ATMOSPHERIC DISPERSION MODELS INTERCOMPARISON UNDER TWO ATMOSPHERIC STABILITY CONDITIONS

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INTRODUCTION

In this work three different Gaussian codes are compared simulating real stability conditions. These codes are:

- AERMOD: developed for regulatory purposes and has a stationary Gaussian dispersion model. This code has a meteorological pre-processor (AERMET), which calculates the atmospheric condition from the meteorological data. [1]
- HPDM has four models for the dispersion calculations: (1) Gaussian model for stable, neutral or slightly unstable atmospheric conditions; (2) Probability Density Function (PDF) model for moderately or very unstable atmospheric conditions; (3) Low wind model for very unstable conditions and (4) Lofting model for neutral or unstable conditions with a low mixing lid. This code has a meteorological pre-processor (SIGPRO). [2]
- PCCOSYMA calculates air concentration, deposition, countermeasures, organ doses, individual and collective risk and economic cost of a nuclear accident. This is a grid code. The dispersion model is a Gaussian-type trajectory one, which breaks the plume according to the actual wind direction at the source location (segmented Gaussian plume model, [3]) and limits its lengh according to the wind speed and the integration time. It uses the source location meteorological data for the complete domain. This code hasn't a meteorological pre-processor; therefore the atmospheric stability must be calculated previously and included in the meteorological file.

SIMULATION INPUT DATA

The source is located at 37.35º N latitude and 78.24º W longitude, the stack height is 60 m with a diameter of 3 m. The terrain is considered flat (z_0 = 0.1 m). The simulation period corresponds to the first 13 hours of 3/25/99. The meteorological data were obtained from an output of the prognostic code RAMS (Regional Atmospheric Modelling System) at the ARL-NOAA web site ([4], [5], [6]) for this period. The emission rate is 0.3 $g \cdot s^{-1}$ for the non-nuclear codes and 0.3 Bq of ^{226}Ra for the nuclear one (PCCOSYMA). This isotope was chosen to guarantee that during the emission period the decay is less than $1x10^{-4}$ %. The release temperature is set at 284 K, in order to have thermal equilibrium with the environment, and without vertical gas velocity. The file supplied by ARL-NOAA must be processed in order to provide the required data for AERMET and SIGPRO. For PCCOSYMA code the Pasquill-Gifford stability class is calculated using the Golder algorithm.

Figure 1 shows the inverse of the Monin-Obukov length calculated by AERMET and SIGPRO for the 13 hours at the source point. In the same chart, the limits (for z_0=0.1m) to define the Pasquill-Gifford atmospheric stability classes are also plotted, and the deduced Pasquill-Gifford classes for each hour are indicated. These classes are used to set-up the PCCOSYMA input file. The inverse of the Monin-Obukov length (L^{-1}) calculated with AERMET and SIGPRO differs from the one calculated directly with the meteorological data. However, for the whole period, AERMET gives values closer to the manually calculated ones than to SIGPRO. At Hours 11 and 12, L^{-1} calculated with AERMET and manually changes from negative to positive values. This is caused by a temporary sensible heat flux (SHTF) sense change (from positive to negative values). SIGPRO keeps L^{-1} unchanged during this period because it restricts the SHTF to only positive values during day light time.

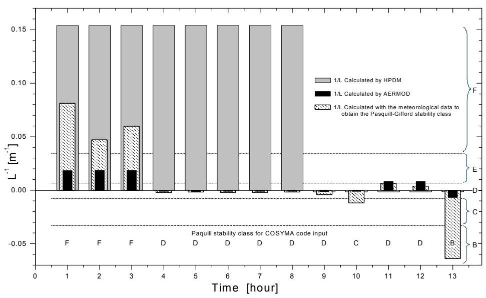

Figure 1: Atmospheric stability and inverse of Monin-Obukov length at the source point. The dash lines show the change from one to another atmospheric stability class for z_0= 0.1 m.

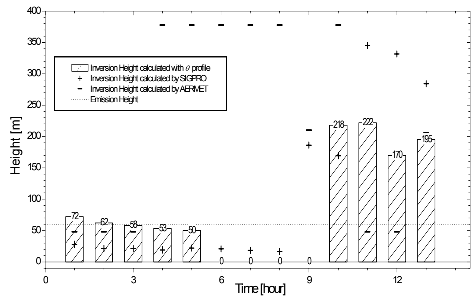

Figure 2: The boxes show the mixed layer height evolution. The plus and minus signs describe the mixed layer height evolution calculated by SIGPRO and AERMET codes respectively. The dash line shows the emission height.

Figure 2 shows the inversion height calculated by means of $\nabla\tilde{\theta}$ which is used in PCCOSYMA input, AERMET and SIGPRO. The values calculated with SIGPRO and by means of $\nabla\theta$ are closer. AERMET calculates that during the night hours (neutral stability class after a stable period) they go up to approximately 400 meters; more than one order of magnitude greater than the HPDM ones. This sharp change at Hour 4 can be correlated with the modification of the SHTF sign that occurs at the same hour from negative to positive values. This behaviour seems to be unrealistic.

RESULTS

Two cases are modelled for a better comparison between AERMOD, HPDM and PCCOSYMA codes, in order to analyse the dispersion parameters by means of their effect on the plume shape. These cases correspond to two periods of the whole interval with different atmospheric stability. Moreover in order to avoid wind effect on the plume spread, the wind direction and speed are fixed in arbitrary values. The analysed cases are the following:

- **Case A**: Hour 1 to 5, atmospheric stability from stable to neutral, wind direction 270º, wind speed 1 $m.s^{-1}$.
- **Case B**: Hour 9 to 13, atmospheric stability from neutral to instable, wind direction 0º, wind speed 1 $m.s^{-1}$.

Figure 3 to Figure 5 show ground-parallel plume sections at 1 m height, where the X direction corresponds to Case A and the Y direction corresponds to Case B, for AERMOD, HPDM and PCCOSYMA respectively. Figures 6 and 7 show for AERMOD and HPDM respectively, plume cross-sections at a radial distance of 200 m (transversal section), the left graph corresponds to Case A and the right one to Case B. Figures 8 and 9 show for AERMOD and HPDM, vertical sections along the plume centreline (longitudinal section). The top graph corresponds to Case A and the bottom one to Case B.

Case A:

During this period the atmospheric stability changes from stable to neutral. For the AERMOD code the plume is composed of two parts (Case A Figures 3, 6 and 8), one with a small vertical dispersion (first three hours) and the other with a greater one (the remaining two hours). Figure Figure 8 shows a Maximum Ground Level Concentration (MGLC) of 1.92 $\mu g \cdot m^{-3}$.

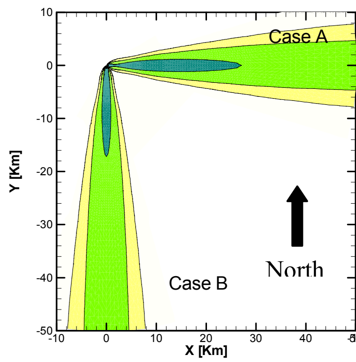

Figure 3: Section for case A and B obtained with AERMOD.

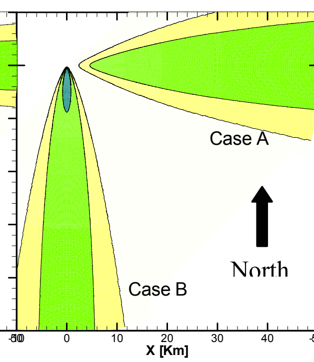

Figure 4: Section for case A and B obtained with HPDM.

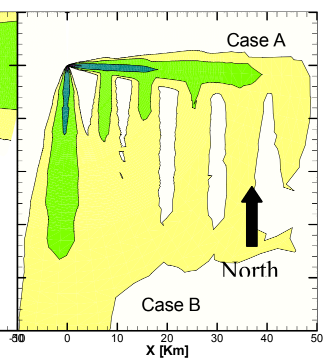

Figure 5: Section for case A and B obtained with PCCOSYMA.

This contour level concentration touches the ground at 190 m from the source (broad contour line Figure 8). Figures 7 and 9 show transversal and longitudinal sections respectively of HPDM results. The MGLC is 0.05 $\mu g \cdot m^{-3}$ at 23000 m from the source. When comparing these sections with the ones of Figure 6 and Figure 8, we notice that the vertical dispersion calculated by HPDM is clearly lower than the one calculated by AERMOD. These results are in accordance with the σ_z values shown in Figure 11 -σ_z values at 3000 m from the source and normalized with the highest value. In another hand the horizontal plume spread obtained with AERMOD is lower than the observed for HPDM. These results are in accordance with the σ_y values shown in Figure 10 -σ_y values at 3000 m from the source and normalized with the highest value. Although the source height is 60 m, AERMOD predicts the plume equilibrium height at 51 m due to the stack tip downwash effect (Figure 6 and Figure 8). The HPDM prediction is 30 m (Figure 7 and Figure 9). Figure 5 shows the result obtained PCCOSYMA. In accordance with the segmented plume model used by this code, the plume turns towards South due to the wind direction change from Case A to Case B, this caused that the release contaminant is advected only 50 Km to the East. The MGLC is 2.34 $\mu Bq \cdot s \cdot m^{-3}$ at 800 m from the source.

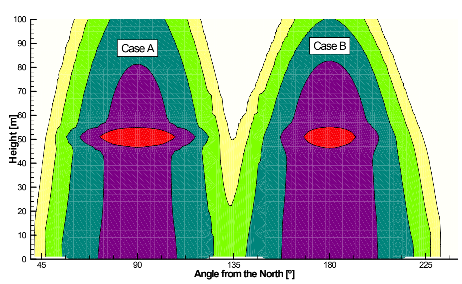

Figure 6: Case A and B AERMOD: plume transversal section at 200 m from the source.

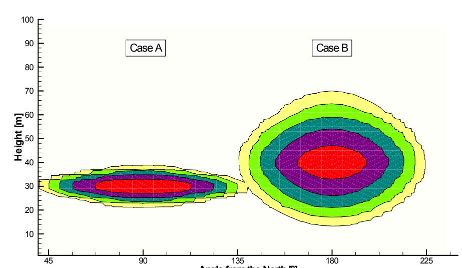

Figure 7: Case A and B HPDM: plume transversal section at 200 m from the source.

Case B:

During this period the atmospheric stability changes from neutral to instable. The vertical plume dispersion calculated by AERMOD for this Case (Figures 3, 6 and 8) is larger than the one predicted for Case A. This agrees with the change in the atmospheric stability conditions, which is also manifested on the MGLC (3.36 µg·m^{-3}, 217 m from the source, broad line in 8) and in the plume width. When the results obtained with HPDM for both cases are compared, it is observed a larger vertical dispersion (Figure 7 and 9) than for Case A.

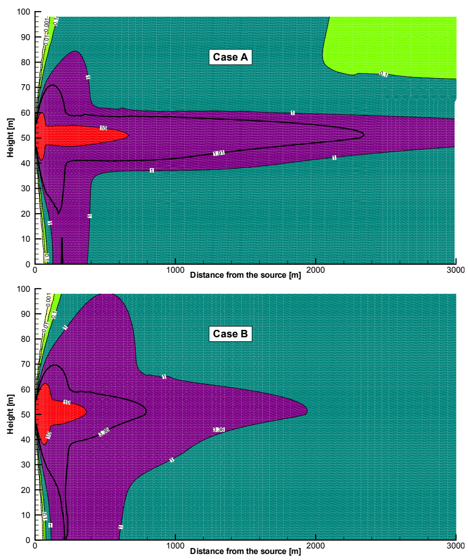

Figure 8: Case A and B for AERMOD: plume longitudinal section.

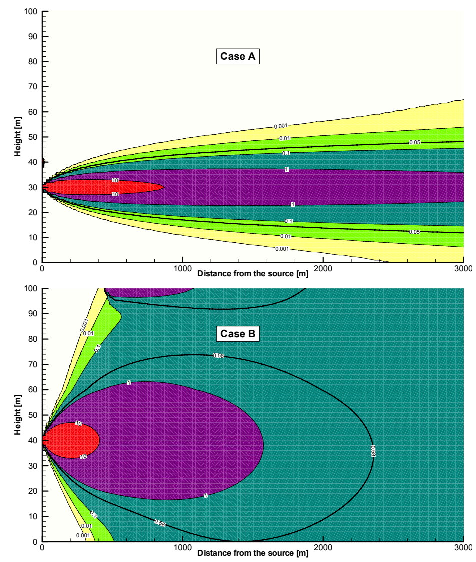

Figure 9: Case A and B for HPDM: plume longitudinal section.

Figure 9 shows a broad contour line for the MGLC (0.58 µg·m^{-3}, at 1400 m from the source). The difference between AERMOD and HPDM predictions comes from the different vertical dispersion parameter calculations (Figure 10 and 11). The maximum concentration for this case is also found at the height of 51 meters (Figure 6 and 8) for AERMOD. For HPDM the plume equilibrium height is 40 meters, which is also lower than the stack top (Figure 7 and 9). The calculations done with PCCOSYMA show that near the source the plume width are comparable with the results obtained with AERMOD and HPDM, while the contaminant concentration is close to the value calculated by AERMOD. The most important difference between PCCOSYMA with the other codes is the distance up to which the contaminant arrives in accordance with the simulated advection time -35 Km, 0.01 µBq·s·m^{-3}, while AERMOD and HPDM exceed amply 50 Km-. Which is obvious due to the stationary models used by AERMOD an HPDM.

Dispersion Parameters

The dispersion parameters used by PCCOSYMA depend on the Pasquill-Gifford stability class. Therefore they keep unchanged during Hours 1, 2 and 3 (Pasquill-Gifford class F) and Hours 4, 5, 9, 11 and 12 (Pasquill-Gifford class D). The different values for atmospheric parameters such as Monin-Obukov length, friction velocity and inversion height, calculated by AERMOD and HPDM meteorological pre-possessors, originate the differences between the dispersion parameters used by these codes. In general, it can be observed that σ_y calculated by PCCOSYMA are the lowest during the first twelve hours. HPDM predicts the lowest σ_z values for each hour, which is a consequence of more stable atmospheric conditions given by SIGPRO.

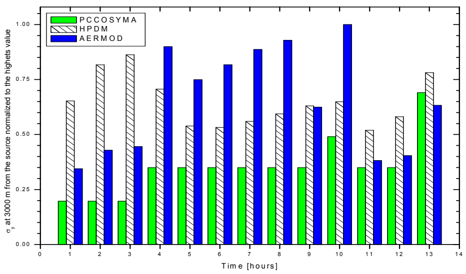

Figure 10: σ_y at 3000 m from the source.

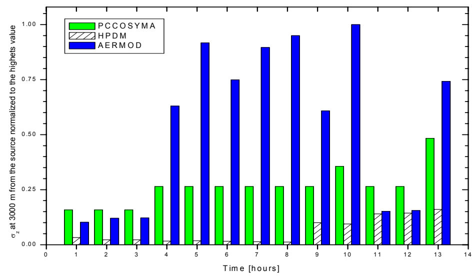

Figure 11: σ_z at 3000 m from the source.

During the first three hours the atmospheric stability condition is stable (positive L^{-1}). AERMOD and HPDM use stable condition algorithms for these hours. The σ_y predicted by HPDM are the highest and therefore the horizontal plume spread is the greatest. The mixing layer depth height calculated by AERMET and SIGPRO are lower than the emission height, causing small vertical plume dispersion. The stability calculated by HPDM is more stable than the AERMOD one, resulting in a comparatively lower σ_z. In the course of the next five hours the atmospheric stability is neutral (slightly positive or negative L^{-1}). The mixing layer depth calculated by AERMET increases sharply, and therefore the stack is now inside the mixing layer. On the other hand SIGPRO predicts that the mixing layer depth remains unchanged, and therefore lower than the stack top, which is the reason why σ_z predicted by HPDM is lower than the AERMOD one. For Hour 9, σ_y calculated by AERMOD and HPDM are similar, while the σ_z predicted by AERMOD is greater than the one calculated by HPDM. This is because the vertical turbulence predicted by AERMOD is 3 times greater than the one predicted by HPDM, due to an increase of vertical velocity scale, (w_*). The σ_z predicted by HPDM for this hour is greater than the calculated for previous hours. For the next hour the instability increases due to the Sensible Heat Flux (SHTF) increment. The meteorological pre-processors AERMET and SIGPRO predict that the inversion height is higher than the stack top. The vertical turbulence calculated by AERMOD goes on increasing, giving higher values than HPDM. In both cases the dispersion parameters increase respect to the previous hours. The meteorological pre-processor AERMET predicts for Hours 11 and 12 different atmospheric conditions than SIGPRO. AERMET sharply decreases the mixing height to values lower than the stack (see Figure 2) and the atmospheric stability becomes barely stable (SHTF changes the sign). So the atmosphere stratifies reducing the mechanical turbulence, and consequently σ_y and σ_z decrease. On the other hand SIGPRO increases the mixing height further, and keeps the atmospheric condition barely instable. For the last simulated hour the atmosphere stability changes clearly to unstable, causing a buoyant force increase and the consequent dispersion parameters increase respect to the previous hours.

CONCLUSIONS

As the stationary Gaussian plume models give a non-zero contaminant concentration in the whole downwind domain, based on the present simulation results, the validity range should be limited to a few tenths of kilometres. In this region, in general, changes in the atmospheric parameters can be neglected and steady state conditions in the concentration can be assumed taking into account the actual wind speed and the advection time. A more realistic description is obtained with the segmented Gaussian plume model because it limits the plume length along the wind direction.

The dispersion parameter (σ) comparative analysis between different codes and stability conditions is a complex task, because to quantify the σ the codes use different algorithms -to evaluate the PBL characteristic variables-, models and stability criteria. Moreover, their evaluation is not always based on the same set of parameters. However, if we accept to perform the comparative analysis according to Pasquill-Gifford stability classes, it becomes simpler and global conclusions are possible. Therefore the σ calculated with each code are grouped imposing the hourly P-G stability class obtained from the meteorological data (shown in Figure 1).

Under this classification, we observed that when comparing σ_y with σ_z for the different atmospheric stabilities analysed (F, D, C and B) their values predicted with AERMOD and PCCOSYMA are of the same order. While the values calculated with HPDM for σ_z are much lower than for σ_y and than the σ_z evaluated by the other codes. The values of σ_z and σ_y calculated with HPDM, PCCOSYMA and AERMOD increase with increasing instability except for the last code, which predicts a lower value for Class B than for Class C. This is correlated with the variation in the mixing layer depth, which for the hour corresponding to Class B it is lower than the one with class C. In addition AERMOD predicts the highest values for all the analysed stability classes, which again can be correlated with the very high values predicted for the mixing layer depth. For example, during the night hours (neutral stability class after a stable period) this parameter calculated with AERMOD is approximately 400 meters, more than one order of magnitude greater than the HPDM ones. The last seems to give a more realistic evolution. An anomaly was found in σ_y calculated with HPDM. The value for the most stable condition is the highest one in opposition to the calculation performed with AERMOD and PCCOSYMA.

The dispersion parameters calculated by means of the similarity theory naturally incorporate more detailed atmospheric conditions than the ones calculated according to Pasquill-Gifford classes, which is obviously an important improvement. However the differences between the meteorological pre-processors calculations and the strong dependence of the results on them, indicates that more development should be done in order to improve the pre-processing algorithms. On the other hand, the main advantage of Pasquill-Gifford atmospheric dispersion parameters is the reduced set of meteorological data needed, which is sometimes enough for regulatory purposes or for a fast accident management response.

REFERENCE

[1] Cimorelli A. J., S. G. Perry, R. F. Lee, R. J. Paine, A. Venkatram, J. C. Weil, R. B. Wilson., 1998, Aermod description of model formulation version: 98314 (aermod & aermet) 98022 (aermap), E.P.A., Draft - 113 pp.

[2] Hanna S., Chang J., 1991, Modification of the Hybrid Plume Dispersion Model (HPDM) for Urban Conditions and Its Evaluation using the Indianapolis Data Set. Volume I: User's Guide for the HPDM-4.0 Software Package, EPRI, 126 pp.

[3] Jones J. A., Hasemann I., 1996, EUR 16239 EN - PC Cosyma (Version 2.0): An accident consequence assessment package for use on a PC , National Radiolagical Protection Board – Forschungszentrum Karlsruhe GmbH, 59pp.

[4] McQueen, J.T., R.A. Valigura, and B.J.B. Stunder, 1997a, Evaluation of the Regional Atmospheric Modelling System for estimating turbulent fluxes over the Chesapeake Bay, Atmos. Environ, 31, 3803-3819.

[5] McQueen, J.T., R.R. Draxler, B.J.B. Stunder and G.D. Rolph, 1997b, An overview of the Regional atmospheric Modeling System (RAMS) as applied at the NOAA/Air Resources Laboratory, NOAA Technical Memorandum ERL ARL-220, 50 pp.

[6] McQueen, J.T., G.D. Rolph, F. Aikman III, J.G.W. Kelley, T.F. Gross, G. Szilagyi, K.K. Fuell, C.J. Tremback, and J. Titlow, 1999, Development and evaluation of a non-hydrostatic atmospheric prediction system for the Chesapeake Bay region., Proceedings 3rd Conference on Coastal Atmospheric and Oceanic Prediction Amer. Meteor, 189-194.