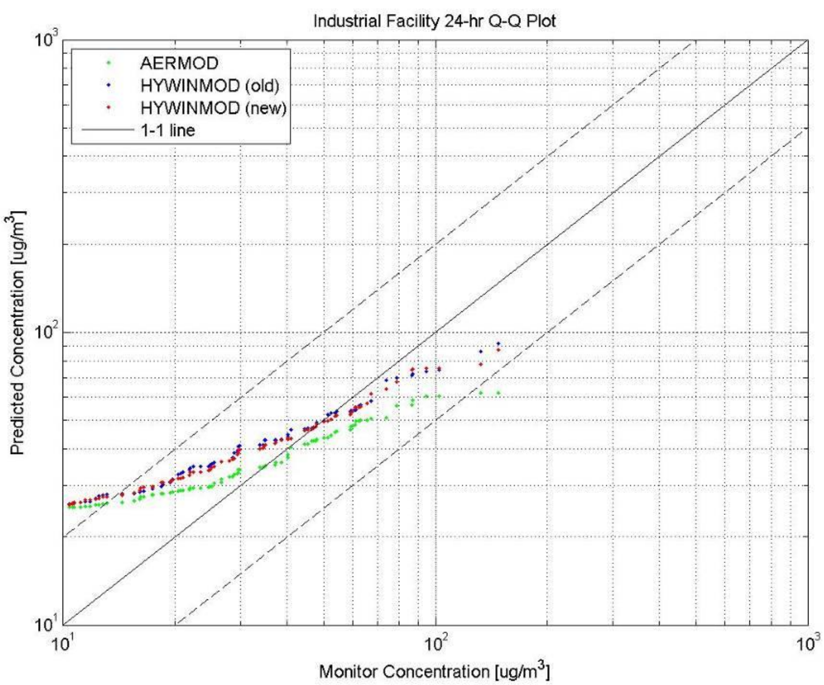


Figure 7. Q-Q plots for Industrial Facility SO_2 Monitor: 24-hr averaging time; green – AERMOD; Blue – HYWINMOD (old); Red – HYWINMOD (new). Hourly background value of 21.8 µg/m^3 was assumed.

DISUCSSION AND CONCLUSIONS

Additional analysis and development of ***HYWINMOD*** will be pursued by the authors for near-field building wake applications that are not regulatory driven but instead real-world design situations where architects, engineers and facility owners are interested in health, safety, energy savings and sustainable design.[13] At some point in future the regulatory process may encourage and allow for more routine use of refined models.

The following conclusions can be drawn from this study:

- The updated version of ***HYWINMOD*** shows good agreement with observations and with generally as good if not better agreement than AERMOD.
- The updated version of ***HYWINMOD*** is preferred due to better science even though in isolated situations the older version gave better agreement with observations (i.e., good agreement for the wrong reason).
- Some practical method for allowing routine use of enhanced models needs to be developed by EPA for situations when AERMOD may not be appropriate or when more accurate estimates are desired. The current regulatory environment is such that industry would be reluctant to pursue the use of more accurate models due to the uncertainty in getting such modeling work approved. Even if such an approach were approved, the time frame to obtain approval would not be practical for most real-world situations.

REFERENCES

1) Petersen, R.L. and A. Beyer-Lout. “Validation of Method for Direct Use of Wind Tunnel Modeling For Regulatory Modeling Applications,” Guideline of Air Quality Models Conference: Next Generation of Models, Research Triangle Park, NC, Paper #23. October, 2009.

2) Petersen, R.L. and A. Beyer-Lout. “Additional Development and Evaluation of HYWINMOD – A Hybrid Wind Tunnel/Numerical Model,” Guideline of Air Quality Models Conference: The Path Forward, Research Triangle Park, NC, Paper #18. March, 2013.

3) Cimorelli, A.J.; S.G. Perry; A. Venkatram; J.C. Weil; R.J. Paine; R.B. Wilson; R.F. Lee; W.D. Peters; and R.W. Brode. “AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization,” JAM, 44, 682-693. American Meteorological Society, Boston, MA. 2005.

4) EPA. AERMOD: Latest Feature and Evaluation Results. EPA-454/R-03-003, June 2003

5) Snyder, W.H. “Guideline for Fluid Modeling of Atmospheric Diffusion,” EPA, Environmental Sciences Research Laboratory, Office of Research and Development, Research Triangle Park, North Carolina, Report No. EPA600/8–81–009, 1981.

6) Cermak, J.E. “Applications of Fluid Mechanics to Wind Engineering,” A Freeman Scholar Lecture, *Journal of Fluids Engineering*, Vol. 97, p. 9, 1975.

7) Shea, D., O. Kostrova, A. MacNutt, R. Paine, D. Cramer, L. Labrie, “Model Evaluation Study of AERMOD Using Wind Tunnel and Ambient Measurements at Elevated Locations,” 100th Annual A&WMA Conference, Pittsburgh, PA, June 2007.

8) Meroney, R.N. “Validation of Fluid Modeling Techniques for Assessing Hazards of Dense Gas Cloud Dispersion,” submitted to *Journal of Hazardous Materials*, April 21, 1986.

[9] Petersen, R.L. "Wind Tunnel Investigation of the Effect of Platform-Type Structures on Dispersion of Effluents from Short Stacks," *JAPCA*, Vol. 36, No. 12, December 1986.

[10] Weil, J.C.; S.C. Traugott; and D.K. Wong. "Stack Plume Interaction and Flow Characteristics for a Notched Ridge," Maryland Power Plant Siting Program, PPRP–61, August 1981.

[11] EPA, *AERSURFACE User's Guide*, EPA–454/B–08–001, USEPA Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group, Research Triangle Park, North Carolina, 2008.

[12] Randerson, D., *Atmospheric Science and Power Production*, Chapter 5, pp. 147-188, US Department of Energy, DOE/TIC-27601, Washington, 1984

[13] Petersen, R.L. J.J. Carter, B.C. Cochran, "Modeling Exhaust Dispersion for Specifying Acceptable Exhaust/Intake Design," Laboratories for the 21st Century: Best Practices," U.S. EPA and U.S. Department of Energy, DOE/GO-122011-3331, September, 2011 www.labs21century.gov/toolkit/bp_guide.htm.

KEYWORDS

HYWINMOD, wind tunnel, AERMOD, buoyancy correction, stability correction