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A comparison of contaminant plume statistics from a Gaussian puff and urban CFD model for two large cities

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Abstract

This paper quantitatively assesses the spatial extent of modeled contaminated regions resulting from hypothetical airborne agent releases in major urban areas. We compare statistics from a release at several different sites in Washington DC and Chicago using a Gaussian puff model (SCIPUFF, version 1.3, with urban parameter settings) and a building-resolving computational fluid dynamics (CFD) model (FAST3D-CT). For a neutrally buoyant gas source term with urban meteorology, we compare near-surface dosage values within several kilometers of the release during the first half hour, before the gas is dispersed beyond the critical lethal level. In particular, using "fine-grain" point-wise statistics such as fractional bias, spatial correlations and the percentage of points lying within a factor of two, we find that dosage distributions from the Gaussian puff and CFD model share few features in common. Yet the "coarse-grain" statistic that compares areas contained within a given contour level reveals that the differences between the models are less pronounced. Most significant among these distinctions is the rapid lofting, leading to enhanced vertical mixing, and projection downwind of the contaminant by the interaction of the winds with the urban landscape in the CFD model. This model-to-model discrepancy is partially ameliorated by supplying the puff model with more detailed information about the urban boundary layer that evolves on the CFD grid. While improving the correspondence of the models when using the "coarse-grain" statistic, the additional information does not lead to quite as substantial an overall agreement between the models when the "fine-grain" statistics are compared. The taller, denser and more variable building landscape of Chicago created increased sensitivity to release site and led to greater divergence in FAST3D-CT and SCIPUFF results relative to the flatter, sparser and more uniform urban morphology of Washington DC.

Keywords: Urban dispersion; Urban meteorology; Emergency response; Modeling

1. Introduction

Hosker (1984, 1987) recognized that the mechanical forcing of flow around buildings spawns distinctive features like lee eddies, vortex shedding and "urban canyons". Recent urban field and modeling campaigns in medium size cities (Urban 2000 and Urban 2003) have

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drawn widespread attention to the intricate small-scale circulation patterns that can develop as winds interact with the urban landscape created by buildings and streets (Allwine et al., 2002). However, there is an additional thermodynamic component to urban flows. These flows are deterministic at the scale of the buildings and are intrinsically convective, not diffusive. Underlying the gross heat island effect (Oke, 1984) are small-scale contributions like the formation of vortices in street canyons due to the differential surface heating of the sidewalls (Oke et al., 1991) which also impacts contaminant transport (Kim and Baik, 1999).

The nascent focus on the real-time use of atmospheric transport and dispersion models for national security raises expectations for accurate models applied to big complex metropolitan settings (NRC, 2003). As the demand for high-fidelity models of large urban environments accelerates, computational advances have not kept pace.

For predicting distribution patterns within a city, a building-resolving CFD model is expected to be unparalleled because it explicitly resolves the relevant physics at the scales of motion and thereby requires minimal parametrizations. Applications that would benefit from such a model include emergency medical response in the immediate aftermath of a release and base or specific building protection. Such a capability would allow rescuers to search the most contaminated portions of a city first and enter buildings as soon as possible after contaminant levels have dropped.

Building-resolving CFD models that explicitly represent the physics on the necessary small scales give detailed results but require significant computing resources and extensive simulation times. Consequently, the operational communities rely on rapidly relocatable relatively simple puff models that ingest limited information about the local meteorology and produce contaminant forecasts (OFCM, 1999). These models tend to generate quite symmetric oval-shaped contaminant footprints, and unfortunately are often insensitive to details of the local urban morphology.

With the microscale meteorological and urban communities intently focused on model validation in medium size non-coastal urban areas (Salt Lake City in Urban 2000 and Oklahoma City in Urban 2003), few high-resolution modeling (CFD) efforts have been mounted for major metropolitan areas. Yet much of the US population lives in big cities along the coasts. Hence there is a pressing need to know to what extent we can rely on operational environmental forecast models when making critical decisions in an emergency when large populations are at risk.

The case studies examined here are designed to probe the differences between a CFD and a puff model by employing several statistical measures to ascertain how these models perform when applied to hypothetical releases in two major urban areas, Washington DC and Chicago. The focus is on timescales on the order of 15 min—which is typically the time within which an emergency response to an airborne chemical release can be most effective (Boris et al., 2002). Chicago buildings are taller on average, more variable in height, and more tightly spaced than the buildings in Washington DC. The impact of this contrast in urban morphology on contaminant distribution will be explored here.

In Section 2, we detail the model configuration and source release specifications. We carry out a model-to-model comparison in the subsequent sections. In Sections 3 and 4, fine- and coarse-grain statistical measures are utilized to compare the puff and CFD model dosage patterns. Section 5 contains a discussion of the agent concentration within the boundary layer. The paper concludes in Section 6.

2. Model configuration

We employ an urban CFD model (FAST3D-CT) developed at the Laboratory for Computational Physics and Fluid Dynamics at the Naval Research Laboratory in Washington DC (Patnaik et al., 2003; Boris, 2002). Originally designed for a range of small-scale fluid dynamic flows including complex flow around ships at sea to assist aircraft landings, the model was successfully evaluated against wind tunnel turbulence experiments (Fureby and Grinstein, 2002). The model solves the high Reynolds number Navier–Stokes equations using a time-dependent, three-dimensional monotone integrated large eddy simulation (MILES) formulation (Oran and Boris, 2001; Boris et al., 1992). This approach has been found to be computationally efficient and adds no extra dissipation (Grinstein and Fureby, 2002). In addition, the model incorporates stochastic backscatter and a fourth-order phase accurate flux-corrected transport finite volume algorithm for detailed building and city aerodynamics. The convective nature of turbulent urban flows is represented in the model physics. Solar heating of surfaces is based on "land use" data tables. Buildings and trees cast shadows (depending on the time of day), and building sides and tops heat the environment (even at night) and transfer heat to the air passing by. Buoyancy is included through a consistent potential temperature computation.

FAST3D-CT, being an LES formulation, responds to time-dependent boundary conditions whose spatial and temporal scales attempt to mimic realistic variability. Coupled with low numerical dissipation, the multi-spectral chaotic fluctuations ensure that turbulent kinetic energy levels are maintained downwind.

FAST3D-CT has been shown to give accurate vortex shedding statistics in a validation study of flow around the Washington monument (Boris, 2002) and in detailed