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Limits of Fidelity in Urban Plume Dispersion Modeling: Sensitivities to the Prevailing Wind Direction

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1. INTRODUCTION

Focused research efforts on the development of urban dispersion models has occurred over the past decade in order to respond to the potential of releases of toxic gases in cities (e.g., Griffiths, 2002; Coirier & Kim, 2006). A key input to these models is the prevailing wind direction, which may be obtained from a nearby (or not-so-nearby) meteorological station or from mesoscale model calculations. There can be considerable uncertainty in the mean wind direction due to a number of factors including the distance of the wind sensor from the release site, poor siting of the instrument (e.g., in the wake of an upwind building or tree), inherent biases or errors in certain types of wind instrumentation, turbulent stochastic uncertainty, and temporal or spatial model errors.

It is well known that the footprint from plumes traveling over relatively flat terrain and the resulting concentrations at particular locations are quite sensitive to the input wind direction since plumes are generally narrow in the cross-wind direction. But it is not clear how sensitive plume transport is to the prevailing wind direction in cities, where buildings significantly alter the flow, the turbulence, and the resulting transport and dispersion of the plume. In this paper, we will look at the sensitivity of transport and dispersion in cities to the prevailing wind direction. This is accomplished by using urban dispersion models to create synthetic data and systematically changing the input wind direction in small increments.

2. BACKGROUND

Urban dispersion models are being evaluated using tracer measurements obtained in cities during big field campaigns (e.g., SLC Urban 2000, OKC Joint Urban 2003, NYC Madison Square Garden, NYC Midtown). One of the key input parameters for the models is the prevailing wind direction, which is often not precisely known even in heavily-instrumented field campaigns. For example, Fig. 1 shows 30 minute averaged wind direction measurements from rooftop anemometers and sodars within a few kilometers of each other during the New York City Midtown experiment. Each of the wind instruments were placed so as to obtain the prevailing background winds, but the wind measurements show differences of 20 to 60°. As a modeler it is not clear what to input as the prevailing wind direction. Using mesoscale model output to drive plume dispersion models is common practice as well, especially in data poor regions. However, differences of 20 to 60° between the model-computed wind direction and the measured wind direction are often found for appreciable periods of time even for "successful" comparisons (e.g., Chin et al, 2005; Lee et al., 2006).

Given these uncertainties in the input wind direction, we look at two metrics commonly used when evaluating plume dispersion models: the factor-of-two metric and the overlap fraction metric. The percentage of model-computed concentrations within a factor-of-two of the measured concentrations has been commonly used as a yardstick to compare air pollution models. We will use the metric for comparing concentrations at paired points in space. Note that for air quality applications, the concern is often the maximum concentration from an industrial source, so that factor the location is often not of the up-most importance, but rather just the magnitude of the concentration. When comparing to other studies, one should recognize that the percentage within a factor-of-two should be much higher when comparing only maximum concentrations that are not paired in space.

The second metric, the overlap fraction, stems from industrial accident, homeland security, and defense-related emergency response applications where there is a need to know how big a hazard zone is and where it's located. The hazard zone might represent, for example, the dosage above which serious health effects are encountered, or the level at which a chemical is flammable, or the deposition threshold above which clean-up must be performed. If the real plume goes off to the south and the modeled plume off to the southwest, the wrong people may be evacuated, medicines may be given to the wrong people, etc. The higher the percent of overlap of the modeled plume with the actual plume, the better from an emergency response perspective. Note that one should also look at the areas of false positives and false negatives to also account for the differences in size between the modeled and actual plume hazard zone areas (see Warner et al., 2004), but in this study we simplify the analysis by only looking at the overlap fraction.

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3. METHODOLOGY

In order to quantify the impact of wind direction on the plume concentration field, we have used transport and dispersion plume models to create synthetic data. The plume models are run several times with identical source terms and meteorological input parameters, but with different prevailing wind directions. The concentration fields in an x-y plane are then compared to look at how much the concentrations have changed point-by-point in response to the wind direction shift.

Plume dispersion models clearly do not produce “real” data and the concentration fields will be different than those in reality. However, models do provide an idealized way of isolating the effects of specific input parameters on the resultant output fields of interest. This is difficult to achieve with real field data. All results presented here, therefore, should be taken with a grain of salt, but we do believe that the comparisons shown here will for the most part have the correct trends and be useful for determining the impact a wind direction error will have on plume model output.

As part of this study, a Gaussian plume model has been used to illustrate points and then an urban dispersion model called QUIC was used to look at how buildings alter the response of the concentration field with respect to changes in the prevailing wind direction. The Gaussian plume model is a standard code using the Briggs’ rural and urban plume spread parameters (e.g., see Arya, 1999). The QUIC (Quick Urban & Industrial Complex) dispersion modeling system contains an empirical-diagnostic wind model that produces 3D wind fields around buildings (e.g., Pardyjak and Brown, 2003; Gowardhan et al., 2007) and a Lagrangian random-walk model that accounts for building reflection and non-local turbulent mixing (e.g., Williams et al., 2002).

4. PLUME SENSITIVITY TO WIND DIRECTION OVER URBAN TERRAIN: NO BUILDINGS

a) Paired-in-space concentration comparisons

The Gaussian plume model was run for a near-surface point source release using urban plume spread parameters under neutral (D) stability conditions for prevailing wind directions of 270, 272, 275, 280, and 290°. Figure 2 shows the $\log_{10}$ contours of the near-surface normalized concentration in the x-y plane for two plumes computed with the 270° and 272° wind directions. Although the plumes look nearly identical, point-by-point comparison of the concentrations from the two plumes reveal that large percentage differences are obtained off the centerline, even for a small wind direction shift of only 2 degrees (Fig. 3). This is of course due to the strong concentration gradient in the lateral (i.e., crosswind) direction, so that small shifts in the plume centerline result in large differences in concentration at a point in space off the centerline.

Figures 4a, b, c, and d show scatterplots of the near-surface concentrations in the x-y plane for wind direction shifts of 2, 5, 10, and 20 degrees. Even a change of only 5 degrees in wind direction results in concentrations being a factor of 10 different near the plume centerline and up to a factor of 100 off the centerline (Fig. 4b). For stable conditions the plume is narrower and the lateral concentration gradient stronger, resulting in even larger point-by-point concentration differences for a given change in prevailing wind direction as compared to the neutral stability case. Conversely, for unstable conditions the plume is wider and the lateral concentration gradient is weaker, producing notably smaller concentration differences for a given shift in wind direction.

Given that there is considerable uncertainty in the prevailing wind direction in even heavily-instrumented urban tracer experiments, the sensitivity of the plume concentrations to relatively small differences in the input wind direction means that model validation using paired-in-space concentrations will be extremely challenging. To expect that a dispersion model should achieve a high fraction of concentrations within a factor of two of the experimental measurements may be unrealistic, unless one only compares concentrations near the plume centerline (i.e., the maximum concentrations at specific downwind distances). These results only apply, however, if the “flat earth” assumption of the Gaussian plume model is valid. In section 5, we repeat these analyses accounting for the effects of buildings using the QUIC dispersion model.

b) Hazard zone overlap comparisons

As noted in section 2, the area covered by a specific level-of-concern (LOC) may be more important for consequence analysis purposes as compared to matching concentrations point-by-point. The example in Fig. 5 depicts two LOC footprints for an arbitrary concentration threshold (in this case $CU/Q = 10^{-4}$) produced by the Gaussian model using the same input as described above for neutral conditions. For this case of a 10 degree wind shift, the concentrations showed huge percentage differences, but the area of overlap of the two plumes is still fairly high at 53%. So even though the concentrations at specific points in space may be off by a factor of 100 to 1000 with an error in the input wind direction of 10°, the location of the hazard zone would still be fairly well approximated.

Figure 6 shows the overlap fraction between the two plumes for four different atmospheric stabilities as a function of the difference in the input wind direction. The overlap fraction is strongly dependent on stability, with more overlap occurring for the wider plumes that develop under strongly unstable conditions (A-B) as compared to the narrower plumes under stable conditions (E-F). For A-B stability conditions, a 5° change in wind direction still has 90% overlap between the two plumes, while the E-F overlap has dropped to 55%. The overlap fraction drops to below 50% for A-B stability when the winds change 23° , for C stability at 20°, D stability at 13°, and E-F stability at 8°.

Based on these results, estimation of the location of the hazard zone is seen to be less sensitive to the input wind direction in comparison to point-by-point evaluation of concentration magnitudes. This is good news from the emergency response perspective, in that the hazard zone regions may be adequately estimated even with the expected errors in the prevailing wind direction input. In section 5, we will see if these results hold up when the effects of buildings are included.

5. PLUME SENSITIVITY TO WIND DIRECTION OVER URBAN TERRAIN: EFFECT OF BUILDINGS

a) Impact of buildings

For a release in a city, the change of the point-by-point concentration comparisons and the overlap fraction of the hazard zone between two plumes will not vary smoothly like the Gaussian plume model shown in the previous section. This is illustrated in Fig. 7 for an idealized array of buildings. As the prevailing wind direction is varied aloft from south-southwesterly, to southerly, to south-southeasterly, the plume centerline (in red) remains channeled down the N-S running street, not responding to the wind direction (note: the edges of the plume vary as the E-W channeling reverses as the wind switches from southwesterly to southeasterly).

In a majority of real cities, the buildings are heterogeneous: of many heights, shapes, sizes, and orientations. Hence, the response of the winds at street level are more complex than the simple illustration shown in Fig. 7. For example, if the prevailing wind hits a tall building straight on, there will be a region of downward winds on the lower part of the front face, that will then impact the street creating a divergence zone with horizontal winds going out in all directions. This will result in complex patterns of channeling in streets. As the prevailing wind direction changes and becomes more oblique to the front face, there will be a point at which the winds will no longer be deflected downwards, but rather will "slip" around the building. At street-level, the winds may suddenly switch direction as the divergence zone disappears.

The spatially-inhomogeneous street-level wind patterns mean that the results of point-by-point comparisons of the concentration and overlap fraction of hazard zones will not only depend on the shift in wind direction, but will also vary depending on the release location, the mean wind direction, and the arrangement of the buildings. In Sections 5b and c, we perform calculations of plume dispersion in Oklahoma City (site of the Joint Urban 2003 tracer field experiment) using the QUIC dispersion model with several different release locations and prevailing mean wind directions.

b) Point-by-point comparisons

Figure 8 shows concentration scatterplots for a 5° shift in wind direction using the Gaussian plume model with urban plume spread parameters (left) and the QUIC urban dispersion model (right). The comparisons of concentrations were done only for $CU/Q > 10^{-7}$ since this was the lower limit for the QUIC random walk model given the 100,000 particles released, the grid size, and the averaging time. The QUIC simulations indicate that there is much less scatter as compared to the Gaussian plume model. This is most likely due to the upwind and lateral dispersion that occurs near the release, making the plume wider in cross-section as compared to the Gaussian urban plume. If the QUIC code is thought to better represent nature, then concentrations at specific points in space will not be as sensitive to changes in wind direction as indicated by the Gaussian plume model. Scatterplots produced by QUIC with a 10° wind shift indicate that the majority of concentrations are within the factor of 10 bin (not shown). At 20° most of the concentrations are bounded by the factor of 100 bin (not shown).

Note, however, that the scatterplots produced with the QUIC output will change for a different release location or prevailing mean wind direction. More simulations need to be performed in order to better understand the variability.

c) Hazard zone overlap comparisons

Figure 9 shows the overlap of two plume footprints within the Oklahoma City domain for a 10° shift in the wind direction. Due to the large amount of upwind and lateral spread near the point source release, the plumes behave as if they are area source releases and thus are quite similar in the downwind region they cover. Figure 9 shows the fraction of overlap as function of change in the input wind direction. There are several curves for the plumes produced with the QUIC model representing several different source locations within the domain. There are slight differences in the curves owing to the complex spatial variations in the channeling behavior at locations near the source in response to the prevailing wind direction. Also shown for comparison is the overlap curve for the Gaussian plume model with urban plume spread parameters. The overlap falls off much more rapidly as compared to the QUIC simulations. This is because although the plume spread parameters have been corrected to account for the additional mixing associated with urban roughness, they do not include any upwind or lateral transport and dispersion at the source location. In a paper at this conference, Hanna and Baja (2008) have proposed just such a correction to the Gaussian plume model and find much better agreement with tracer data from the New York City Madison Square Garden experiment.

6. CONCLUSION

We will show that rooftop and sodar wind direction measurements obtained in cities show significant scatter making it unclear exactly what wind direction to use as input. We will demonstrate that plume concentrations at specific points in space can change several orders of magnitude with only a 10 degree change in the prevailing wind direction. When evaluating models using paired-in-space and paired-in-time concentrations, we show that it will be very difficult to achieve the commonly-used "factor-of-two" metric. We will also discuss other sensitivities of plume transport in cities to wind direction, including how the street-level flow patterns in cities can be very robust (i.e., unchanging) as the upper-level wind direction changes, and then suddenly shift 180 degrees at critical upper-level wind directions. And how slight changes in wind direction can result in a plume being caught in the updraft on the downwind side of a tall building leading to low surface-level concentrations or being caught in the downdraft on the front side of a tall building leading to high surface-level concentrations. These sensitivities to building geometry and wind direction make it extremely challenging to do well when evaluating urban dispersion models against concentration measurements in cities.

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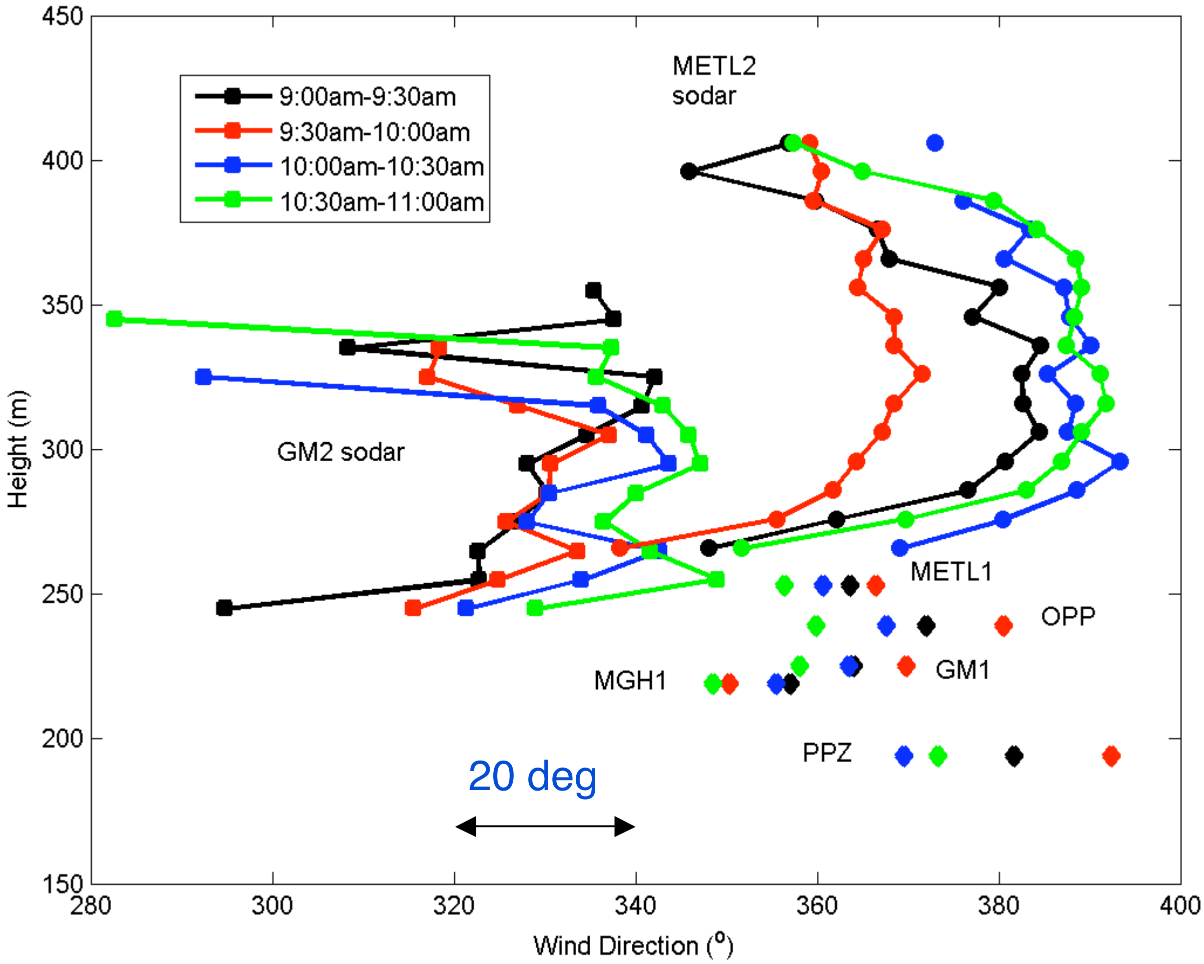

Figure 1. Thirty-minute averaged wind direction measurements from two rooftop sodars and four rooftop anemometers obtained over a two hour period during the New York City Midtown field experiment (see Allwine and Flaherty, 2007). All the instruments were within a 2 km domain, with spacing between instruments ranging from roughly 500 to 1000 m. The choice of what to input into a dispersion model for the prevailing wind direction for each half hour period is not entirely clear. Is the low-level wind direction shear found in the sodars real or an artifact of the signal processing? Are the 40-50° differences between the two sodars spaced a little over a kilometer apart real? If so, then why do the rooftop measurements at the GM site (GM1) not agree with the sodar at that site (GM2)? Are the rooftop measurements representative of the background wind, or are there effects from upwind buildings and/or does the building itself perturb the flow on the rooftop where the sensors are located? Even if all the measurements perfectly represent the background wind, in a non-field-campaign situation, when the density of wind sensors in a city is much lower, can one trust a sensor that is far from the release location?

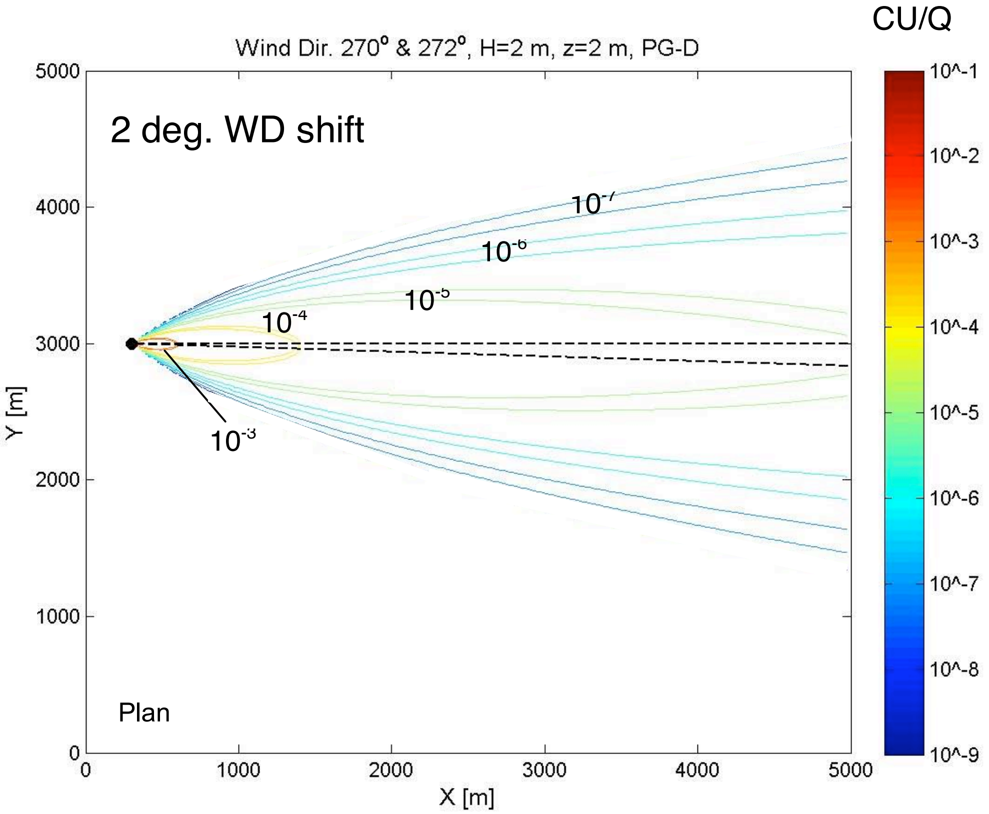

Figure 2. Plan view of normalized near-surface concentration contours for two plumes created with a Gaussian plume model with urban spread parameters for neutral stability, a point source release near the ground, and a 270° and 272° input wind direction, respectively.

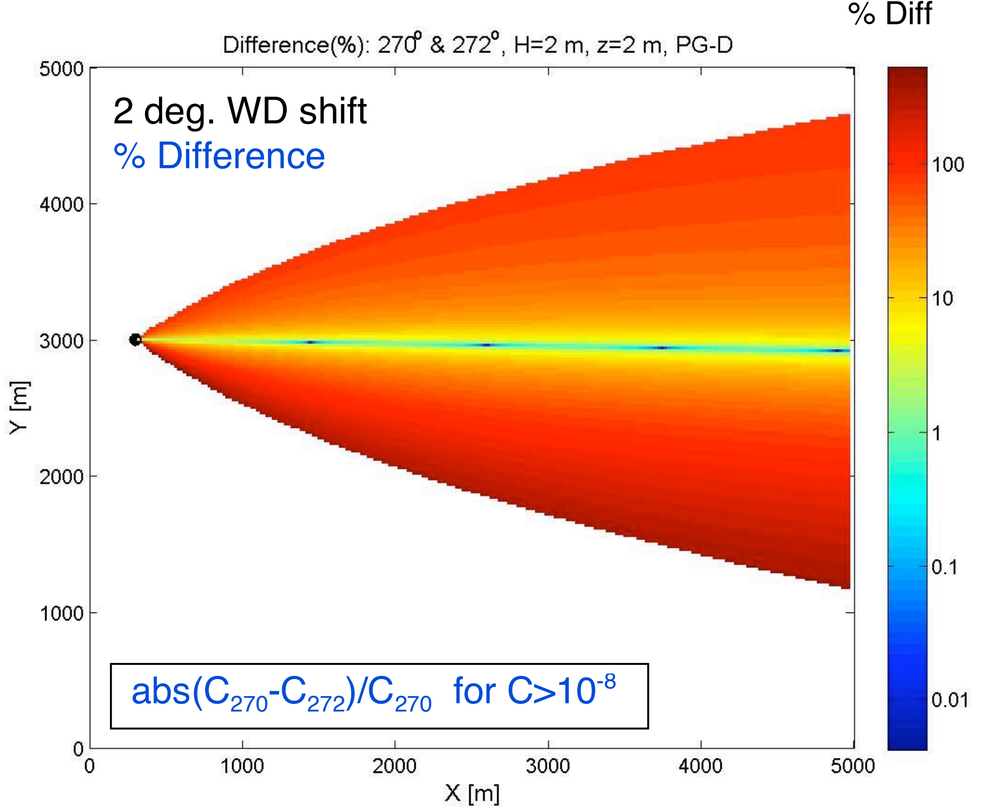

Figure 3. Plan view showing the percentage difference between the concentrations of the two plumes.

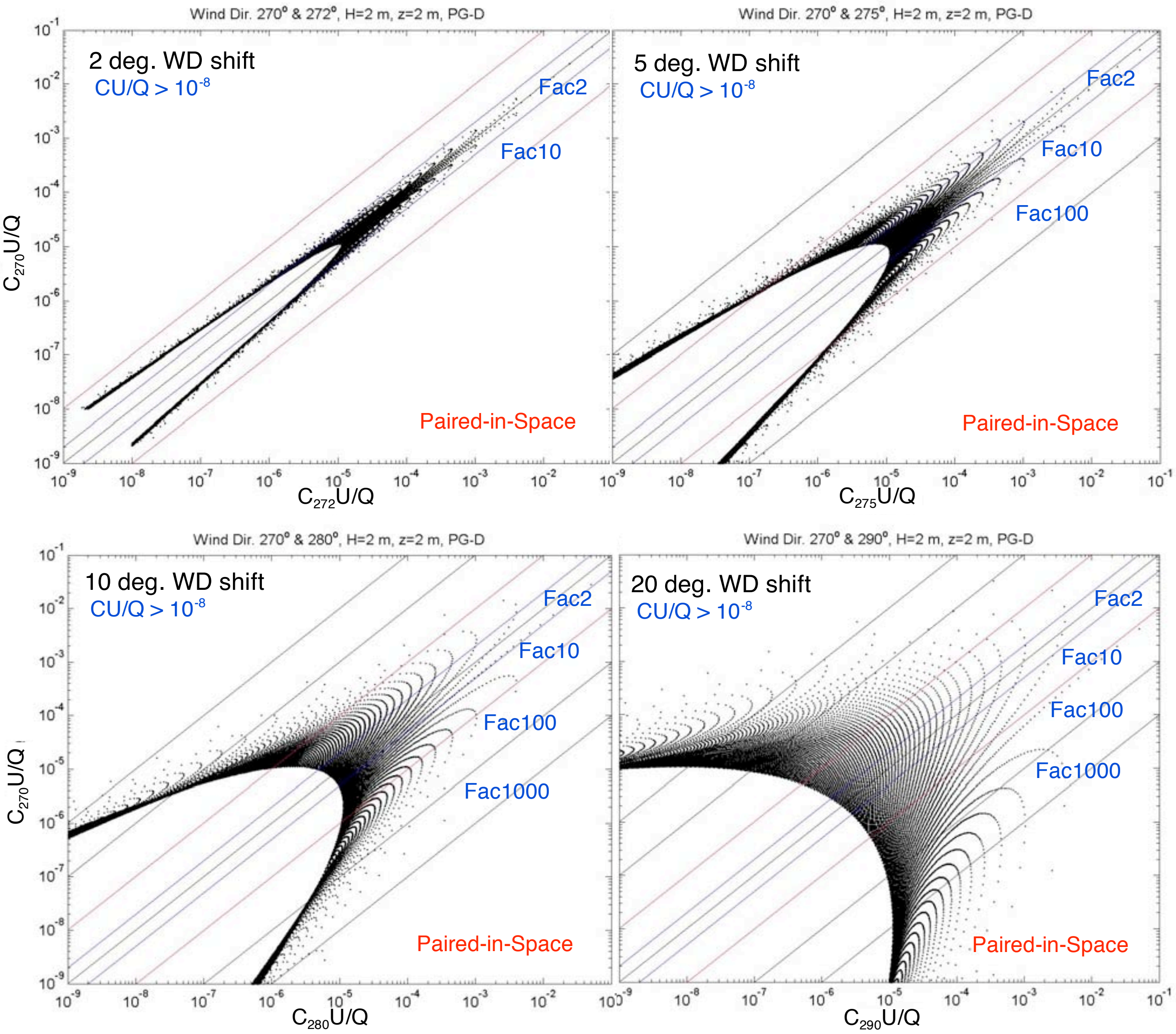

Figure 4. Scatter plots showing the comparison of near-surface concentrations produced by two plumes for a wind direction shift of: (top-left) 2°, (top-right) 5°, (bottom-left) 10°, and (bottom-right) 20°. The plume concentrations were produced using a Gaussian plume model with urban spread parameters under neutral stability and a point-source release near the ground.

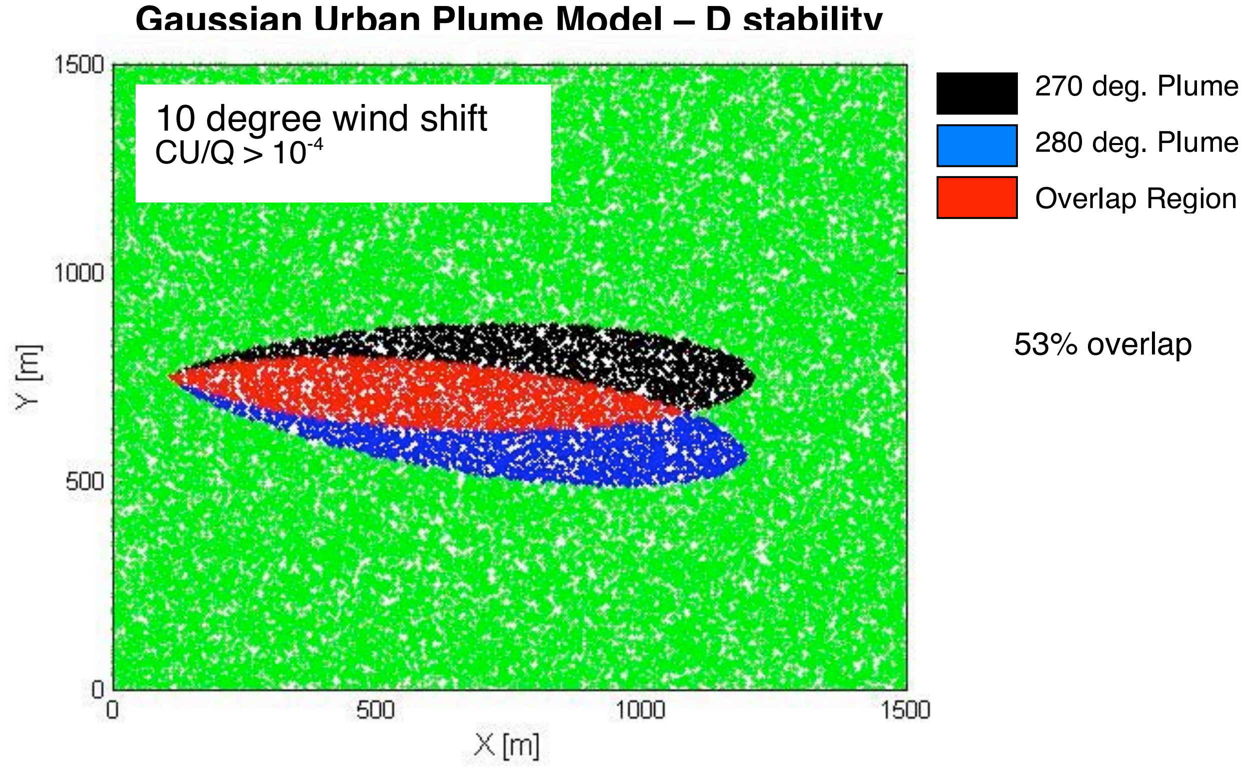

Figure 5. Comparison of the “hazard“ zones (defined by $CU/Q>10^{-4}$) created using a Gaussian plume model with urban spread parameters for a near-surface point source release under neutral stability. A 10 degree shift in the wind direction results in a 53% overlap of the hazard zone areas.

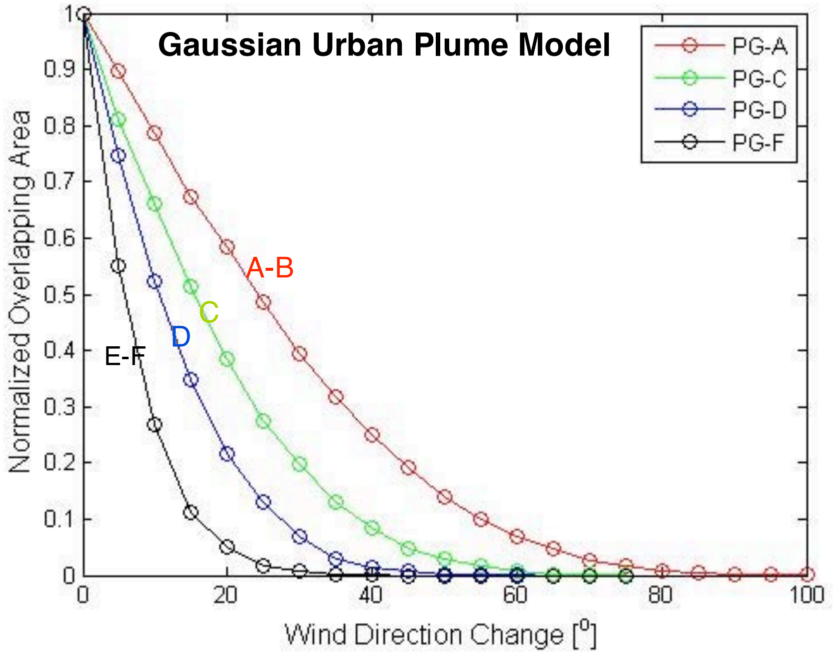

Figure 6. Comparison of the “hazard“ zone overlap fraction as a function of the shift in wind direction and the atmospheric stability. The hazard zone is defined by $CU/Q>10^{-4}$. Computations performed with a Gaussian urban plume model for a near-surface point source release.

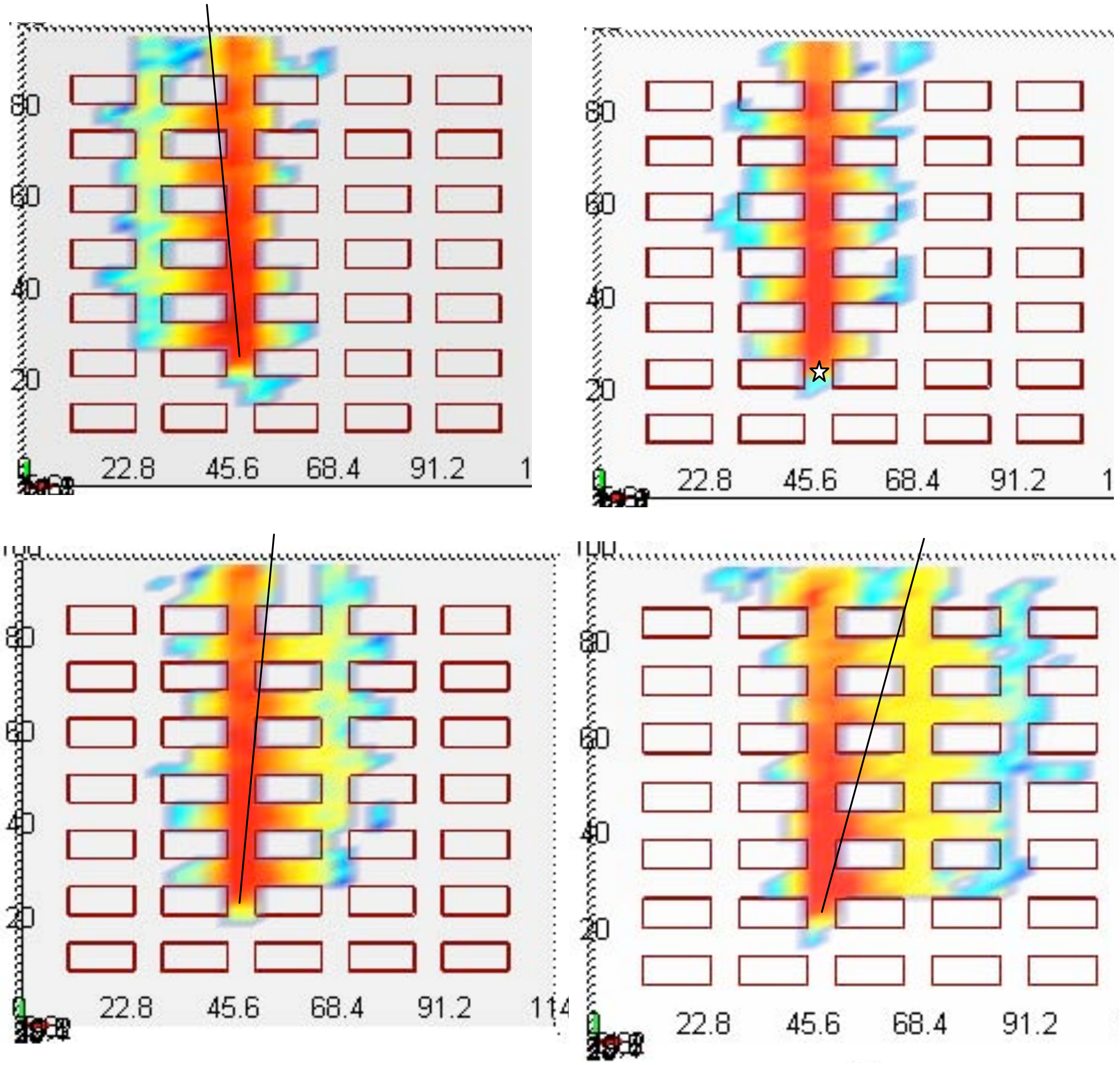

Figure 7. Plan view of plume concentrations in an idealized array showing how as the prevailing wind direction is varied the centerline of the plume defined by the maximum concentration does not respond, remaining channeled down the north-south street. Rainbow color scale with high concentrations in red and low concentrations in blue. Prevailing winds are 175, 180, 185, and 195° clockwise from upper left. The plumes were created using the QUIC dispersion modeling system. Release location at the star.

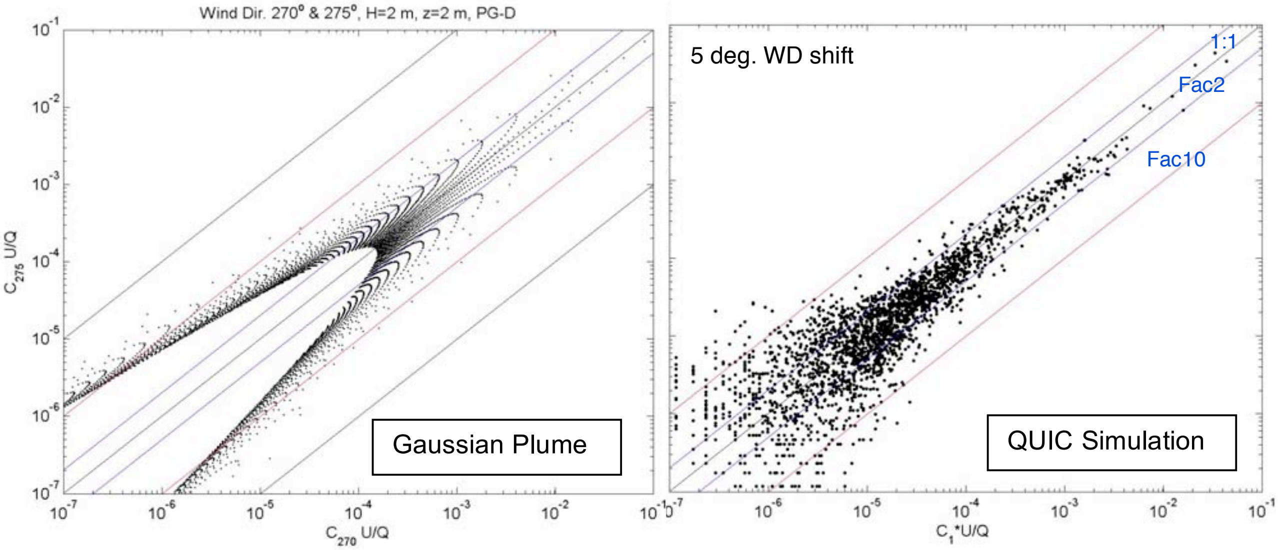

Figure 8. Comparison of the scatterplot of concentrations for a 5° wind shift when using the (left) Gaussian plume model with urban spread parameters and the (right) QUIC dispersion model. The plume is wider near the source and concentration gradients not as severe for the QUIC model simulation, thus resulting in less differences in the concentrations when the wind is changed 5°.

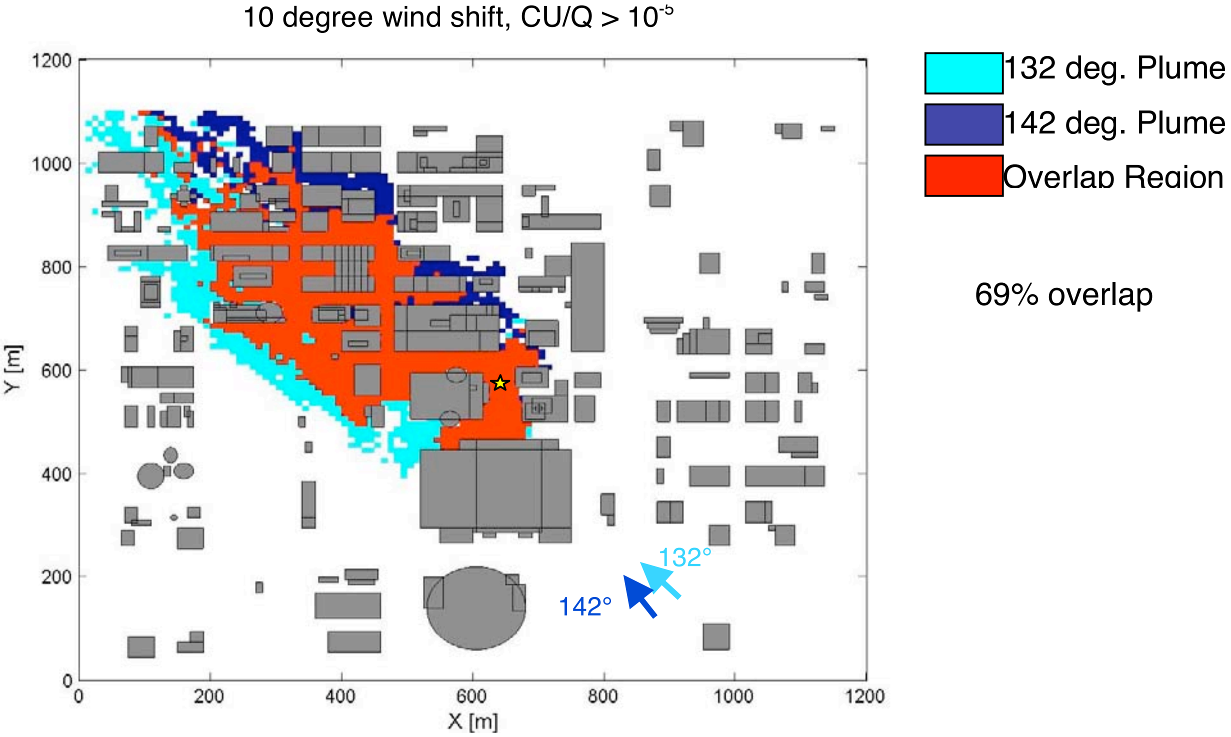

Figure 9. Comparison of the "hazard" zones (defined by $CU/Q>10^{-5}$) created using the QUIC plume model for a near-surface point source release (star) under neutral stability. A 10 degree shift in the wind direction results in a 69% overlap of the hazard zone areas.

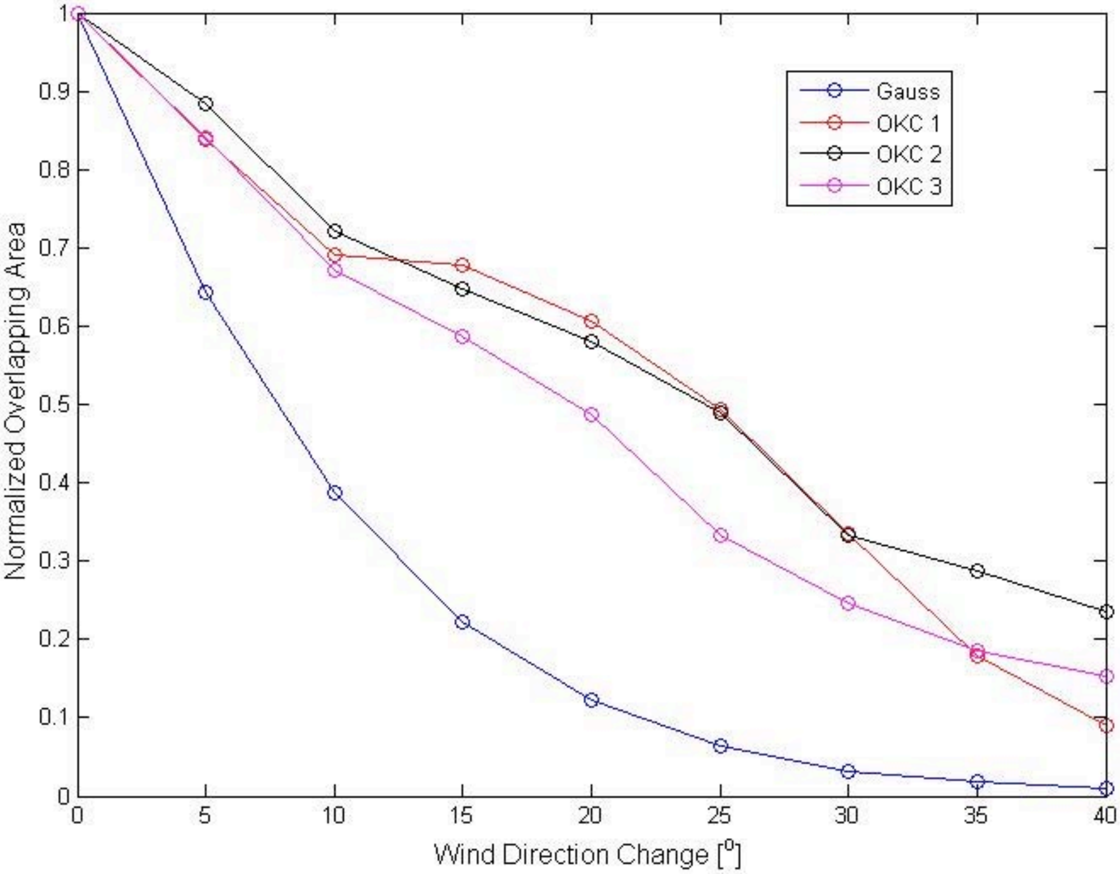

Figure 9. Comparison of the "hazard" zone overlap fraction as a function of the shift in wind direction. The hazard zone is defined by $CU/Q>10^{-5}$. Computations performed with the QUIC dispersion model for 3 different source locations and a Gaussian urban plume model for a near-surface point source release.