EVALUATION OF THE WAKE OF AN AGRICULTURAL GROUND SPRAYER

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ABSTRACT. *A subscale tractor and spray boom model was placed in a wind tunnel to determine the dominant air motions around and downwind of a "typical" ground sprayer. Velocity and turbulence levels (in three directions), generated by the presence of the subscale model, were measured and are presented and interpreted herein. The goal of this effort is to combine these measurements into a database that describes the full-scale wake of a tractor and spray boom combination, and then use the wake model to augment local atmospheric and surface effects to better predict the behavior of material released from nozzles on a spray boom during actual ground sprayer operation.*

Keywords. *AGDISP, Ground sprayer, Subscale model, Tractor wake, Wind tunnel.*

A recent article (Teske et al., 2011) summarized the present state of computer model simulation for pesticide deposition predictions. Development of an applied mechanistic ground sprayer model and model validation appear to be the next achievements needed in pesticide deposition modeling. Such a model was suggested by Teske et al. (2009), based on the same modeling approach used in AGDISP (Teske et al., 2003) for aerial spraying. Comparisons with field data available to these authors demonstrated the potential of this approach.

Separately, an alternative effort has been undertaken for ground sprayer modeling by Butler Ellis and Miller (2010a, 2010b). Their approach involved the use of a computational technique known as random walk, which was initially formulated into a particle-tracking algorithm by Miller and Hadfield (1989) and subsequently implemented by Butler Ellis and Miller in their ground model.

Both modeling approaches would be enhanced by an accurate representation of the sprayer wake, as neither model includes this effect. Currently, AGDISP (Teske et al., 2009) does not have a tractor wake model, only a description of the wind velocity and direction toward the spray boom, and the initial droplet velocity. The random walk model (Butler Ellis and Miller 2010b) incorporates a more complex sprayer wake model than AGDISP but again relies on a description of wind velocity and spray direction, and the initial droplet velocity.

As an initial step toward describing the details of the wake behind a tractor/boom combination, the USDA Forest Service conducted two subscale model tests that simulated the wake effects around a generic John Deere tractor (Petersen and Lawton, 2013; Petersen et al., 2014). The goals of this research effort were to present a more detailed look at the wake generated by a tractor/boom combination, so as to describe the full-scale velocity and turbulence field for modeling purposes. This article summarizes the wind tunnel results and parameterizes the wind and turbulent energy field generated in the wake of this subscale tractor/boom model.

The wake of a tractor/boom combination is complex, with the wake responding to ambient wind effects, the sprayer body, boom geometry, sprayer sheet blockage from the nozzle effluent, tractor thermal exhaust and engine heating, tire motion, and surface effects from the ground and crop. It seems instructive to grasp what details can be obtained from simplified studies, before attempting full-scale field experiments or undertaking extensive computational fluid dynamics simulations. Such an approach is therefore well suited for wind tunnel examination.

One such previous approach can be found in Murphy et al. (2000), where the flow around short sections of two spray booms, fitted with three nozzles each, was studied for two nozzle types in a wind tunnel. The disturbance of the flow field due to the downwash of the spray and the presence of the spray boom is apparent from the measured velocity vectors. This previous work, however, did not include the presence of a tractor body.

APPROACH

The wind tunnel used for the wake mapping is a closed-

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circuit boundary-layer wind tunnel with a 20.7 m long and 3.66 m wide test section, with wind speeds ranging from 1.5 to 13.0 m s^{-1}. Its nominal roof height of 2.13 m can be adjusted so as to zero the streamwise pressure gradient. This wind tunnel is one of three boundary-layer wind tunnels operated by CPP, Inc., in Fort Collins, Colorado, and includes a computer-controlled traverse system that can map velocity (and other flow properties) at any *x-y-z* location to a high degree of precision (±5 mm in the *x* direction, ±1 mm in the *y* direction, and ±0.5 mm in the *z* direction). These wind tunnels have been used to document dispersion, wind loads, and velocity fields in complex flow fields for over 1000 projects since the mid-1980s (Cermak, 1977; Petersen, 1997; Petersen and Cochran, 2008).

The position of the tractor/boom model in the wind tunnel and a view of the model are shown in figure 1. A boundary layer profile generation system, comprising a trip, spires, and a development fetch of about 15.2 m of 5 and 10 cm cuboid roughness elements, was placed upwind of the model (roughness elements were spaced more uniformly near the model, so as to facilitate wake measurements there). The roughness elements generated a subscale surface roughness suggestive of agricultural land. The tractor was mounted on a turntable, but in the results reported here the wind direction was down the centerline of the tractor.

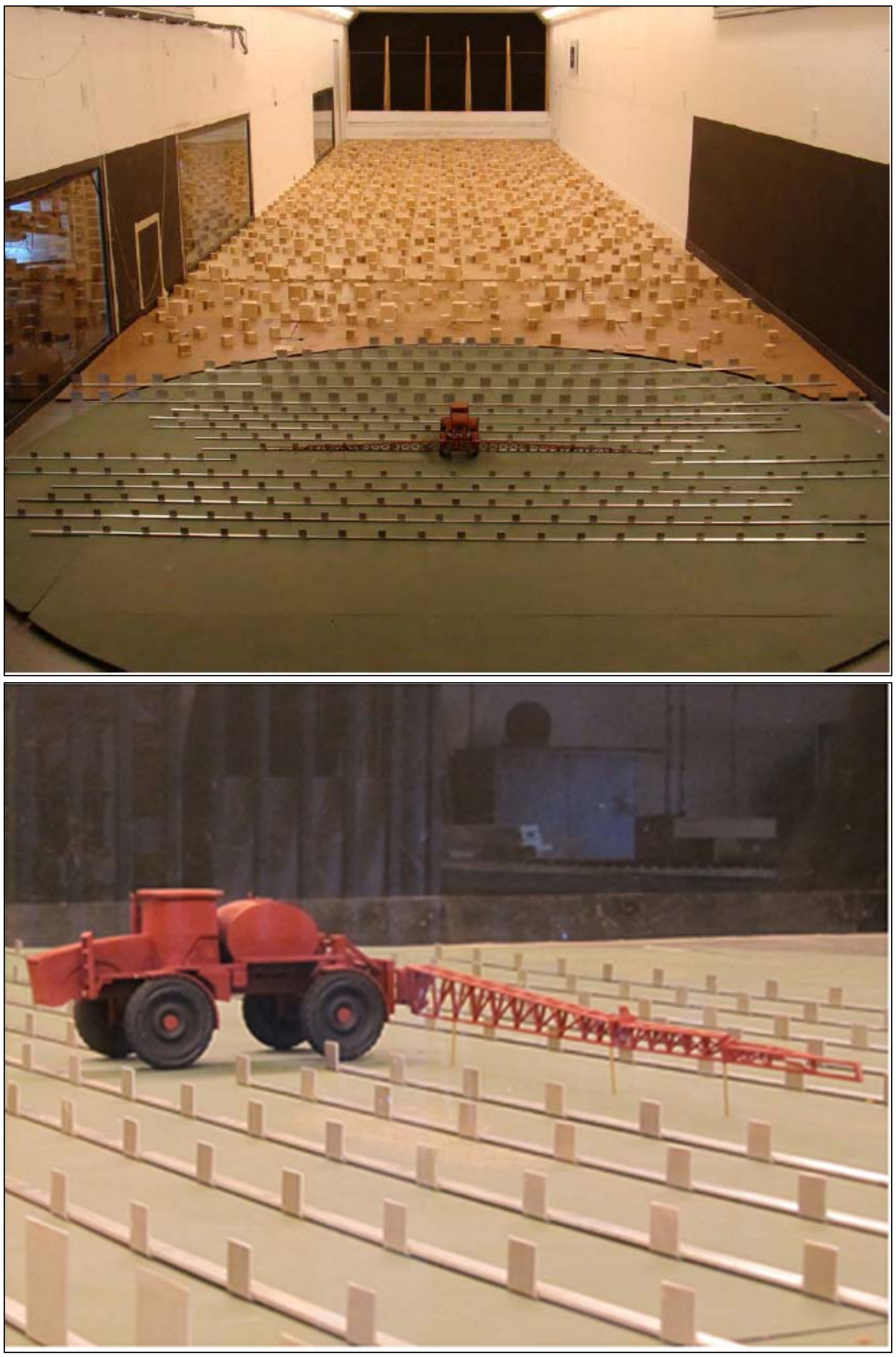

Figure 1. (top) Layout of the tunnel, looking upwind, and (bottom) side view of subscale tractor/boom model.

Measurements were made with an Aeroprobe five-hole probe (Aeroprobe Corp., Christiansburg, Va.), a compact 3 mm diameter pitot-type probe capable of resolving three components of velocity. The probe is comprised of a conical tip in which five holes were drilled; these holes lead to tubes that run through the body of the probe and are connected via flexible tubing to precision pressure transducers. A calibration file and data reduction routine convert the five measured pressures into a three-dimensional velocity vector. In this application, the probe was mounted on a computer-controlled three-axis traverse, which allowed it to be positioned anywhere around the model.

As noted on the Aeroprobe home page, the probe can have an effect on transitional and vortex flows; in addition, care should be taken when measuring thin, naturally developed boundary layers, as acceleration will occur between the probe tip and the surface when the probe is within a few tip diameters of the surface. However, given the size of model, the size of the tunnel relative to the size of the probe, and the inherent turbulence of the boundary layer wind tunnel, probe interference effects were considered minimal.

Data were acquired at a sampling rate of 1 kHz for approximately 60 s per measurement point. This time interval reflected the time needed to achieve acceptably settled values of mean velocity and turbulence intensity (TI). One minute of sampling (with approximately 12 s between data samples) resulted in mean velocity values settled to have a standard error on average of less than 1.5% of their value, the standard deviation of the standard error percentage being less than 0.5%. Maximum standard error was always less than 4.0% of the measured value.

Turbulence intensity is defined as the ratio of the standard deviation of the velocity to a mean value, expressed as a percentage, and is discussed below. Some of the particulars of the tests were the following:

- All tunnel measurements were done at subscale and are reported here at full scale.
- The tractor/boom model was scaled to 1:25. The reference wind speed (U_{ref}), measured at the standard reference height of 1.265 m, was approximately 10.8 m s^{-1}. Before performing full wake traverses, trial runs were performed to ensure Reynolds number independence in the collected data. By taking measurements over a range of tunnel speeds, it was shown that at speeds below U_{ref}, the nature of the tractor wake was a function of speed, while at U_{ref} and above, the nature of the wake no longer varied with speed. Generally, the atmosphere is neutrally stratified, like the wind tunnel, for wind speeds of 6 m s^{-1} or greater. The effect of atmospheric stability on boom wake effects is not simulated here.
- Wind speed data were taken with and without the presence of the tractor/boom model. Missing data away from the model were assumed at their background values for velocity and turbulence level (collected when the tractor/boom model was not in the wind tunnel).
- The model was stationary in the wind tunnel, eliminating any possibility of boom motion (such as the up-and-down effect of a moving sprayer, whose motion is minimized by modern boom stabilizers). The boom articulation linkages were ±42 and ±58 cm from the centerline of the tractor (highlighted in fig. 2). Boom height was maintained by six vertical pins (three on each side of the boom) of 26 mm length (0.65 m full scale) and 2.4 mm diameter, positioned at distances of ±9, ±42, and ±69 cm from the center of the tractor, as seen upon close inspection of the bottom photo in figure 1 and highlighted in figure 2. The pins do not appear to affect the wake. Note that a stationary tractor means that tunnel speed is the relative speed for a tractor traveling into the wind.
- The subscale boom length was 1.45 m. Thus, the full-scale boom length would be 36.25 m, near the average length of typical spray booms (lengths between 25 and 45 m) operating in the U.S.
- The coordinate system was (*X*, *Y*, *Z*), with *X* and *Y* centered on the center of the spray boom and *Z* measured vertically from the surface. *X* was pointed in the downwind direction, parallel to the tunnel walls (with velocity *U*), *Y* was pointed to the right side of the tunnel walls (from the position of the tractor driver, with velocity *V*), and *Z* was pointed vertically toward the tunnel ceiling (with velocity *W*). As defined, the coordinate system is identical to the system assumed in AGDISP, thus simplifying model building and comparison.
- Tunnel measurements were recorded in Excel spreadsheets for the three wind speeds and the three turbulence intensities. Wind speeds are normalized by the reference wind speed U_{ref}, while the turbulence intensities are given in percentages, based on the local *U* velocity.
- Petersen et al. (2014) included data when the tractor/boom model was positioned 45° to the wind and perpendicular to the wind, blowing along the spray boom. These data will be evaluated in a later publication.

Turbulence Intensity

Turbulence intensities are multiplied by 100 to give the following ratios:

$$I_X = \frac{u'}{\overline{U}}, I_Y = \frac{v'}{\overline{U}}, I_Z = \frac{w'}{\overline{U}} \quad (1)$$

where u', v', and w' are the turbulence fluctuations in the *X*, *Y*, and *Z* directions, respectively, and $\overline{U}$ is a mean velocity. By definition:

$$U = \overline{U} + u', V = \overline{V} + v', W = \overline{W} + w' \quad (2)$$

where *U*, *V*, and *W* are the flow velocities fluctuating about their mean values $\overline{U}$, $\overline{V}$, and $\overline{W}$, respectively.

Equation 2 can be rewritten in u', v', and w', squared, and then averaged in time to give:

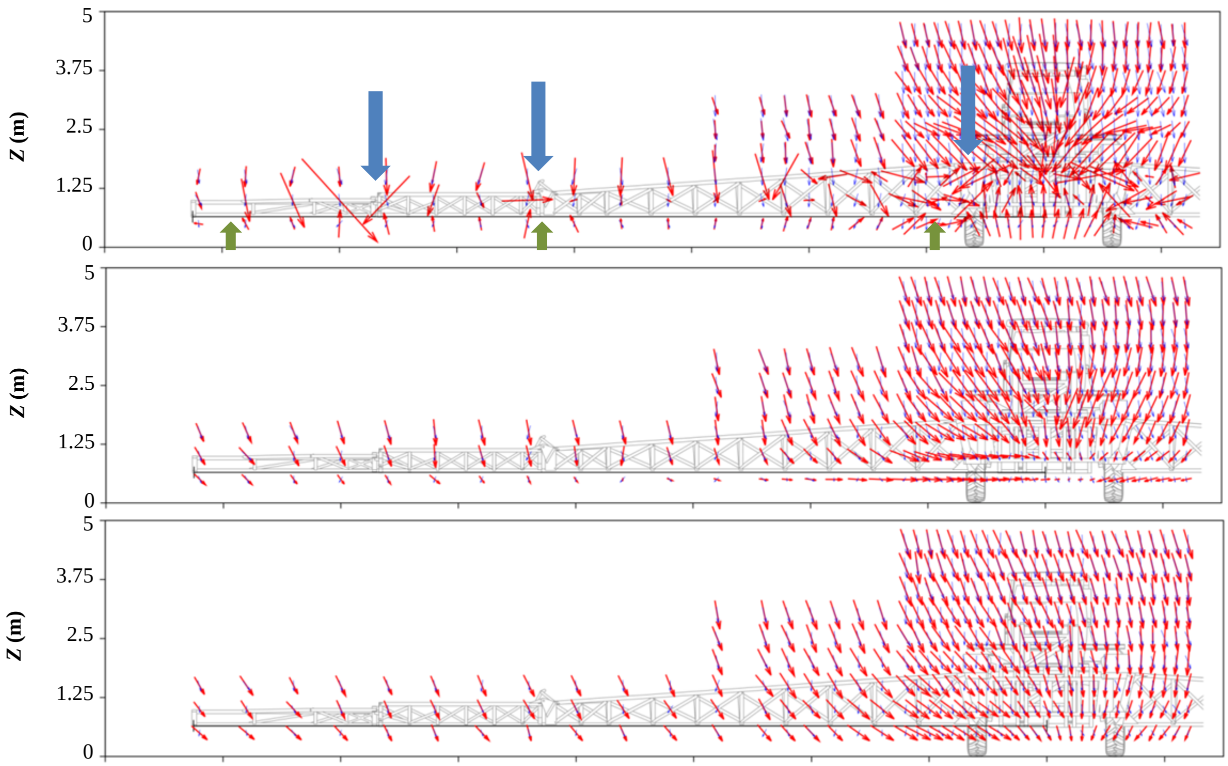

Figure 2. Secondary flow field behind the left side of the tractor/boom model (Petersen et al., 2014) for X = 0.9 m (top), X = 5 m (middle), and X = 11.9 m (bottom) full scale downstream of the model. In the top plot, the boom articulation linkages are identified by the large blue arrows (pointing downward), and the boom support locations are identified by the small green arrows (pointing upward).

$$\overline{u'u'} = \frac{1}{T}\int_0^T \left(U - \overline{U}\right)^2 dt$$
$$\overline{v'v'} = \frac{1}{T}\int_0^T \left(V - \overline{V}\right)^2 dt \qquad (3)$$
$$\overline{w'w'} = \frac{1}{T}\int_0^T \left(W - \overline{W}\right)^2 dt$$

for the time interval T. In AGDISP, twice the turbulence kinetic energy is defined as q^2, so that:

$$q^2 = \overline{u'u'} + \overline{v'v'} + \overline{w'w'} \qquad (4)$$

by adding together the three component contributions. The turbulence level q^2 influences the growth of the cloud of droplets released from each spray nozzle. Thus, the turbulence level data provided from the tests can be reinterpreted as:

$$\frac{q^2}{U_{ref}^2} = \left(I_X{}^2 + I_Y{}^2 + I_Z{}^2\right)\left(\frac{\overline{U}}{U_{ref}}\right)^2 \qquad (5)$$

Results

Petersen and Lawton (2013) collected scoping data on the tractor/boom model, followed by a more extensive data collection by Petersen et al. (2014). The contents of these two references form the basis for the results shown here.

The data included the three coordinates of the data collection points, in (X, Y, Z), the three velocity components (normalized by U_{ref} = 10.8 m s^{-1}), in U/U_{ref}, V/U_{ref}, and W/U_{ref}, the three turbulence intensities (normalized by the local value of $\overline{U}$ and presented as percentages), as a function of wind direction (azimuth) and sprayer boom height. Petersen et al. (2014) collected data for three wind directions, but only the azimuth = 0° (parallel to the centerline of the tractor) will be discussed here.

The first step in data reduction was to examine the data collected without the tractor/boom model present in the wind tunnel (identified as "tunnel background" in the datasets). A total of 900 velocity measurements were made at three X locations (0.9, 5, and 11.9 m full scale downwind of the assumed boom location at X = 0 m), at multiple Y locations (between -18 and 3 m full scale across the tunnel with centerline at Y = 0 m), and at nine Z locations (vertical from the surface between 0.5 and 4.5 m full scale). The average values of the measurements are shown in the last line in table 1. The behavior of the background vertical velocity (W) is ascribed to the structure of the roughness elements around and behind the tractor/boom model, enabling velocity and turbulence measurements close and low to the model. The left-to-right crosswind velocity (V) is small.

Fitting the data to a logarithmic profile, such that $\overline{U}/U_{ref}$ = 1 at $Z = Z_{ref}$ gives:

$$\frac{\overline{U}}{U_{ref}} = \frac{U_0}{U_{ref}}\ln\left(\frac{Z}{z_0}\right) \qquad (6)$$

Table 1. Average values of the three velocity components and turbulence level, with averages of the averages in the bottom row.

Z (m full scale)	U/U_{ref}	V/U_{ref}	W/U_{ref}	q^2/U_{ref}^2
0.5	0.5166	0.0013	-0.0146	0.0415
1.0	0.5590	0.0019	-0.0214	0.0453
1.5	0.5896	0.0032	-0.0285	0.0483
2.0	0.6217	0.0043	-0.0340	0.0515
2.5	0.6495	0.0055	-0.0379	0.0526
3.0	0.6774	0.0052	-0.0400	0.0534
3.5	0.7049	0.0065	-0.0425	0.0538
4.0	0.7298	0.0063	-0.0438	0.0527
4.5	0.7508	0.0057	-0.0447	0.0520
Averages	0.6530	0.0044	-0.0342	0.0501

where $U_0/U_{ref} = 0.129$, and $z_0 = 0.0138$ m ($R^2 = 0.91$).

Flow results from the wind tunnel are shown in figure 2. The tractor/boom combination clearly stirs the velocity patterns within and near the tractor wake. This figure demonstrates the variation from background conditions that could be expected for the velocity profiles in the tractor/boom wake. These results represent one of the first mappings of this wake and its potential downwind influence on subsequent ground boom spraying.

The wake fills in with distance behind the tractor body. This effect may be most easily seen in figure 3, where the measured centerline value of the U velocity is plotted as a function of height for three distances behind the tractor/boom model.

Comparable plots to those shown in figure 2, tracing the velocity and turbulence across the wake, are shown in figures 4 to 6. The following observations may be made:

- The region behind the tractor appears more chaotic, as expected (fig. 4).
- Standing crops (not represented in the tunnel) may further obstruct the flow beneath the tractor (shown in fig. 3 at $X = 0.9$ m).
- The average headwind over the tractor/boom model was 7.1 m s^{-1} (integrating eq. 6 between 0.5 and 4.5 m, and averaging). Operational tractor speeds may reach 8.8 m s^{-1} in the U.S. and 17.8 m s^{-1} in Australia. As noted previously, the tunnel speed was needed to ensure turbulent flow over the tractor/boom model.
- The wake directly behind the tractor/boom begins to settle out by 5 m downwind (fig. 5); V, W, and q^2 all transition relatively quickly from their tractor/boom wake values toward their background values. The U velocity (fig. 3) is returning to background values even though the length of the wind tunnel prevented measurements farther downwind.

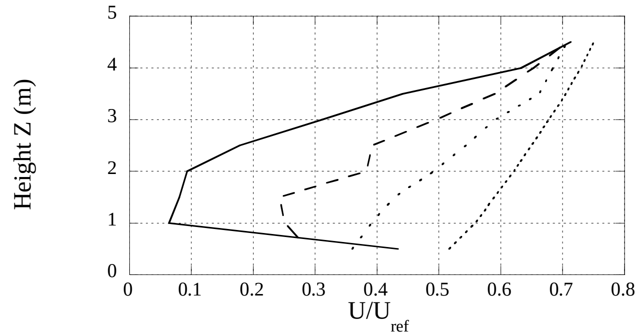

Figure 3. Behavior of the centerline U/U_{ref} velocity as a function of height and distance downwind of the tractor/boom model with the boom at a height of $Z = 0.65$ m full scale. The curves reflect the profile at $X = 0.9$ m (solid curve), 5 m (long-dashed curve), and 11.9 m (short-dashed curve), along with the background wind speed (dotted curve).

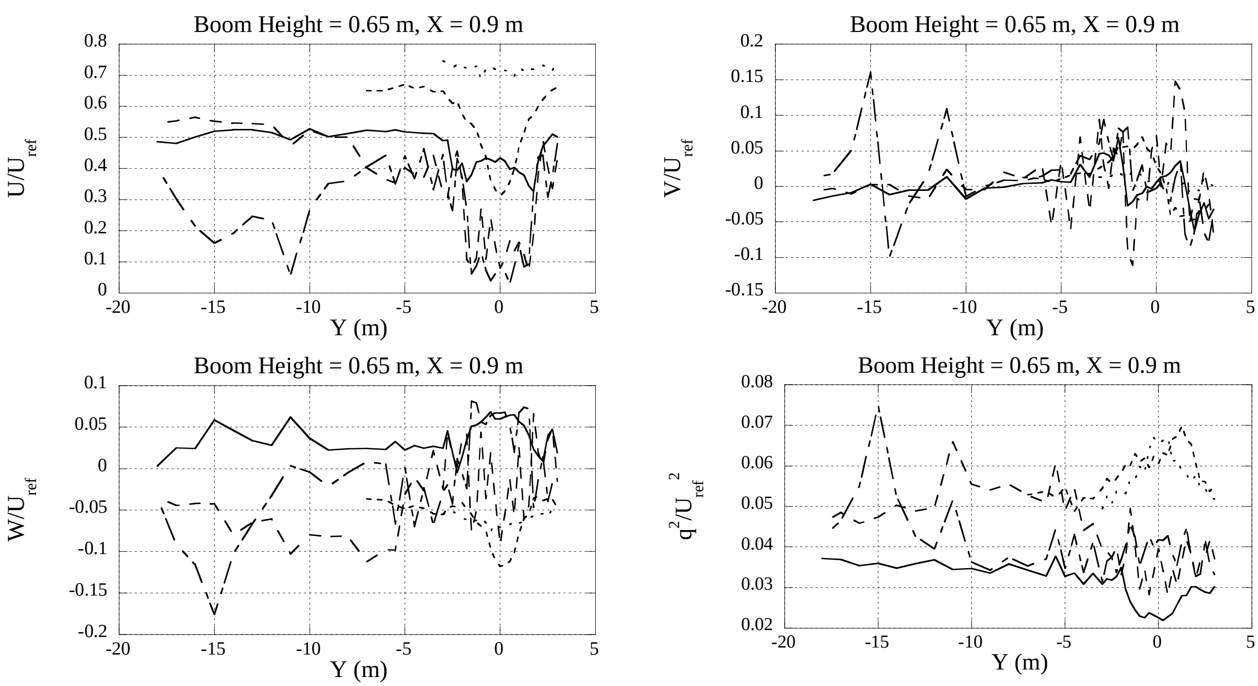

Figure 4. Velocities U/U_{ref}, V/U_{ref}, and W/U_{ref} and turbulence level q^2/U_{ref}^2 at a distance of $X = 0.9$ m behind the tractor/boom model with a boom height of 0.65 m. The traces are for heights $Z = 0.5$ m (solid curves), 1 m (dashed-dotted curves), 1.5 m (dashed curves), 3 m (small dashed curves), and 4.5 m (dotted curves). The tractor/boom centerline is at $Y = 0$ m, and only the left side of the model was probed to the end of the boom.

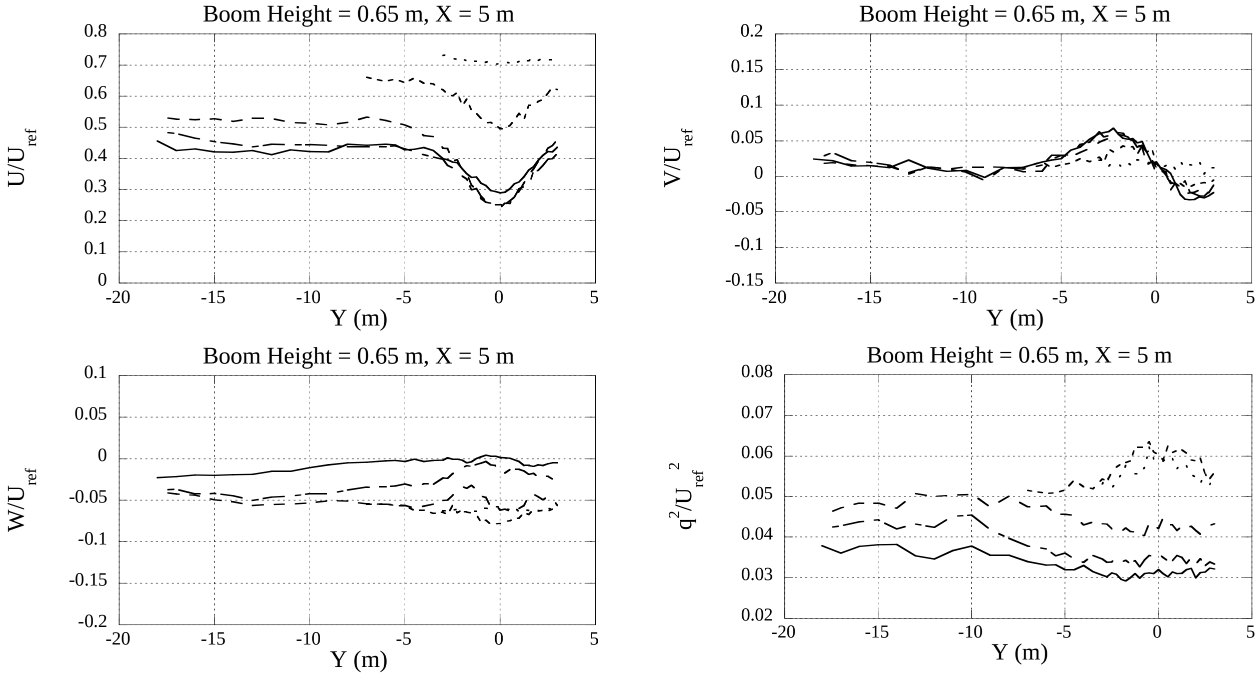

Figure 5. Velocities U/U_{ref}, V/U_{ref}, and W/U_{ref} and turbulence level q^2/U_{ref}^2 at a distance of X = 5 m behind the tractor/boom model with a boom height of 0.65 m. The traces are for heights Z = 0.5 m (solid curves), 1 m (dashed-dotted curves), 1.5 m (dashed curves), 3 m (small dashed curves), and 4.5 m (dotted curves). The tractor centerline is at Y = 0 m, and only the left side of the model was probed to the end of the boom.

- Significant data spikes are seen in figure 4 at the positions of the outboard boom articulation linkages. From this figure as well, it appears that the fine structure of the model boom wake is captured (X = 0.9 m).
- The wake continues to fill in by X = 11.9 m (fig. 6).

Discussion

The velocity and turbulence profiles shown in figures 4 to 6 downwind of the subscale tractor/boom configuration can be used to represent a typical full-scale tractor/boom combination within an applied model such as AGDISP. The subroutines developed here to test the use of these data will be inserted into the ground sprayer model to act as the

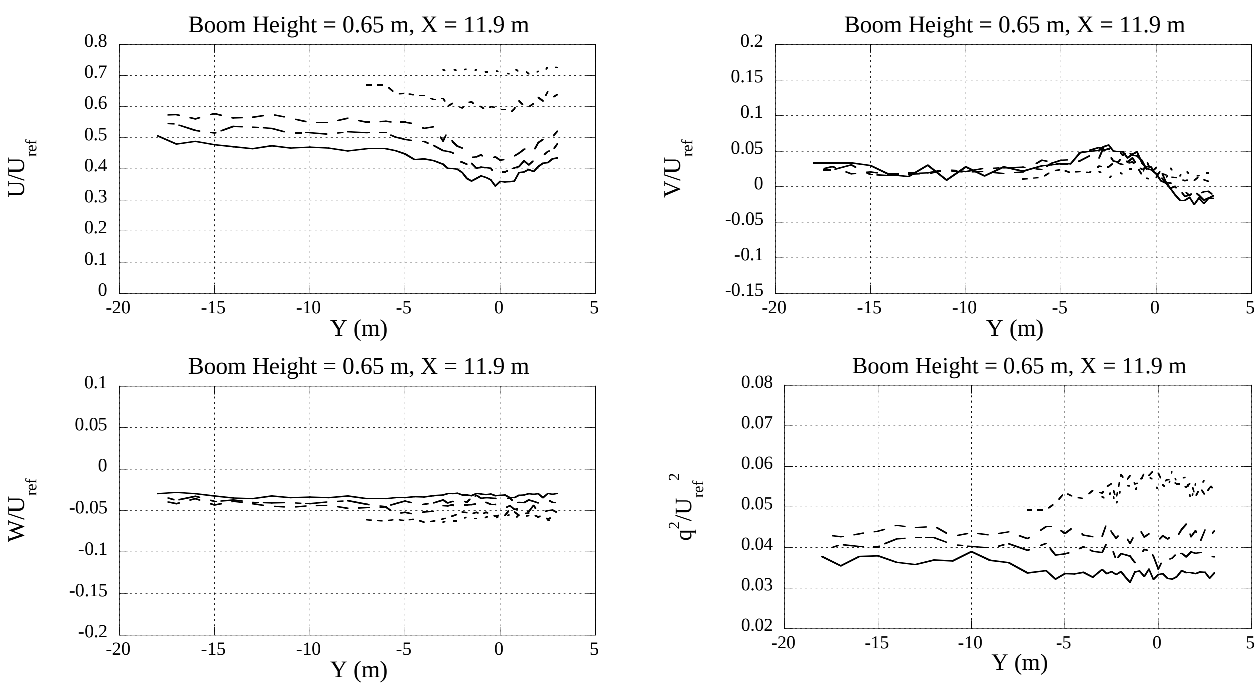

Figure 6. Velocities U/U_{ref}, V/U_{ref}, and W/U_{ref} and turbulence level q^2/U_{ref}^2 at a distance of X = 11.9 m behind the tractor/boom model with a boom height of 0.65 m. The traces are for heights Z = 0.5 m (solid curves), 1 m (dashed-dotted curves), 1.5 m (dashed curves), 3 m (small dashed curves), and 4.5 m (dotted curves). The tractor centerline is at Y = 0 m, and only the left side of the model was probed to the end of the boom.

flow fields through which ground sprayer droplet release can be tracked.

As an example, the model prediction summarized below releases 20 μm particles from a height of 0.5 m along and below the spray boom (after accounting for the presence of spray nozzles). The flow field measured at the height of the spray boom is used throughout, in addition to linear interpolation between *X* distances downwind. The calculation continues until all of the released particles reach the surface.

The results shown in figure 7 illustrate the effects of the tractor/boom wake on the particles. In particular, it can be seen that the vertical velocity *W* (shown in fig. 4) is positive across the spray boom at *X* = 0.9 m, keeping the particles aloft, especially around the articulation linkages (at -14.5 and -10.5 m) and the tractor centerline, which appears responsible for the longer downwind distances that particles near these locations travel before reaching the surface. Particles near the tractor centerline are also held aloft downwind by the near-zero (and slightly positive) *W* velocity at *X* = 5 m (fig. 5). The sharp decrease in downwind distance for the particles released at -2.5 m can be explained by the near-zero value of *W* at this location at *X* = 0.9 m, while particles at either side (at -3 and -2 m) are subject to positive *W* values.

The time needed to reach the surface (also shown in fig. 7) supports the prediction of additional time spent aloft by the particles, which, along with the crosswind velocity *V* (shown in figs. 4 to 6) moving the particles left to right behind the tractor/boom model, suggests that the tractor/boom wake could increase airborne particle drift (especially for smaller particles), as shown previously in field studies conducted by Nuyttens et al. (2007).

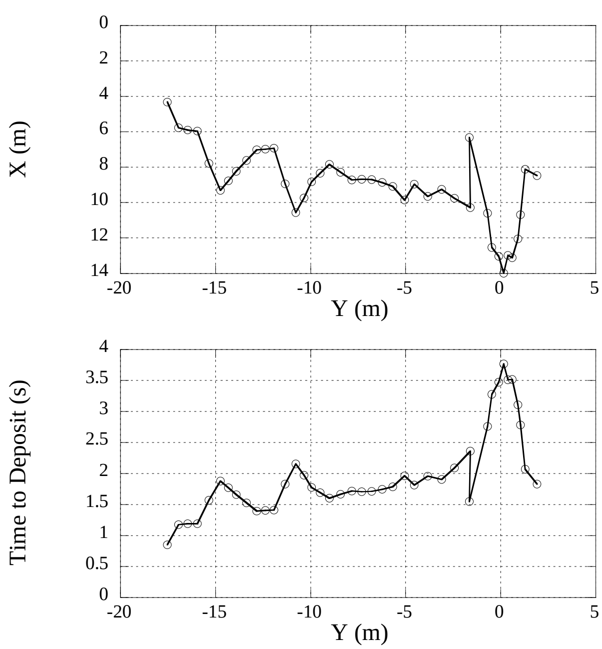

Figure 7. (top) Ground deposition pattern downwind from a single uniform release of 20 μm particles in the *Y* direction at a height of 0.5 m into the velocity field measured in figures 4 to 6 at a height of 0.65 m, and (bottom) time from particle release to ground deposition. Particle locations are identified by open circles.

CONCLUSIONS AND RECOMMENDATIONS

This article examines wind tunnel test data generated over a subscale (1:25) tractor and spray boom model. The generic model permits the measurement of wind speeds and turbulence fluctuations near and behind the model, recovering the local wind field that provides the ambient background setting into which spray material may be released from the boom. As such, these subscale tests can be used to represent tractor/boom wake features that have to this point been neglected in existing ground sprayer models. The wind tunnel tests demonstrate the usefulness and practicality of data collected in this manner. Further data collection should consider the following changes:

- To complete the data collection for wind directions other than a headwind, the tractor azimuth to the wind should be 22.5°, 45°, 67.5°, and 90°, with the data recorded in planes parallel to the spray boom.
- *X* data slices were taken at 0.9, 5, and 11.9 m. Because the wake flow field changes so much between the first two data slices, additional slices at *X* distances of 1.8, 2.5, and 3.75 m full scale should be taken.
- The last *X* distance examined was 11.9 m full scale. Additional *X* distances farther back from the spray boom would be desirable to quantify the continued filling in of the wake behind the tractor/boom model (such distances may not be possible in the wind tunnel). An *X* location closer to the boom than 0.9 m would be beneficial as well.
- While mapping of the tractor/boom wake above the boom is certainly instructional, it is more important to capture the wake effects between the surface and up to twice the height of the spray boom, since that is where the spray material will be released and tracked. It can be seen in figures 4 and 5 that the wake structure behind the tractor/boom has smoothed rapidly between *X* = 0.9 m and 5 m full scale.
- A follow-on effort, similar to that discussed by Murphy et al. (2000), mapped the behavior of spray from a set of full-scale spray nozzles; this work will be described in a subsequent publication.

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