2.4 DOPPLER LIDAR DATA FUSION WITH A 3-DIMENSIONAL WIND FIELD MODEL IN AN URBAN DOMAIN

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1. INTRODUCTION

The U.S. Army Research Laboratory (ARL) has developed a diagnostic 3-dimensional wind field (3DWF) model for fast microscale applications over complex terrain and in urban domains. The model is a high-resolution mass-consistent model with a very efficient multigrid computation method for real time applications. In the past, this type of model has usually been initialized with one or more observed wind profiles or with the profiles from a mesoscale numerical weather prediction model. We propose a new method to initialize the model using the wind observation data from Doppler lidar. This method first retrieves the horizontal wind from the radial wind in the lidar scanning plane. The horizontal wind field is then fused in a mass consistent model using a minimization algorithm. The accuracy of the model prediction in an urban domain is tested using the data collected during JU2003 in Oklahoma City (OKC).

2. DOPPLER LIDAR DATA

The Joint Urban 2003 (JU2003) project, a cooperative undertaking by several U.S. government agencies and universities to study turbulent transport and dispersion in urban atmospheric boundary layers, was conducted in Oklahoma City in June and July of 2003 (Allwine et al. 2004). The Doppler lidars deployed in the JU2003 project are WindTracer® Systems, products of Coherent Technologies, Inc. in Lafayette, Colorado. The systems were designed specifically for atmospheric boundary layer observations and research (Grund et al., 2001). The laser system is operated at a wavelength of 2025nm with 2.5 μJ laser pulse energy. The pulse repetition is 48Hz and the gate range varied from 66 to 71m depending upon the data set. The system measures range-gate resolved backscatter intensity and the Doppler radial velocity. The location of the ARL lidar is shown in Fig. 1a, where the lidar is located at the top of a two story parking garage (Global Position System (GPS) coordinate: N35^{0}28.385',

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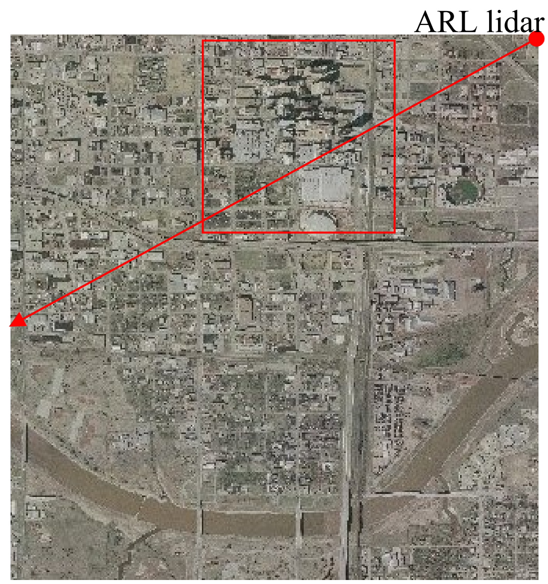


Fig.1 Aerial photography showing the ARL lidar site. The red square is the central business district (CBD) of Oklahoma City. The red arrow line indicates the laser beam.

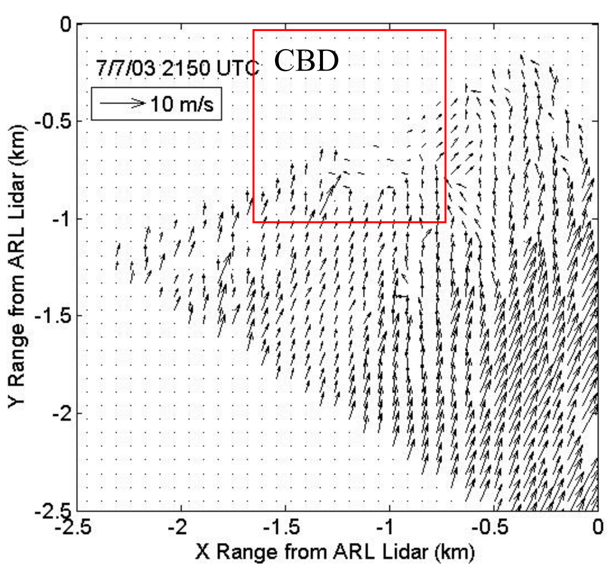


Fig.2 The horizontal wind field (2150 UTC July 7 2003, at Z=20m above ground levlel) retrieved by dual Doppler method using ARL and ASU lidars.

W 97^0 30.266', 380m above sea level). The ASU (Arizona State University) lidar is located south of OKC (GPS coordinate: N35^{0}26.330', W97^{0}29.553', 380m above sea level), outside of the domain shown in Fig. 1. Both systems functioned well during the JU2003, and a large amount of data were collected.

There are 10 IOPs (intensive observation periods), covering different atmospheric conditions from slightly stable (night time), to neutral (transitional time), to afternoon unstable conditions. During the IOPs, the tracer gas SF_6 was released and intensively sampled. The wind field in the city was monitored continuously by many sonic anemometers and two Doppler lidars. The observation results presented here represent a small fraction of the data collected during IOP 3, July 7, of the JU2003. Fig. 1b shows a dual Doppler lidar retrieved horizontal wind field at the height of 20 m. The enclosed area corresponds to the area of the photograph displayed in Fig 1a. For this time period, the wind field displays a large spatial variability with much weaker wind over the urban area. The urban heat island and friction effects play an important role in decreasing the wind speed in the urban area.

At the CBD area, very few data points are available due to the blocking of lidar beams by tall buildings. Because of the large spatial variability of the wind field, a single wind profile from the VAD (Velocity Azimuth Display) is not adequate to initialize the model. Using a VAD profile, as in Wang et al. (2004b), results in the model over-predicting the wind speed for lower levels in the urban area. Since the VAD profile is an average over a large inhomogeneous area, its profile does not characterize the lower level urban profile very well. For a better initialization over an urban domain, a detailed wind retrieval that accounts for the wind field spatial variability is preferred.

3. THE 3DWF MODEL

Modeling the wind field in the urban domain is a very difficult problem since the urban domain is much more complex both dynamically and thermodynamically. Many researchers are using computational fluid dynamics (CFD) methods to simulate the wind field given boundary conditions from observations or from mesoscale numerical prediction results. However, this approach does not produce real-time results due to current limitations of computational power.

To achieve the speed for real time simulation on a PC platform with reasonable accuracy, we have chosen the mass consistent model instead of using the CFD approach. The model is based on the mass conservation principle, which eliminates the divergence in a flow field. Given a limited number of observations or a coarsely modeled wind field over complex terrain, the wind field is physically interpolated in such way that mass conservation is satisfied. Mathematically, the problem is to minimize the functional (Sasaki, 1970; Sherman, 1978)

$$E(u,v,w,\lambda) = \int_V [\ \beta_1^2(u-u^0)^2 + \beta_1^2(v-v^0)^2 + \beta_2^2(w-w^0)^2 + \lambda(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z})\ ]dxdydz$$

where x, y are the horizontal coordinates, z the vertical coordinate, u^0 , v^0 , w^0 the initial observed velocity components, u, v, w the modeled velocity components, λ the Lagrange multiplier, and β_1, β_2 Gauss precision moduli, which are the wind vector partitioning factors in the horizontal and vertical directions respectively. The Euler-Lagrange equation corresponding to the variational equation is a Poisson equation of λ. At the lateral boundaries λ is set equal to zero to allow "flow through". At the bottom of the domain, "no-flow is satisfied by having the normal derivative of λ vanish, i.e. $\partial\lambda/\partial n = 0$. A more detailed description of the model is provided in Wang et al. (2003). A multigrid numerical method was applied to solve the Euler-Lagrange equation. In our comparison test, the multigrid method is about 20 to 30 times faster than the traditional Gauss-Seidel relaxation method. A more detailed numerical implementation of this model using the multigrid method is given in Wang et al. (2004a).

One deficiency of a mass consistent model is that it is unable to simulate the vortices or wakes in the lee of steep topography since momentum conservation is not considered. However, features of this kind can be parameterized or inserted in the initial field according to observational studies (Hunt and Snyder, 1980; Röckle, 1990). We are developing a parameterization scheme to account for the wakes and reversal flow at the lee of the steep topography or building. The effects of vegetation canopies (Cionco 1965) are also parameterized.

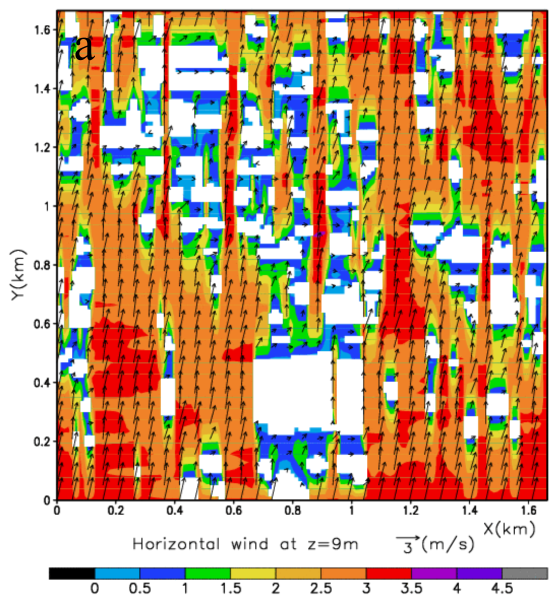
4. DATA FUSION WITH 3DWF

The horizontal wind field can be derived from Doppler lidar observed radial velocities using different retrieval methods. These methods are classified into single Doppler wind retrieval and multiple Doppler wind retrieval method. The single Doppler wind retrieval methods, such as VAD (Browning and Wexler, 1968) and VVP (velocity volume processing, Waldteufel and Corbin, 1979) assume the horizontal wind is homogenous within the retrieval domain. When this condition is satisfied, the retrieved wind profile is highly accurate. Another type of single Doppler wind retrieval, based on the local uniform wind (UW) assumption (Persson and Andersson, 1987; Hagen et al., 2002) gives the average horizontal wind field with reasonable accuracy. But for the situation of a wind field having large spatial variability (Wang et al. 2004c), dual or multiple Doppler lidar retrieved wind fields are desirable. Recently, Calhoun et al. (2004) have used data from two Doppler lidars from JU2003 to retrieve several vertical profiles of horizontal wind, which can be used to initialize wind models.

In many urban environments, tall buildings often block the lidar beams and make the wind retrieval near ground impossible. The in-situ wind observations of sonic or cup anemometers are required. During the JU2003, the ARL had several towers of sonic anemometers located both in urban and suburban areas. The data are used for the lower level wind initialization.

The 3DWF model is used to simulate the wind field in the CBD area. The model domain consists of a 1.6 x 1.6 km area, covering most of the CBD. The resolution is 13m in both the x and y directions, and 3m in the vertical. The model grid number is 129 x 129 x 65. The building locations, shapes, and sizes were obtained from a geographical information system, and interpolated to the model grid, and used for the surface morphology or geometry for the model simulation (Fig.1). The computation for this case takes about 2 minutes CPU time on a dual 2 GHz Pentium 4 linux PC.

The initial winds for this simulation are stitched together from three data sources: the sonic anemometer data at 5m and 10m, the dual Doppler wind retrieved at 20m, and the VAD profile at heights above 40m. The data from 2150 to 2155 UTC July 7 were used. The sonic anemometer winds are the 5 minute average from ARL tower 2 in an urban area and the dual Doppler wind is an average for the wind at the inflow south boundary. Fig.3a displays modeled horizontal wind and Fig.3b shows the vertical wind both at z=9m. The mass consistent model showed that mean southwest wind exhibited clockwise turning when approaching a building having east-west orientation. The wind fields around the buildings are modified a great deal. The horizontal wind on the south and north sides of the buildings show significant slow down “shadows”. The mean wind increased considerably in some narrow north-south street canyons. For the locations without buildings, the horizontal wind retained its initial value. The vertical wind values (Fig. 3b) show the upward and downward distribution as expected. The windward side of the



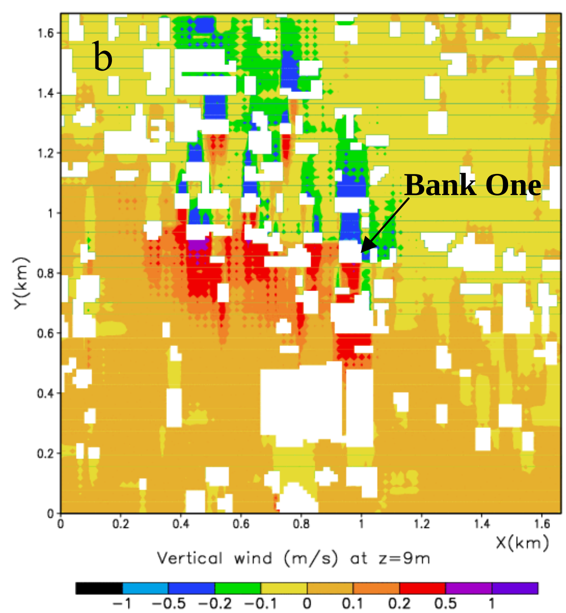


Fig.3 3DWF simulation of the mean wind over CBD of the OKC, (a) horizontal wind at z=9m. (b) vertical wind distribution at z=9m. The white blocks are buildings. The tallest building is the Bank One tower.

buildings had upward motion about 0.2 to 0.5 m/s, while the lee side of buildings had downward wind about 0.2 to 0.5 m/s.

5. SUMMARY

The JU2003 filed campaign has resulted in a rich data set for the wind flow in an urban domain. We have used the dual Doppler lidar wind (dual retrieval for lower level and VAD above the city) and sonic anemometer wind profile as initial input for the 3DWF estimate to simulate the average wind field in the CBD. This type of initialization appears to be better than a single VAD profile in the case of large spatial variation observed over an urban domain. We intend to use the JU2003 data extensively to validate and perhaps enhance the 3DWF model for various wind and stability conditions.

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