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INFLUENCE OF AIRCRAFT VORTICES ON SPRAY CLOUD BEHAVIOR

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ABSTRACT. For small droplet spraying, the spray cloud is initially entrained into the wingtip vortices so that the ultimate fate of the spray is controlled by the motion of these vortices. In close to 100 aerial sprays, the emitted spray cloud has been mapped using a scanning laser system that displays diffusion and transport of the spray cloud. Results detailing the concentrations within the spray cloud in space and time are given for sprays in parallel and crosswinds. Wind direction is seen to potentially alter the vortex motion and hence the fate of the spray cloud. In crosswind spraying, the vortex behavior associated with the 2 wings is found to differ, which leads to enhanced deposition from the upwind wing and enhanced drift from the downwind wing.

INTRODUCTION

The application of larvicides and adulticides by aircraft has been an effective mechanism for mosquito control. However, the benefits of spraying are accompanied by the difficulty in targeting small droplets and by the potential environmental impact of applying any chemical into the environment in quantities that may be toxic to nontarget species. The success of spraying is driven by timing of the application and in particular by the applicator, who ultimately is responsible for placing the pesticide into the target area. Typically, aerial spraying for mosquitoes incorporates an emission droplet size distribution with a volume median diameter ($D_{v0.5}$) below 100 µm. Given the slow settling velocities of these droplets, their initial motion is controlled by the wingtip vortices of the spray aircraft (Drummond 1987). Such small droplets have the disadvantage, however, that if they do not impact the target in a short time, they are highly susceptible to drift (Picot et al. 1986, Crabbe and McCooeye 1989, Akesson et al. 1992, Crabbe et al. 1994).

In order to diagnose the aerodynamics of the application technique, the Atmospheric Environment Service (AES) of Environment Canada undertook the construction of a lidar system (Hoff et al. 1989, Mickle 1994) that was capable of monitoring the spray drift cloud in real time. The lidar system measures the intensity of the returned laser pulse as a function of time (range) thereby mapping the cloud density cross section as it moves away from the aircraft flight line. From cross-sectional lidar profiles, it is possible to visualize the spray cloud application and, given the initial spray droplet size distribution and a model for subsequent evaporation of the droplets (Dumbauld et al. 1980, Picot et al. 1981, Mickle 1987, Teske et al. 1993), estimates of the deposit and drift fractions can be calculated.

EXPERIMENTAL METHODS

The ARAL (AES Rapid Acquisition Lidar) has been used in 2 experiments to map close to 100 different spray scenarios in a variety of meteorological conditions (stable and unstable) encompassing light to high winds at cross and parallel angles to the flight line. Aircraft used in these studies have included a Cessna 188, TBM (Hoff et al. 1989, Mickle 1994), and a Bell 206B Jetranger. Atomizers have included 11010 T-jets and wind-driven and high (14,000)-rpm electrically driven Micronair AU4000 rotary atomizers. Simulants with physical properties similar to forestry insecticide formulations were used to produce representative emission droplet size distributions. A computer-generated graphics presentation of examples from both experiments can be obtained from the author.

The ARAL cloud mapper comprises a small Nd-Yag laser pulsing at 10 Hz and receiving optics to capture the returning signal. Under the control of a laptop computer, the laser beam is scanned through the spray cloud every 4 sec with a sweep taking slightly more than 2 sec. The time of flight of each laser pulse backscattered from the droplets in the spray cloud gives the range of the cloud from the ARAL, whereas the intensity of the returning pulse is a measure of the droplet density within the reflecting volume of the cloud. Laser beam and receiving optics divergences permit volume sampling of 1 m^3 of the cloud at distances of 1 km from the ARAL system. The system is, therefore, capable of clearly defining the spray cloud distribution within the wingtip vortices.

Within the vortices (Fig. 1A), the cloud density, as seen from a single laser pulse, was found to have 2 maxima of concentration, each associated with a center of the vortex pair. This distribution characterized the vast majority of the operational atomizer configurations for ULV

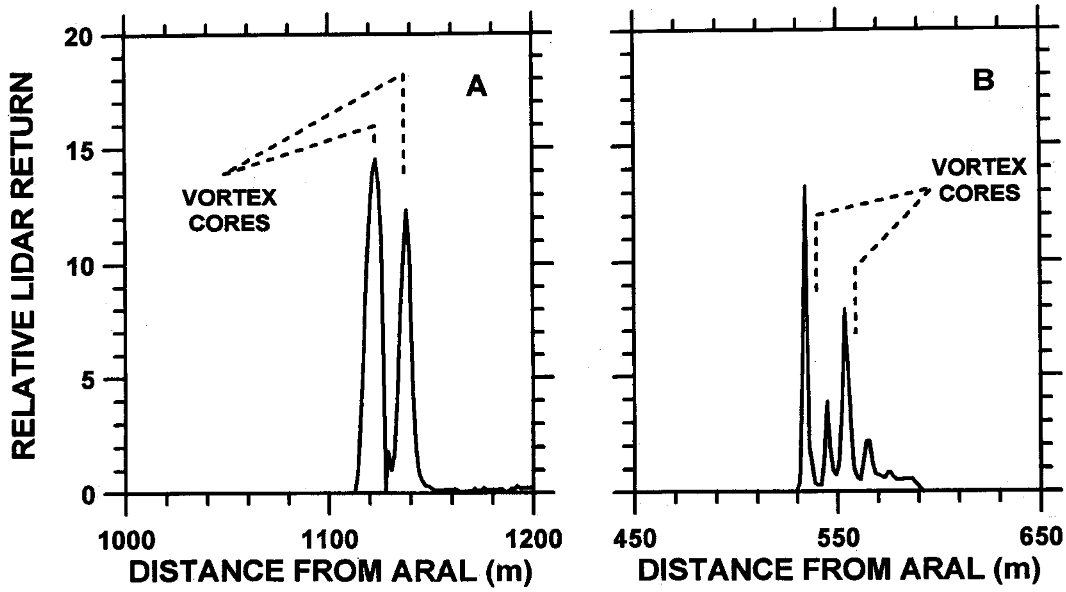

Fig. 1. Backscatter return from a single lidar pulse. A. TBM with 10 wind-driven AU4000 at 10,000 rpm. B. Bell 206B with 2 electrically driven AU4000 at 14,000 rpm.

spraying regardless of atomizer configuration or type. The example in Fig. 1A is for a TBM configured with 5 AU4000 atomizers mounted approximately 1 m below mid-chord of each wing. The outermost atomizer was located at 56% of the wing span. Despite the low mounting below the wing, clearly the material has been moved spanwise towards the vortex core as the vortices were formed. No atomizers were mounted at the position of the vortex cores. The minimum between the peaks is associated with the lack of atomizers below the center of the aircraft. It is interesting that the shape of the droplet density within the cloud is characteristic of the expected deposit profile if an aircraft was flying close to the ground. The only exception (Fig. 1B) to this general shape was observed for a specialized mounting of 2 AU4000 atomizers near the center of a pallet slung approximately 3 m below a Bell 206B Jetranger. In this case, the spray from each atomizer formed an annulus around the vortex center at a distance characteristic of its lateral position from the aircraft center line. Although material was found towards the center of the vortex, clearly the contribution to spray within the vortex core from atomizers at these in-board locations is limited compared to the more outboard locations as shown in the previous example.

CASE STUDIES

Of the many flights that have been mapped, the following 2 examples tend to characterize the differences between spraying in parallel and crosswinds. Selected cross sections of the spray cloud for parallel and crosswind cases are compared in Fig. 2 for various times after the aircraft had passed a vertical plane swept by the laser beam. In both cases, the aircraft is flying away from the observer (i.e., into the page) at a distance of 1–2 km from the ARAL located on the port side of the aircraft. Areas of equal droplet density (concentration) are mapped with colors ranging from black (high concentration) to light gray (less than 0.5% of the high concentration). A more detailed analysis of this case can be found in Mickle (1994). Figure 3 presents the time-integrated concentration (dosage) for these 2 spray cases at different heights and distances relative to the flight line. Figure 4 presents the breathing height concentration of the spray with time, and Fig. 5 gives the accumulated deposit from the loss of material in the surface layer.

Crosswind spray: In this example, a TBM with 5 Micronair AU4000 rotary atomizers (flow rate = 2 liters/min/head; $D_{v0.5}$ = 40–50 μm) mounted under each wing was flown at a height of 25 m above a clear-cut area. Winds at aircraft height were light (1.8 m/sec) at 70° to the flight line. Temperatures during this early morning stable spray run (0650 h AST) were near 9°C with relative humidity near 90%. Within 9 sec after aircraft passage, the ULV spray had been swept into the wingtip vortices (Fig. 2A) with the highest concentration (black) found at the vortex centers. Within these 9 sec, the

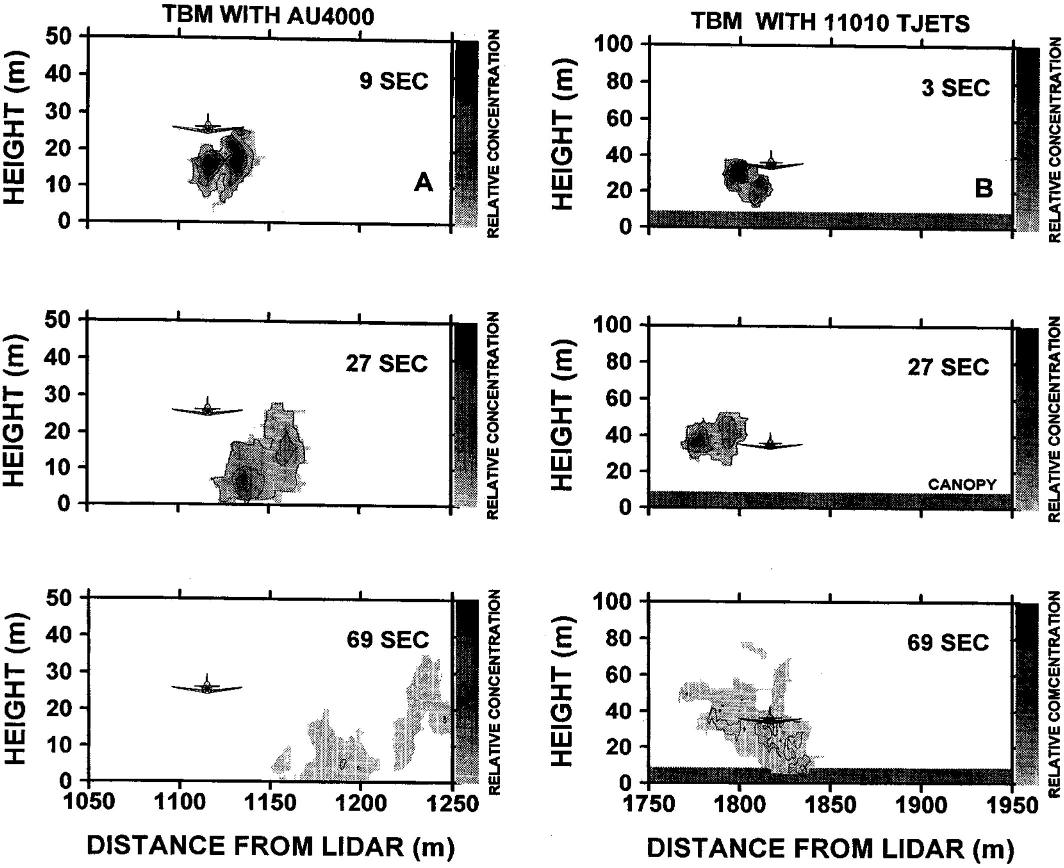

Fig. 2. Spray cloud concentration cross sections. A. Crosswind spray. B. Parallel wind spray. Contours represent a 2-fold change in concentration.

spray cloud had descended nearly 10 m, which is characteristic of the vortex descent rate for the TBM. Over the next 20–30 sec, the upwind vortex maintained its shape, carrying the spray from the port wing as it impacted the ground approximately 25 sec after release and 20–30 m downwind from the flight line. In this particular case, the starboard vortex diffused quickly so that at 27 sec, its vertical motion had arrested, leaving the spray from the starboard wing drifting away from the flight line. The early erosion of the starboard vortex was probably due to combined effects of prop wash and crosswind shear. The net effect of this early vortex destruction was to leave the spray from the downwind wing airborne to be transported away from the flight line as a drifting cloud with concentrations diluted to 20–40% of the maximum concentration. The potential for a high drift fraction during stable conditions has been observed elsewhere during forestry trials to relate atmospheric stability to wind drift (Crabbe and McCooeye 1989, Crabbe et al. 1994). By 69 sec, the cloud continued to drift downwind, stretching longitudinally due to wind shear and with a vertical extent comparable to the aircraft height. Concentrations within the cloud were typically less than 10% of the maximum concentration at 9 sec. Whereas the spray from the upwind wing quickly impacted the surface, spray from the downwind wing tended to remain airborne longer as it diffused. The total dosage cross section (Fig. 3A) clearly shows the bulk of the spray cloud impacting the surface at 1,150 m, the location of the peak deposit (Fig. 5A). Beyond the location of initial descent of the vortices (i.e., 1,150 m), the remaining cloud begins to diffuse vertically above the height of the aircraft. The observed downwind distance of drift is limited by the 2-min tracking duration. The concentration of the spray at breathing height (2 m) (Fig. 4A) shows that the maximum concentration occurred 25–30 sec after the aircraft had passed and was associated with the vortex from the port wing impacting the ground. Breathing-height concentrations in the remainder of the spray cloud decreased as the

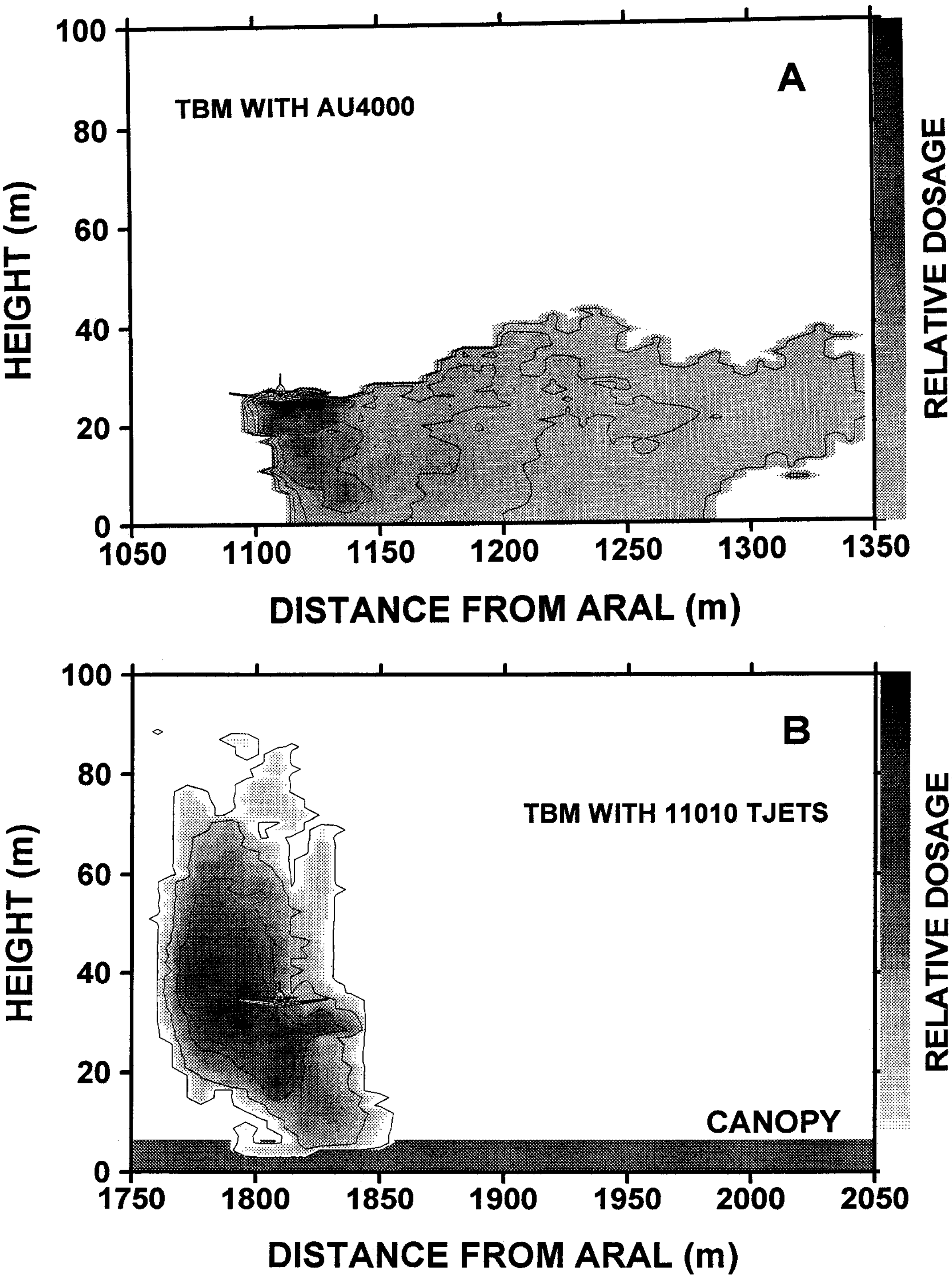

Fig. 3. Total dosage cross sections. A. Crosswind spray. Contours represent a 2-fold change in dosage. B. Parallel wind spray. Contours represent a 5-fold change in dosage.

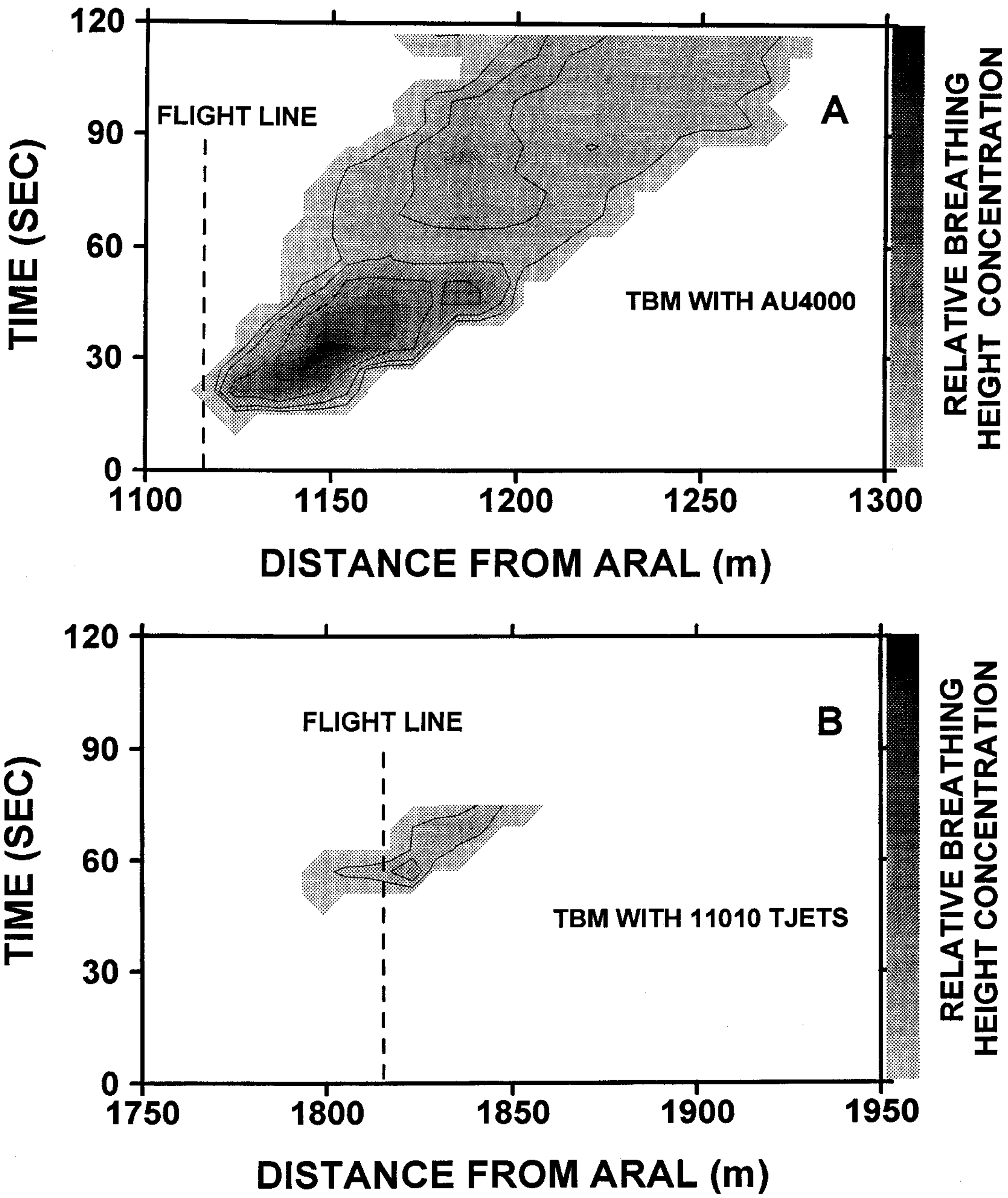

Fig. 4. Temporal and spatial variation in breathing-height concentrations. A. Crosswind spray. B. Parallel wind spray. Contours represent a 2-fold change in concentration.

cloud diffused further downwind. Beyond 60 sec, the concentration is uniform within the surface layer with a secondary concentration maximum (gray) lingering near 1,200 m. The result of this is reflected in a small secondary maximum in the total deposit profile (Fig. 5A) at 1,200 m. A calculation of the rate of deposit from Fig. 4A indicates a nearly constant deposit with time beyond 60 sec at a rate that is 40% of the deposit rate associated with the upwind vortex.

Breathing-height concentrations close to the spray line have been plotted as a function of time in Fig. 6. At 35 m downwind of the spray

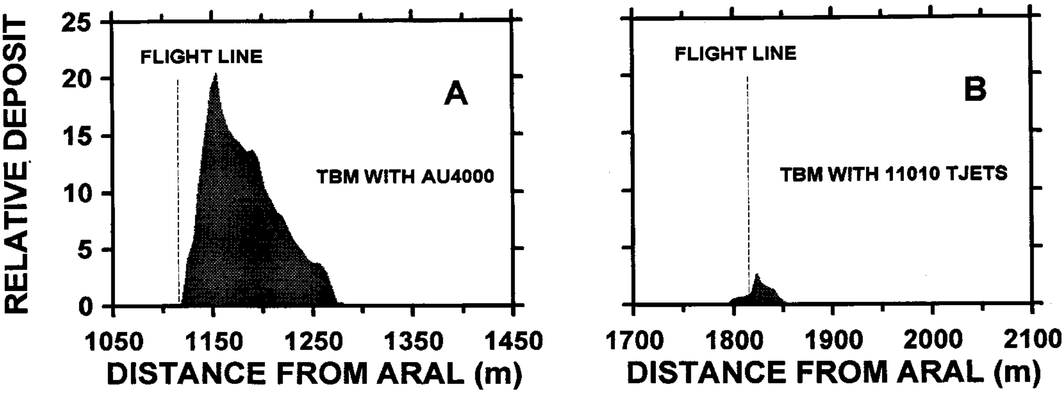

Fig. 5. Total deposit. A. Crosswind spray. B. Parallel wind spray.

line (i.e., 1,150 m from the ARAL), air concentrations peak 27 sec after the aircraft has passed. This maximum in concentration is associated with the spray entrained in the upwind vortex with the material in the downwind vortex having passed overhead. Concentrations decrease over the subsequent 40 sec as the spray cloud translates further downwind. At the 85-m (i.e., 1,200 m from the ARAL) station, peak concentrations are about one-third of those at the closer site. With lateral diffusion of the cloud, the lifetime of the cloud at this location is in excess of 80 sec.

Similar results were presented in Crabbe et al. (1984) and are reproduced in Fig. 7. These data were taken using chemical sequential samplers placed at 3 downwind locations from a single spray line. The measurements were taken during an aerial application to a forest during very stable meteorological conditions. Figure 7 presents the temporal variation in concentration after 3 spray passes on the same spray line. At the 200-m station, variations on the order of a factor of 2 are observed in the peak tracer concentrations associated with each spray pass. By 400 m, peak concentrations were diminished by a factor of 4 from those at 200 m, whereas by 1,200 m, peak concentrations were about 5% of those at 200 m. Whereas each spray cloud took about 100 sec to pass the 200-m station, by 1,200 m, it appears

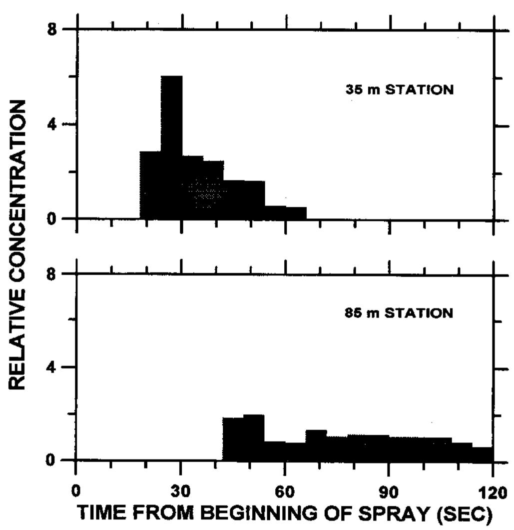

Fig. 6. Temporal variation in breathing-height concentrations at 2 locations downwind of the spray line for crosswind spray.

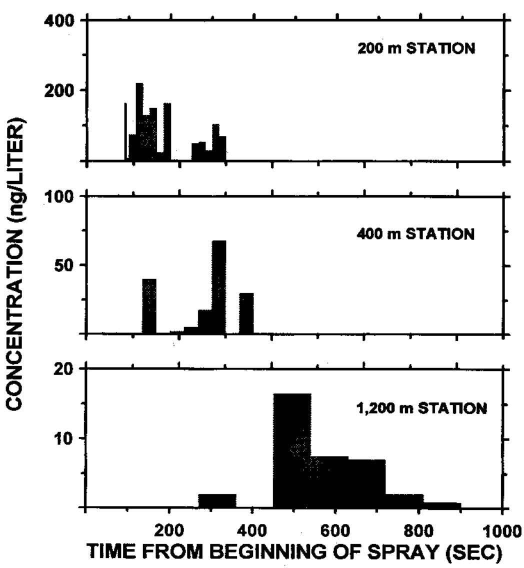

Fig. 7. Tracer concentration at tree height (from Crabbe et al. 1984).

that the clouds from the separate sprays had merged, taking close to 500 sec to pass.

Parallel wind spray: In this case, the TBM aircraft with 12 11010 T-jets per wing (flow rate 3.8 liters/min/head; $D_{v0.5}$ = 60–70 μm) was flown along a line 1,820 m from the ARAL and at a height of 34 m above ground level over a canopy during midmorning neutral conditions. Average canopy height was 10 m. The tail winds were moderate (4 m/sec) at 15° to the flight line. Temperature and relative humidity were 13°C and 80%, respectively. As in the previous case, at 9 sec, the bulk of the material was wrapped into the vortices, which had tended to rotate around each other (Fig. 2B). However, unlike the crosswind case, the downwind vertical motion of the vortices was quickly arrested. By 27 sec, the bulk of the spray had risen to a height above the original release height. In this parallel spray, each cross section is for a new volume of spray that has been transported down the spray line and into the field of view of the laser. By 69 sec, the cloud extended to 80 m, 2 times the original spray height. The total dosage profile (Fig. 3B) shows the dosage evenly distributed around the spray height with the majority of the cloud remaining airborne. Unlike the crosswind case, the high concentration of material (dark colors) remained aloft for up to 80 sec with only a low concentration (light shade) actually reaching the target. The majority of the spray cloud was skewed to the port side of the aircraft, reflecting the slight off-axis direction of the wind. Deposition (Fig. 4B) to the surface only began to occur about 60 sec after the aircraft had passed and was associated with the spray emitted nearly 200 m upwind along the spray line. Despite an application rate of nearly 4.5 times greater than the previous case, the total deposit (Fig. 5B) over the first 80 sec after the aircraft had passed was substantially less than in the crosswind case. For spray control strategies employing drift techniques, this spray strategy resulted in a cloud that diffused extensively and was slow to impact the ground.

CONCLUSIONS AND RECOMMENDATIONS

Two case studies of parallel and crosswind spraying have been presented to highlight the role that wind direction plays on the drift and deposit from ULV spraying. Lidar mapping of the ULV spray cloud shortly after emission has clearly shown that the ULV spray is quickly entrained and redistributed within the vortices. For ULV sprays, the concentration within the cloud is controlled by the vortex roll up. Spanwise movement of the small drops tends to redistribute the small drops towards the vortex core.

Although only 2 studies have been given, they tend to represent the majority of cases that were mapped. Consistently, sprays that were made in parallel winds from high-flying aircraft resulted in the potential for drifting clouds that remained airborne for longer periods of time. Deposition was slow compared to the crosswind cases. Faced with targeted spraying of small areas, the influence of wind direction on vortex behavior, especially when flying high above ground, should be considered. For ULV spraying of small blocks, it is recommended that applicators should attempt to spray in crosswinds in order to enhance rapid transport of the pesticide into the target area. For large block drift spraying, spraying in parallel winds appears to reduce the rate of deposit at ground level.

The crosswind example shown here has also indicated that vortex behavior can significantly influence spray fate during conditions where vortex lifetimes are long. Preferential deposition from the upwind wing could be utilized to better target deposit into a selected area. Quantification of preferential deposit from the upwind wing has been observed by McCooeye et al. (1993). On the other hand, spraying from the downwind wing appears to increase the potential for drift and hence could be utilized where drift spraying is desired.

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