EVALUATION OF REALTIME SPRAY DRIFT USING RTDRIFT GAUSSIAN ADVECTION-DIFFUSION MODEL

Frédéric Lebeau[1], Arnaud Verstraete[1], Bruno Schiffers[2], Marie-France Destain[1]

[1] Mechanics and Construction Department, Gembloux Agricultural University, Belgium
[2] Laboratory of phytopharmacy, Gembloux Agricultural University, Belgium
UMC-FUSAGx passage des déportés, 2, 5030 Gembloux.
Corresponding author e-mail: lebeau.f@fsagx.ac.be

SUMMARY

A spray drift model was developed to deliver real time information to the pesticide applicator. The sprayer is equipped with sensors to deliver real time measurement of operational parameters as spray pressure, boom height, horizontal boom movements and geolocalization. The spray droplet size spectrum as a function of pressure was characterized using PDI measurements. Wind speed and direction were measured using a sprayer mounted 2-D ultrasonic anemometer. For each successive boom position, a diffusion-advection Gaussian tilting plume model is used to compute the spray drift deposits downwind. Drift is computed independently for each droplet classes and each nozzle based on the operating parameters. Field trials were performed on a test plot in various wind conditions. The ground drift was measured for different drift distances using fluorimetry analysis. Results show that drift deposits are mainly affected by wind speed and direction what was correctly accounted for by the model. Short distance drift deposits values were overestimated by the model while long distance drift was underestimated. It appears that this most probably origins from embarked wind speed measurements and diffusion parameter. It is concluded that a treatment of embarked wind speed and diffusion measurement should be used to minimize these errors.

Keywords: spray controller, drift model, embarked anemometer, pesticide application.

INTRODUCTION

After WW2, shortage of agricultural product was a major problem. Chemical application grew during the fifties simultaneously with mechanization and fertilization. In the sixties, the alarm sounded with the Rachel Carson book ‘silent spring’. From this time, pesticide limitation plans started to flourish in national legislations and are ever developing based on accumulated scientific evidence of pesticides adverse effects. At redaction time, the Commission proposes a Regulation intended to replace Directive 91/414/EEC in the context of the thematic strategy on the sustainable use of pesticides. Once adopted, this will reinforce control measures by requiring farmers and other professional users to keep registers of the plant protection products they use (registers which may be consulted on request by neighbours or by the drinking water industry).

Pesticides drift in non-target sensitive areas is one key point amongst environmental risks. Drift is dependant on different factors as spray application technique but also physicochemical properties of the spray liquid (Butler Ellis and Tuck, 1999; Stainier et al., 2006) and meteorological conditions (Thistle, 2000). Particularly, wind speed, direction and turbulence are known to be the most important environmental parameters on the spray drift distance (Miller et al., 2000).

A number of models have been developed in order to predict the field drift and deposition from spray applications. These spray models fall into empirical and mechanistic categories.
The empirical ones are based on field measurements of spray drift. The most famous databases originate from the SDTF (spray Drift Task Force) and BBA (Ganzelmeier and Rautmann, 2000) studies but many other are developed around the world. Therefore a more ideal model for evaluating pesticides drift needs to include mechanistic descriptions of relevant physical processes. Mechanistic models developed on this basis generally fall into two categories depending on the mathematical approach to turbulent mixing.
The first category includes particle tracking models. These lagrangian approach models (Thompson and Ley, 1983; Miller and Hadfield, 1989; Zhu et al., 1994; Holterman et al., 1997) track a big amount of droplets in a different drop size category on the basis of the equations of motion including a random component on the movement of the droplets to account for atmospheric turbulence. This approach is valuable to predict the effects of application equipment on spray dispersal and thus effectively meets the needs for a regulatory assessment tool that can be used to evaluate the mitigating effects of alternative equipment uses and near-field buffer zones. However, their mathematical complexity still limits their practical use. None of these models predict the high variability found in drift values during field experiments. (Nuyttens et al., 2006). Up to now, no simulation including all the variability of the relevant operational and environmental parameters during field scale application has been performed.
A balance between physical meaning and mathematical complexity of the equations is needed to ensure practical use of models. Gaussian models have been developed for this purpose based on the diffusion–advection equation. Gaussian modelling is a classical approach used in atmospheric dispersion modelling of releases from tall stacks and line, area, and volume sources (Pal Arya, 1999) and has proved to be well suited for modelling medium range drift on the basis of wind speed and atmospheric stability (Bache and Sayer, 1975). The Gaussian plume model has been mostly used for drift prediction from aerial applications (Craig, 2004). This modelling approach is not well developed for ground applications because the Gaussian approach does not provide much resolution in the representation of equipment and near-field dynamics in the flow field.
Stainier (2006) proposed a methodology to adapt Gaussian theory to near field drift modelling. This approach is based on a discretization of the spray in several droplet classes, and the use of tilting plume approach (Reibble, 1999) to take into account of sedimentation process of drops.

MATERIALS AND METHOD

Embarked measurements

A measurement chain was installed on a 27 m wide FORTIS Evolution 3300 (Tecnoma) trailed sprayer. Recorded parameters during field application are wind, flow rate and nozzles trajectories according to ISO 14131:2005. Specifications of the sensors installed on the sprayer (Figure 1) are :

- Three CXL04M3 accelerometers (Crossbow Technology) are fixed on the boom (AC1 to AC3) to measure horizontal boom movement due to the yaw and jolting motions. These DC to 100Hz accelerometers have a 500 mV/g sensitivity and ± 4g range.
- Two HT77MGV80 (Wenglor) distance-meters (IR1 and IR2) are located on each part of the boom. Their measuring range is 300 to 1300 mm.

- One 2200BGB1001A3UA001 pressure sensor (Gems Sensors) (P) is fixed on the central section of the boom. Its pressure range is 0 to 10 bars.
- One 2-axis Windsonic (Gil Instrument) anemometer (AN) measures the wind speed and direction. The measurement frequency is 4 Hz and the range of wind speed is 0 to 60 m/s. The sensor is located at the front of and 1.15 m above the sprayer tank, 3.6 m high from the ground.
- A Navman 3260 GPS furnishes the global position at 1 Hz. Its absolute horizontal accuracy is about 8 m.
- The factory installed turbine flow-meter furnishes a pulsed signal proportional to the applied flow.
- The factory installed wheel rotation sensor furnishes a pulsed signal whose frequency is proportional to the sprayer speed.

The analogue sensors are connected using a SCB-68 connector to a daqcard - 6036E (National Instruments) data acquisition system installed in a CF71 toughbook (Panasonic). RS-232 sensors are connected to the laptop using a NI PCMCIA 232/4 card. An acquisition program was developed on *Labview* (National Instruments) to record measurements at 200 Hz in a data file.

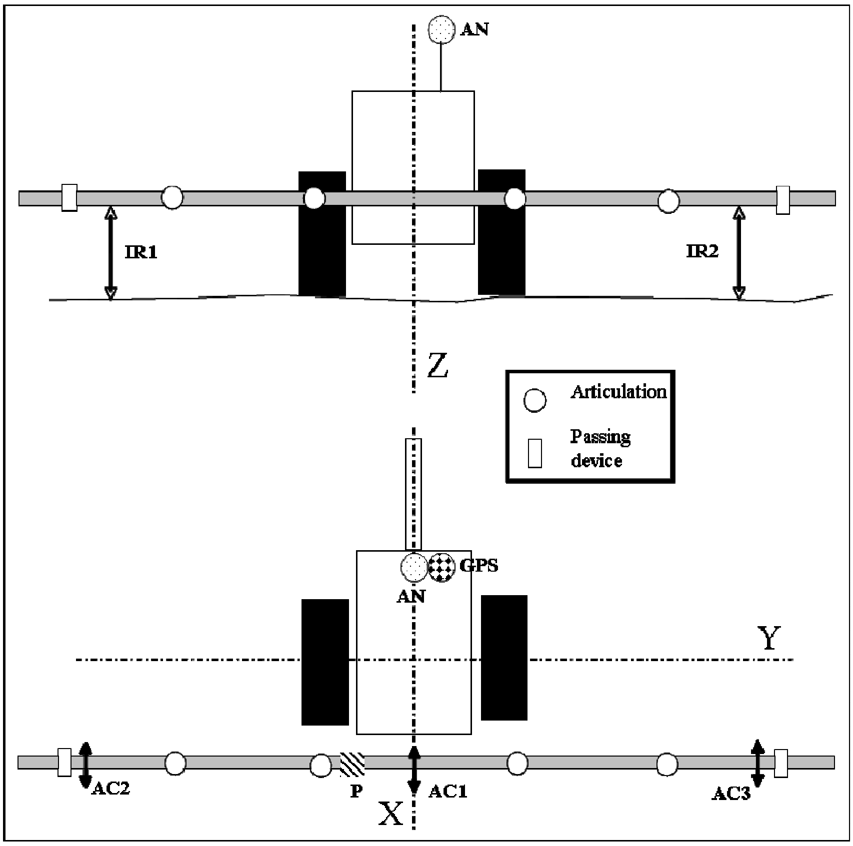

Figure 1 : Disposition of the sensors on a trailed spraying machine

Field trials

Five spray drift trials are performed on a meadow surrounded by a wheat field and a broad beans field. A volume per hectare of 200 l/ha is applied at 2m/s using flat fan AFX 110-04 nozzles (Nozal). To quantify the drift, fluorescein sodium (F6377, Sigma-aldrich) tracer is added to water at a concentration of about 1 g/l that is precisely measured for each trial on spray mixture samples.

Drift measurements are conducted according to ISO 22886 recommendations except restrictions about the wind direction relative to travel direction. The same 130 m long spray track centred in the meadow is used for the five trials. Figure 2 presents the experimental layout. Three sampling lines are placed on both side of the spray track at 10 metres interval. For each line, 2 collectors are placed in the direct spray area. Drift is measured at 0.5, 1, 2, 5, 10, 15, 20 and 30 metres. On each collector, two 2.5*10 cm² fibber glass samplers are maintained on ceramic tiles with rubber bands. The tiles are placed horizontally on supports at the top of the vegetation level. 60 fluorescence measurements are preformed for each run.
A CR1000 meteorological station (Campbell Scientific) is placed in the drift sampling area. A 25Hz triaxial ultrasonic anemometer USA-1 (METEK) with 0 to 50 m/s range is used to measure wind speed, direction and turbulence at 3m high. A hygroclip S3 (ROTRONIC) is used to measure air temperature and humidity at 2.4 m high. A second temperature sensor is located 1.4 m high (LM35, National Semiconductor).
After the spraying, the collectors are quickly picked up and put in the shade in boxes and sent to the laboratory for analyse. Collectors are washed using a phosphate buffer solution and analysed using a RF-1501 spectrofluorophotometer (Shimadzu).

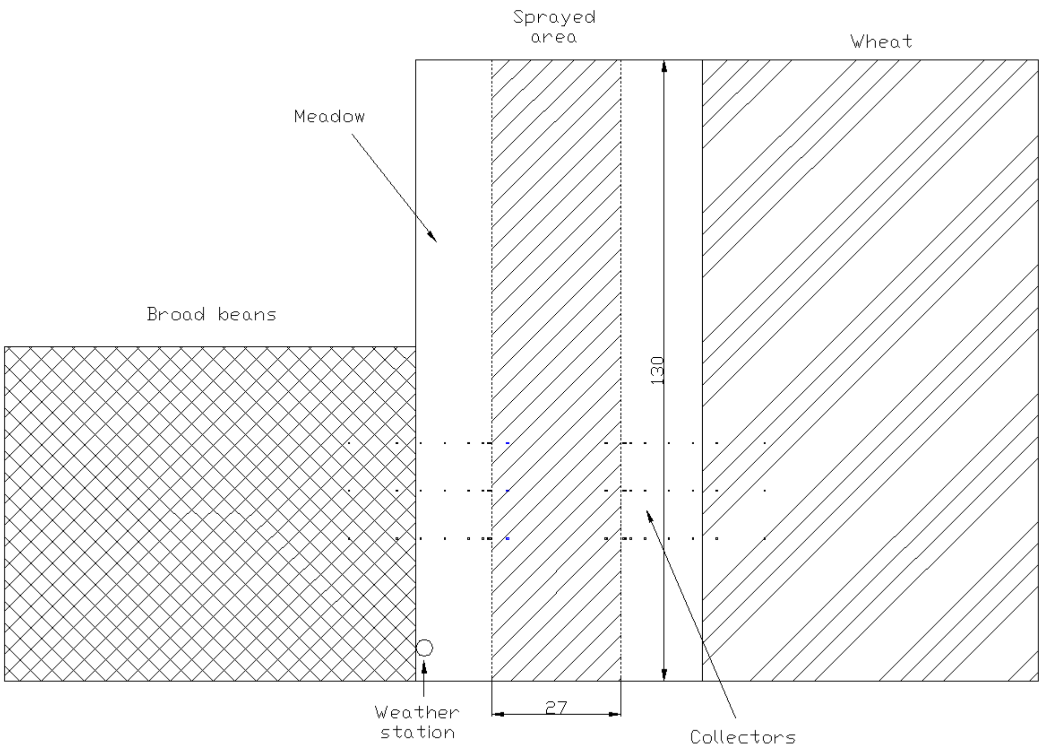

Figure 2 : Localisation of collectors in the meadow

Data processing

Embarked measurements are processed using MATLAB software (Mathworks) to supply inputs for drift modelling. The processing steps are:

- Scaling up of the sensor data to physical units;
- Conversion of GPS global coordinates (degrees-minutes-seconds) to the Belgian local coordinates system, Lambert 2008 (metres);
- Embarked anemometer measurements coordinate system change from the sprayer local frame to Lambert 2008 in order to derive absolute wind speed and direction;

- Trajectory for every 54 nozzles is computed from boom movements' measurement (Ooms *& al.,* 2002). The relative acceleration of the two boom ends is obtained by subtraction of the central accelerometer data. DC-0.3 Hz frequencies are filtered. Signals are integrated to obtain relative speed and position estimations. A linear interpolation is used to estimate relative movement for every nozzle. One nozzle trajectory is obtained from sprayer trajectory addition to this relative movement.

As a result of this data processing, a 200 Hz data file characterises wind speed and direction as well as the localisation in the field (X,Y), the emission height relative to the canopy, the flow and pressure for the 54 nozzles.

Spray deposits modelling

The sprayed area is divided in meshes using a 50 cm square grid. For each mesh, nozzle height and spray pressure as well as the time passed by nozzles to estimate the applied volume are computed at this location.

For every mesh, the absolute wind speed and direction are estimated from a 30 seconds moving average of the embarked wind data. The 30 seconds period was chosen as a rough estimate of mean time covered by a droplet since its outlet of the nozzle until its deposit on the ground.

A Gaussian tilted plume advection-diffusion model is used to compute spray deposits. The RTDrift (Figure 3) model is an adaption of this robust atmospheric pollution approach to the pesticides drift characteristics. It supposes that the panache settles and disperses along a central line depending on dispersion coefficients, wind speed and direction as well as particulates sedimentation velocity. The basic equation of the model is:

$$q_m = v_p C(x, y, z; H_s) = \frac{Q_m v_p}{2\pi\sigma_y\sigma_z U} \exp\left(\left[-\frac{y^2}{2\sigma_y^2}\right] - \left[\frac{\left\{z - \left(H_s - \frac{v_p x}{U}\right)\right\}^2}{2\sigma_z^2}\right]\right) \qquad [1]$$

where :

- v_p : sedimentation velocity of droplets [m/s];
- $C(x,y,z\ ;\ H_s)$: droplets concentration [ml/m³];
- x : horizontal distance along the wind direction [m];
- y : horizontal distance perpendicular to the wind direction [m];
- z : height from the ground [m];
- H_s : modified emission height of droplets [m];
- Q_m : emission rate of droplets [ml/s];
- σ_y : dispersion coefficient according to the y axis [m];
- σ_z : dispersion coefficient according to the z axis [m];
- U : mean wind speed according to the x axis [m/s].

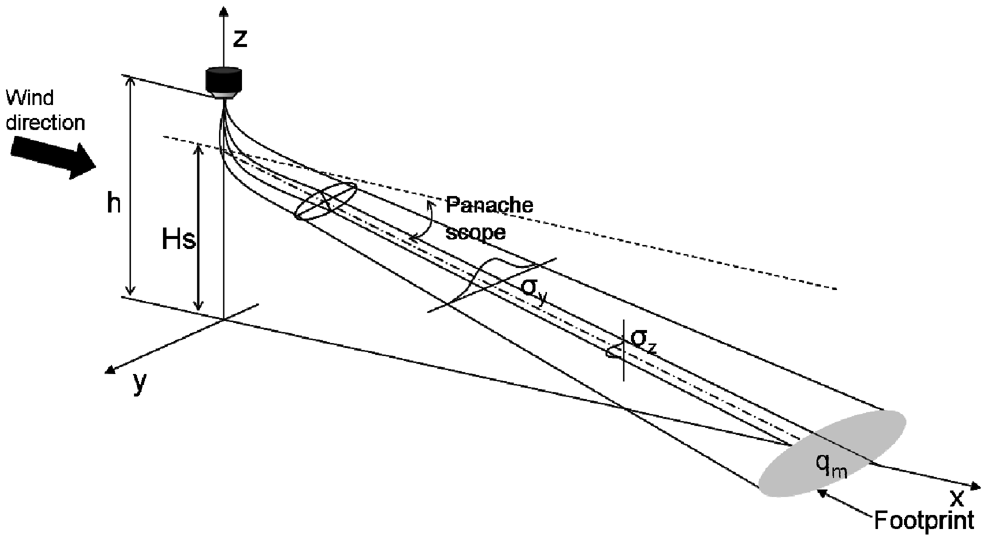

Figure 3 : Idealization of contaminant dispersion from an isolated nozzle

Nozzle droplet size distribution was measured according to ISO/CD 25358 (2007) recommendations with a PDI-300 (Artium).

Droplets produced by a nozzle at a particular pressure are divided in homogeneous diameter classes that are stated to drift independently.

The first assumption of this model is the absence of interaction between drops. This hypothesis is supported by the effect of the nozzle movements, which segregates droplets from different sizes and drastically reduces the droplet density comparatively to a static nozzle.
The second hypothesis relates to the transfer of the droplet quantity of movement to the air. Droplets are decelerated from initial speed by the drag force from static air interaction, not taking any entrained air effect into account. On the basis of these hypotheses, the forces acting on a particular droplet class are used to compute modified emission height and sedimentation speed.

The modified emission height H_s of a diameter d spherical drop emitted with an initial vertical speed v_i at an height of emission h_i and submitted to an horizontal wind u is presented on Figure 4. The emission height is set at the level where the liquid sheet breakup to form individual droplets. H_s corresponds to the height from which a drop of same diameter settling at its terminal velocity and moving sideways at speed u would fall on the ground at the same horizontal distance x_f from the point of emission.

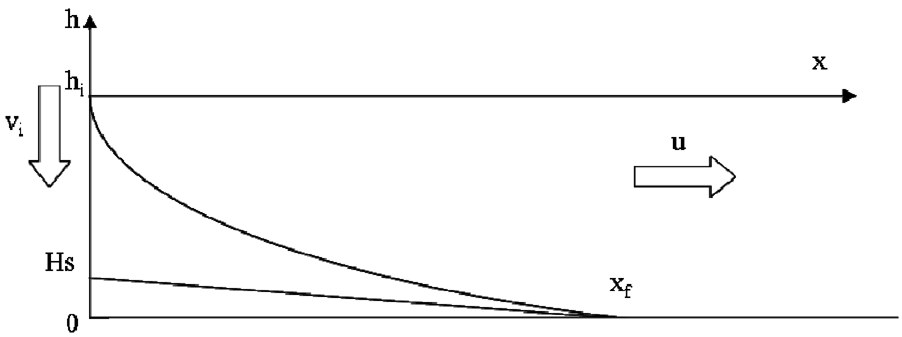

Figure 4 : Representation of the modified emission height

The impact point x_f of the drop is calculated using ballistics, on the basis of initial vertical speed, buoyancy force F_B and drag force F_D. Integration of the movements equations is realised from initial conditions v_i and h_i until the impact on the ground for h=0 at an abscise x_f. The height H_s is then calculated in dividing the product of the sedimentation velocity v_p of the particle with the abscise x_f by the horizontal wind speed u.

$$H_s = \frac{v_p x_f}{u} \qquad [2]$$

The buoyancy force is given by :

$$F_B = (\rho_p - \rho_a).\pi.\frac{d_p^3}{6}.g \qquad [3]$$

with ρ_p : density of the particle [kg/m³];
ρ_a : density of the air [kg/m³];
d_p : the diameter of the particle [m].

The drag force F_D is given by :

$$F_D = C_D\left(\pi.\frac{d_p^2}{4}\right)\left(\rho_a\frac{v_p^2}{2}\right) \qquad [4]$$

with v_p : particle speed [m/s];
C_D : drag coefficient [];
$\rho_a.v_p^2/2$: kinetic energy per unit volume in the fluid displaced by the particle [kg/(m.s²)];
$\pi.d_p^2/4$: projected area of the droplet assumed spherical [m²].

The drag coefficient is function of the Reynolds number. For slow relative velocities ($N_{\mathrm{Re}} \le 1$), it is set as :

$$C_D = \frac{24}{N_{\mathrm{Re}}} \qquad [5] \qquad \text{with} \qquad N_{\mathrm{Re}} = \frac{\rho_a v_p d_p}{\mu_a} \qquad [6]$$

For larger values N_{Re}, an usual experimental relationship between drag coefficient and N_{Re} is used :

$$C_D = 0.22 + \frac{24}{N_{\mathrm{Re}}}[1 + 0.15(N_{\mathrm{Re}})^{0.6}] \qquad [7]$$

The steady velocity is reached when the buoyancy and drag forces are balanced. For $N_{\mathrm{Re}} > 1$, the sedimentation velocity v_{sp} of the particle relative to the fluid is obtained through iterative method using :

$$v_p = \left[\frac{4}{3}\frac{d_p g(\rho_p - \rho_a)}{C_D \rho_a}\right]^{1/2} \qquad [8]$$

For $N_{\mathrm{Re}} \le 1$, the terminal velocity is equal to :

$$v_{sp} = \frac{d_p^2 g(\rho_p - \rho_a)}{18\mu_a} \qquad [9]$$

Dispersion coefficient σ_y and σ_z are computed along x axis using equation 10 :

$$\sigma_x = \sqrt{2D_x \frac{x}{u}} \; and \; \sigma_y = \sqrt{2D_y \frac{x}{u}} \qquad [10]$$

with D_x and D_y respectively diffusivity along x and y axes [m²/s].

These parameters are related to wind turbulence. In the present modelling, diffusivity along both axes were set constant at a 0,005 m²/s value. These parameters can be adapted to wind turbulence intensity measurements, what will be discussed in future work.

The drift for every mesh is computed as the sum of the contribution from different droplet classes. The ground footprint of the volume fraction sprayed in a specific diameter class *Qm* is computed using equation 1 with a 5 by 5 cm² resolution. This approach allows easy adaptation to any droplet size distribution, i.e. because of pressure change or nozzle modification.

The geo-referenced footprint is oriented in the wind direction and added to the spray application map with 50 by 50 cm² resolution. The summation of every mesh footprint results in a map of the actual drift.

RESULTS AND DISCUSSION

Trials

Table 1 presents a description of the five trials.

Table 1 : Description of trials

	datum	wind speed (m/s)	culture submitted to the drift	meadow height (cm)	wheat height (cm)	broad beans height (cm)
test 2	26/06/2008	4,9	broad beans	20-30	75	110-120
test 3	01/07/2008	1,1	wheat	20-35	75	120-130
test 4	23/07/2008	2,9	wheat	25-40	75	150-160
test 5	29/07/2008	3,2	broad beans	25-40	75	150-160
test 6	31/07/2008	2	broad beans	25-40	75	150-160

Modelling

Figure 5 presents maps of the spray application respectively for trials 2 and 3 to illustrate the global effect of wind speed and direction. The localisation of spray drift collectors is specified on the map. During trial 2, huge variations of the spray deposits along the driving direction are observed (logarithmic colour scale). These result from both boom movements and, mainly, wind gusts. It has to be highlighted that the modelling of wind turbulence effect on drift deposits is not entirely taken into account by dispersion coefficient, what is rather uncommon for Gaussian dispersion modelling. Large eddies occurring during the trial are modelled through the variations of the 30 seconds moving average wind values. The effect of wind deviation during the trial is obvious for trial 3. Spray deposits in the directly sprayed area present some heterogeneities because of the nozzles movements.

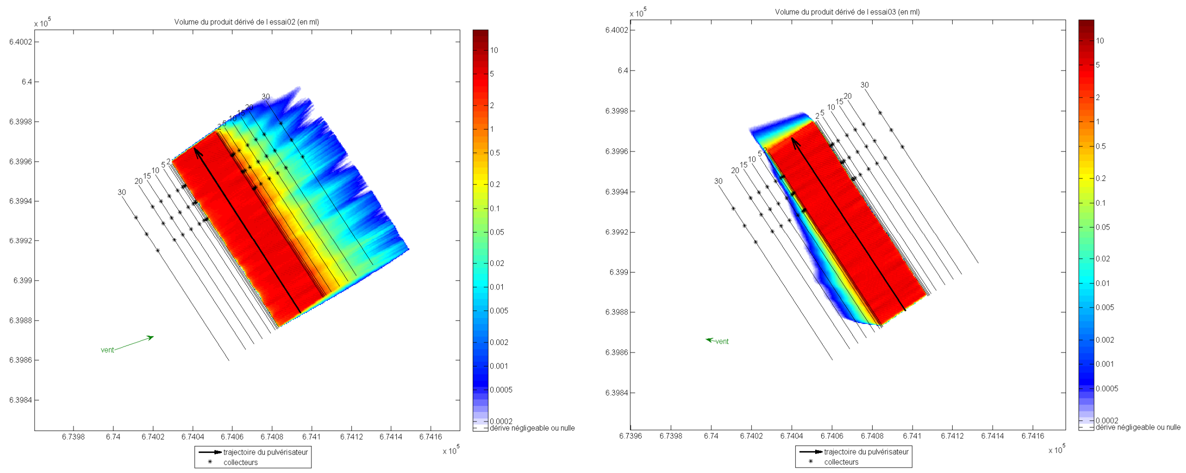

Figure 5 : Maps of test 2 on left hand and test 3 on right hand with a logarithmic colour scale

Figure 1Figure 5 illustrates also the longitudinal variations of the drift. The modelling of trial 2 highlights the sampling problem associated with field drift measurements.

<u>Comparison with field measurements</u>

Table 2 presents values of spray drift deposits downwind for the three collector lines as a percentage of the application rate. No significant deposits were found windward for the 5 trials. As expected, the deposits decrease with downwind distances. The very high variation between the measurements at a given downwind distance between the three collector lines reflects the great heterogeneity of drift deposits.

Table 2 : Percentages of drift for the tests at different distances

Downwind distance		0,5	1	2	5	10	15	20	30
test 2	L1	13,34%	10,16%	4,95%	1,63%	0,78%	0,41%	0,22%	0,22%
	L2	20,55%	10,16%	4,84%	2,40%	1,63%	2,74%	0,55%	0,55%
	L3	36,67%	27,46%	12,42%	3,62%	2,37%	1,11%	0,26%	0,22%
test 3	L1	33,35%	6,34%	0,92%	0,33%	0,04%	0,04%	< LOQ	< LOQ
	L2	36,27%	11,40%	6,37%	0,77%	0,04%	< LOQ	< LOQ	< LOQ
	L3	29,30%	14,98%	2,26%	0,12%	0,05%	< LOQ	< LOQ	< LOQ
test 4	L1	15,19%	10,49%	6,47%	1,76%	0,83%	0,51%	0,12%	< LOQ
	L2	17,25%	4,14%	1,89%	0,91%	0,17%	0,17%	0,11%	0,03%
	L3	-	17,88%	7,25%	1,86%	0,07%	0,08%	0,06%	0,04%
test 5	L1	5,96%	2,80%	1,28%	0,21%	0,18%	0,13%	0,08%	< LOQ
	L2	4,40%	1,49%	1,47%	1,33%	0,77%	0,07%	< LOQ	< LOQ
	L3	38,20%	12,08%	2,37%	0,83%	0,03%	0,03%	< LOQ	0,04%
test 6	L1	3,57%	1,19%	0,04%	< LOQ	0,04%	< LOQ	< LOQ	< LOQ
	L2	1,66%	0,56%	1,66%	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
	L3	17,00%	4,51%	0,09%	0,15%	0,02%	< LOQ	< LOQ	< LOQ

Table 3 presents mean and standard deviation of the modelled spray deposits (in percentages) for 30 metres lines located at different sampling distance downwind centred in the drift measurement area. These values are expected to be representative of the deposits in the sampling area.

Table 3 : Mean and standard deviation of the modelled spray deposits

Downwind distance		0,5	1	2	5	10	15	20	30
test 2	mean	77,80%	56,74%	35,64%	13,25%	4,26%	1,59%	0,63%	0,16%
	std	17,48%	14,16%	8,84%	3,35%	1,40%	0,63%	0,31%	0,11%
test 3	mean	10,90%	2,95%	0,43%	0,01%	0,00%	0,00%	0,00%	0,00%
	std	8,84%	2,09%	0,35%	0,01%	0,00%	0,00%	0,00%	0,00%
test 4	mean	49,17%	33,96%	16,53%	4,45%	0,81%	0,17%	0,04%	0,00%
	std	11,15%	10,18%	4,47%	1,41%	0,38%	0,11%	0,03%	0,00%
test 5	mean	26,68%	16,59%	8,12%	1,48%	0,19%	0,04%	0,01%	0,00%
	std	5,22%	2,24%	0,95%	0,36%	0,11%	0,02%	0,00%	0,00%
test 6	mean	19,93%	7,86%	2,04%	0,06%	0,00%	0,00%	0,00%	0,00%
	std	9,62%	2,75%	0,72%	0,02%	0,00%	0,00%	0,00%	0,00%

Comparison of spray deposits measurements with modelled spray deposits shows an overestimation of the short range drift by the model under the current assumptions. The most obvious explanation lays in the inappropriate use of the raw wind speed measurements from the embarked ultrasonic sensor. The obstruction effect of the sprayer and the height of the sensor furnish obviously a higher wind speed that the one governing drift phenomenon.
A ranking of the drift during the 5 trials results in a similar results for modelled and measured deposits except for the two lower, test 3 and test 6 that are inverted. This error may be linked to the diffusivity difference because test 6 was the only one realized in the morning.

CONCLUSIONS

The RTDrift model is able to produce a realistic map of drift deposits based on embarked measurements. The use of a bi-axial ultrasonic anemometer permitted to correctly identify the drift area. Further improvements of the model lie in the processing of embarked wind measurements to derive a more representative wind speed in the boundary layer. The issue of real time dispersion coefficient identification must also be addressed to further increase model performance. The model is a sound basis for the development of a real time drift monitor to be included in a spray controller.

ACKNOWLEDGMENTS

The DRIFT-INDIC project n°2907 was funded by the SERVICE PUBLIC DE WALLONIE, Direction Générale Opérationnelle Agriculture, Ressources naturelles et Environnement (DGO 3) - Direction du Développement et de la Vulgarisation.

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