Urban Transport and Dispersion Model Sensitivity to Wind Direction Errors and Source Location

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ABSTRACT

Many transport and dispersion (T&D) models need prevailing winds and source location to forecast concentration and dosage fields. Therefore, the models use observational data or mesoscale-model-generated forecast winds as the prevailing winds. This research examines how errors in these input wind fields may translate into T&D model solution errors. In particular, this study focuses on street-level plume errors that occur in building aware T&D models for a set of hazardous scenarios where the release location varies relative to the building locations and city building configurations. This problem was evaluated by first creating a “truth” plume for a given release location and wind direction. Then the T&D model errors associated with input wind errors were determined by comparing plumes calculated using wind directions varied at 2 degree increments to the truth plume. The errors are quantified as fraction of overlap (FOO), figure of merit in space (FMS), measure of effectiveness (MOE), and normalized absolute difference (NAD). These errors were evaluated for a non urban, an urban grid, and urban radial domain. Then two case studies modeled after common city setups. Results show that the relative impact of input errors vary significantly with the release location and the wind direction relative to buildings.

1. Introduction

Since September 11, 2001, the Government has made significant investments in sensing and modeling technologies designed to protect the United States of America (USA) armed services and homeland against the threats posed by weapons of mass destruction (WMD). These technologies include development of fast response transport and dispersion (T&D) models that can account for the dispersion of biological and chemical agent contaminant sources in urban areas. Rife (2004), stated that the need for accurate T&D forecasting techniques had become increasingly important because of the threat of an intentional release of hazardous material into the atmosphere, particularly in areas of complex local surface forcing and for longer transport distances. Although there has been extensive research to make these T&D models more accurate.
within the context of an urban building-aware setting, local wind observations and/or mesoscale-model-generated forecast winds must still be employed as input in T&D models. Chang (2003) determined that in cases where meteorological models were coupled with T&D models the T&D models were strongly influenced by the diagnostic wind model that was used to generate gridded wind fields from observed winds. Brown (2007) showed that the 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. Therefore, this paper’s research consists of determining how errors in the mesoscale-model-input wind directions translate into street level T&D errors, specifically, into errors in hazardous zone areas. These errors are quantified for different generalized urban settings and source release locations.

The urban settings evaluated in this study are modeled after two commonly occurring city design characteristics. The first is modeled after a modern city with a rectangular grid design and the other is modeled after an older more historic city, which typically have a mix of rectangular grids and a hub-spoke design. Due to the historic significance, related to its recent use in the USA and the ready availability of lethal dosage (LD) amounts this study used anthrax and its corresponding lethal exposure concentrations (LCt) values to define hazard thresholds. Detailed information on the city designs, source characteristics, and release locations can be found in Sections 2.a and 2.b, respectively.

This study used the Röckle (1990) based Quick Urban Industrial Complex (QUIC) Dispersion Modeling System developed at the Los Alamos National Laboratory (LANL) to evaluate the errors associated with wind direction. QUIC is a fast-response, urban dispersion modeling system capable of computing three-dimensional wind patterns and dispersion of airborne contaminants around clusters of buildings. The system is comprised of a wind model (QUIC-URB) and a Lagrangian dispersion model (QUIC-PLUME) and a graphical user interface (GUI), QUIC-GUI (LANL, 2007). This model was chosen because its performance is generally representative of this class of and is currently used in an operational facility protection system developed for the Pentagon and surrounding facilities.

2. Methods

a. Domain Characteristics

To evaluate the effect of errors in T&D solutions associated with the input winds over a generalized set of operational conditions and release source locations, domains representing a non-urban domain (Figure 1), an urban grid domain (Figure 2), and an urban radial domain where several major streets converge on at the center of the domain (Figure 2) were created. Figure 1 shows the non-urban domain (no buildings) with the source location place in the center of the domain. Figure 2 shows the generalized urban grid and radial domains and the locations of the release source locations that were evaluated. The non-urban, urban grid, and urban radial domains were assessed for comparison with, modern rectangular grid city center design (Figure 3) and historic (Figure 4) hub and spoke city center design. The location of the source in each of the domains including the case studies (Figure 5) was strategically placed to capture wind
direction effects as the urban canyon, but also to assess the influence of building corners and building obstructions. The characteristics of these domains can be found in Table 1.

Figure 1. Non-Urban domain showing no buildings and the source location in the center of the domain.

Figure 2. Urban grid and radial 1500 x 1500 x 100 m³ domains with 100 x 100 x 30 m³ average size building blocks. The source locations are marked with a red crosses.
Figure 3. Modern city configuration modeled after Denver, CO with grid like streets and the largest buildings in the center of the domain.
Figure 4. Historic city configuration modeled after Boston, MA with radial streets and the largest buildings in the center of the domain.

Figure 5. Source location shown as red cross in Modern and Historic domain case studies.
Table 1. Description of city characteristics.

<table>
<thead>
<tr>
<th>Area (km)</th>
<th>Number of Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non Urban</td>
<td>1.5 X 1.5</td>
</tr>
<tr>
<td>Urban Grid</td>
<td>1.5 X 1.5</td>
</tr>
<tr>
<td>Urban Radial</td>
<td>1.5 X 1.5</td>
</tr>
<tr>
<td>Modern</td>
<td>1.6 X 1.6</td>
</tr>
<tr>
<td>Historic</td>
<td>1.6 X 1.6</td>
</tr>
</tbody>
</table>

b. Source Characteristics

The anthrax characteristics used (Table 2) and the LCt calculations made are derived from the Lawrence Berkeley National Laboratory database of physical, chemical and toxicological properties of chemical and biological (CB) warfare agents for modeling airborne dispersion in and around buildings (Thatcher et. al. 2000).

Table 2. Anthrax characteristics from the Lawrence Berkeley National Laboratory database of physical, chemical and toxicological properties of chemical and biological (CB) warfare agents for modeling airborne dispersion in and around buildings.

<table>
<thead>
<tr>
<th>Biological Class</th>
<th>Spore forming</th>
<th>Persistence</th>
<th>Size (μm)</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acillus anthracis</td>
<td>2 hours</td>
<td>Years</td>
<td>~1 diameter X ~1.5 length</td>
<td>rod</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dissemination/Route of Entry</th>
<th>Incubation/Onset</th>
<th>Contagious</th>
<th>50% Infective Dose (organisms/person)</th>
<th>Untreated Lethality (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spore inhalation, ingestion (rare), broken skin</td>
<td>1-2 hrs, 1-7 days</td>
<td>No</td>
<td>8,000 to 20,000</td>
<td>100</td>
</tr>
</tbody>
</table>

To quantify mortality due to anthrax exposure we use different dosage thresholds to identify hazardous areas. These areas are defined within the 50 and 10 LCt (Table 3). The LCt is defined as

$$LCt = \frac{LD}{SR \times BR},$$

where LD is the lethal dosage, SR is the spore ratio, and BR is the breathing ratio. The thresholds represent the minimum value used to define a hazard zone with an anticipated level of health response within a given population. Any dosage above that value is considered hazardous and any dosage below that value is non-hazardous, relative to this population health response.

Table 3. LCt values for Anthrax using a probit slope, a spore ratio of 3X10⁷ spores/mg, and a light breathing rate of 0.02 m³/mg. Calculated using the Lawrence Berkeley National Laboratory database of physical, chemical and toxicological properties of chemical and biological (CB) warfare agents for modeling airborne dispersion in and around buildings.

<table>
<thead>
<tr>
<th>LCt percent</th>
<th>LCt value (g s/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.00078</td>
</tr>
<tr>
<td>10</td>
<td>0.000012</td>
</tr>
</tbody>
</table>

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c. Error Calculation Procedure

An identical twin setup using the QUIC system is used to make the error computations. First, QUIC is used to calculate a plume with a wind speed of 1 m/s and a “true” wind direction on the upwind side of a non-urban domain (Figure 1). Next, plumes from the same release location are computed with QUIC using winds that emulate direction errors that depart from the “true” wind direction value by, 2° direction increments for 40° counter-clockwise and clockwise of the “true” wind direction. The plume sensitivity to wind direction error at ground level (2m) and a LCT are then determined by fraction of overlap (FOO), figure of merit in space (FMS), measure of effectiveness (MOE), and normalized absolute difference (NAD) (Warner et al., 2003). Subsequently, the “true” wind direction is changed by 5° degrees from 180° through 360° and then once again error winds are computed and their metrics of FOO, MOE, FMS, and NAD are quantified. This is also done for two different source release locations (Figure 2) on a symmetric rectangular urban grid and then on a radial domain. These domains have equal size average buildings blocks addressing the question of whether the urban T&D problem was more sensitive to large-scale wind error than it is to a non-urban problem. This procedure is applied as well, to our case studies for a more realistic look at wind direction induced plume errors in an urban environment.

3. Results and Discussion

The results for this paper focus on wind direction errors due to source location effects and city building configurations of urban canyons. When we speak of urban canyons we refer to when streets act as canyons separating large groups of buildings with the source location located in the center of one of these canyons. Figures 6-10 show each metric for a “true” wind direction of 270° of a non-urban (Figure 6), urban grid (Figure 7), and modern (Figure 8) domain using an LCT10.
Figure 6. The fraction of overlap (FOO), figure of merit in space (FMS), measure of effectiveness (MOE), and normalized absolute difference (NAD) for a Non Urban domain using a LCt10 and a true wind direction 270°.
Figure 7. The fraction of overlap (FOO), figure of merit in space (FMS), measure of effectiveness (MOE), and normalized absolute difference (NAD) for a Urban grid domain using a LCt10 and a true wind direction 270°.
Figure 8. The fraction of overlap (FOO), figure of merit in space (FMS), measure of effectiveness (MOE), and normalized absolute difference (NAD) for a Modern domain using a LCt10 and a true wind direction 270°.

Figure 6 shows the metrics for a non-urban setting where, as expected, there is a gradual degradation of accuracy when the difference between the “true” wind direction and the error wind direction is increased. On the other hand, figures 7 and 8 show the metrics of the urban grid and modern setup which include buildings that channel the transport and dispersion of the plume, consequently, making these setups more tolerant to wind direction induced errors.

Figures 9 and 10 show each metric for a “true” wind direction of 325° of an urban radial (Figure 9), and historic (Figure 10) domain using an LCt10. Figures 9 and 10 show the same effect, less sensitivity to wind direction error compared to a non-urban domain, but using the urban radial and historic setup. However, figures 9 and 10 also show less tolerance to wind direction error than figures 7 and 8, implying that the urban grid and modern domains are more tolerant to wind direction error than the urban radial and historic domains. Then the tolerance to wind direction error is due to the geometry of the of the domain and source location with respect to the building geometry. Hence, the plume errors induced by wind direction errors are significantly dependent on this.
Figure 9. The fraction of overlap (FOO), figure of merit in space (FMS), measure of effectiveness (MOE), and normalized absolute difference (NAD) for a Radial domain using a LCt10 and a true wind direction 325°.
Figure 10. The fraction of overlap (FOO), figure of merit in space (FMS), measure of effectiveness (MOE), and normalized absolute difference (NAD) for a Historic domain using a LCt10 and a true wind direction 325°.

4. Conclusions

We expect that the plume prediction will degrade as the difference in the “true” wind direction and the predicted wind direction increase. However, the urban grid and modern setup showed how the addition of buildings makes these setups more tolerant to wind direction induced errors. The urban radial and historic show the same effect, less sensitivity to wind direction error compared to a non-urban domain. Although, the radial and the historic show tolerance to wind direction error they are not as tolerant as the urban grid and the modern city. Then the tolerance to wind direction error is due to the geometry of the domain and source location with respect to the building geometry. Hence, the plume errors induced by wind direction errors are significantly dependent on this and more so in older cities that have this hub and spoke feature.

REFERENCES

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