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Numerical modelling of the aerial drop of firefighting agents by fixed-wing aircraft. Part II: model validation

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Abstract. The validation of the Aerial Drop Model consisted of the comparison of computed ground patterns with experimental data from a set of real-scale drop tests using water and a wide range of fire retardant viscosities. Results were analysed in terms of pattern length and area. A total of 78% of the computed line lengths per coverage level were within a 10% error, with an average normalised mean squared error of 0.01 and a Pearson correlation coefficient above 0.9. In all cases, nearly 90% of the results were within a factor of 2 of observations. The accuracy of the simulations showed no strong relation with the viscosity, although better results were obtained in the range from 700 to 1100 cP. In general, the model produced a good representation of the spatial distribution of the agent for various coverage levels and its accuracy was, in fact, within the statistical uncertainty of the cup-and-grid sampling method. The good performance obtained demonstrates that this tool, for the tested range of drop conditions, fulfils the requirements for use in the optimisation of firefighting operations, as a complementary method to real-scale drop testing, and in firefighter training activities.

Additional keywords: drop effectiveness, drop testing, model evaluation.

Introduction and background

The Aerial Drop Model (ADM) was developed with the aim of providing an improved simulation of the physical mechanisms occurring during an aerial drop of firefighting liquids, with the ultimate purpose of supporting the optimisation of the overall efficiency of aerial firefighting (Amorim 2011). In this scope, the present document describes the process of evaluation of ADM's performance through the comparison of the simulated ground concentrations of product with the experimental dataset obtained from a series of real-scale drop tests. These experiments were conducted in two locations, one in France and the other in the United States, with the purpose of evaluating the effect of changing operating parameters (such as aircraft height and speed), meteorological conditions and rheological properties on drop efficiency. In this sense, the use of products with very distinct characteristics under varying flight conditions allows the evaluation of model performance, accuracy and quality within a wide range of input conditions.

Since the first attempts at using airtankers in firefighting tasks early in the 1920s in the US and in New Zealand, and Canada in the 1940s and early 1950s, the development and testing of more efficient products and discharge systems have been largely supported by drop tests conducted at real scale, usually in open areas (George *et al.* 1976; Newstead and Lieskovsky 1985; George and Johnson 1990; Pickler 1994; Robertson *et al.* 1997*a*). These tests are, however, highly expensive and pose other types of problems inherent to field experiments, such as the irreproducibility of trials.

The first and most detailed study on the behaviour of aerially dropped firefighting liquids was undertaken by the Shock Hydrodynamics Division of the Whittaker Corporation (California, US), under contract to the Intermountain Forest and Range Experiment Station of the US Forest Service (USDA-FS). The Honeywell Corporation continued the investigation under a project named ETAGS (Experimental Tank and Gating System). The results were published in several reports in the mid-70s (Andersen *et al.* 1974*a*, 1974*b*, 1976). This broad investigation, focussing on many aspects related to the quality, effectiveness and application of firefighting products, involved the performance of numerous experimental real-scale drop tests. Drop testing, which consists of the dropping of different types of liquids over a regularly spaced array of sampling cups, is still a common practice for the evaluation of retardant effectiveness, although modern equipment has improved the accuracy of the measurements. Most drop-pattern studies have been conducted in open areas, such as airport runways, under low-wind conditions (Davis 1960; George and Blakely 1973; George 1975; Andersen *et al.* 1976; George and Johnson 1990; Robertson *et al.* 1997*a*, 1997*b*; Suter 2000; Lovellette 2004). In particular, few studies have considered the effect of canopy interception (except for work by Stechishen (1976), Rawson (1977), Newstead and Lieskovsky (1985) and Robertson *et al.* (1997*a*)). Field trials have also been complemented by static testing (Blakely *et al.* 1982; Lovellette 2005), laboratory measurements (Andersen *et al.* 1974*a*, 1974*b*; Van Meter 1983), and wind-tunnel experiments (Van Meter and George 1981).

Real-scale drop testing

The first set of experimental data used in the validation of ADM were from real-scale drops (see Fig. 1*a*) conducted in 2000 at Marseille, France, during the research project ACRE (Additifs Chimiques Rheologie Evaluation – project number

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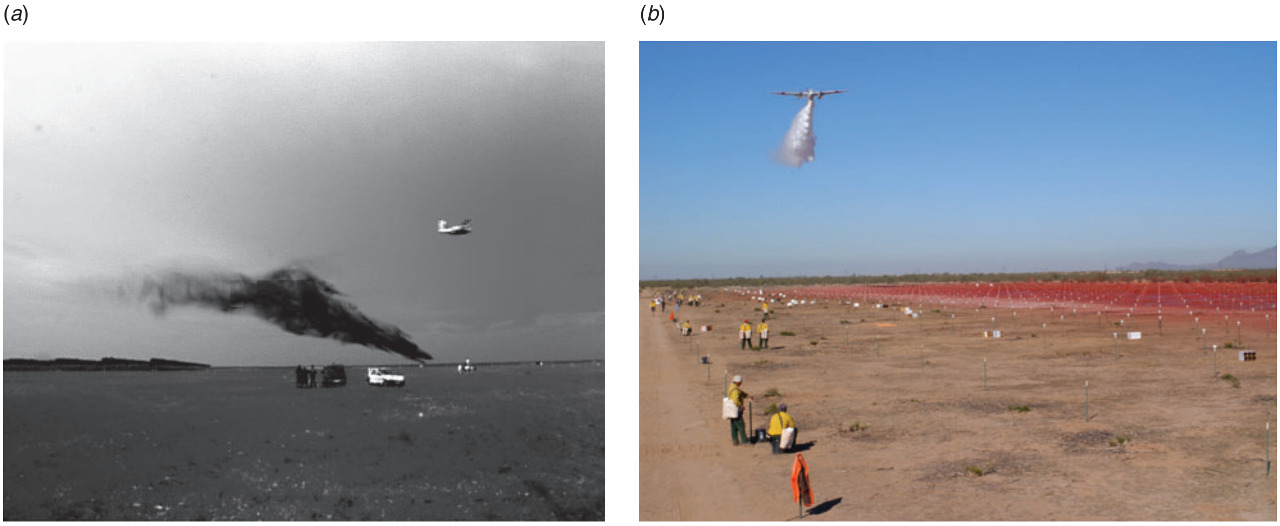

Fig. 1. Retardant drop during Marseille tests (*a*) and water drop in Marana test area (*b*).

Table 1. Drop tests general characterisation

FT 931, Fire Trol 931 (an ammonium polyphosphate solution); PC LV, Phos-Check low viscosity product; PC MV, Phos-Check medium viscosity product; PC HV, Phos-Check high viscosity product

Location	Delivery system	Product	Viscosity (cP)	Drop height (m)	Wind velocity (m s^{-1})
Marseille	Conventional (salvo drop)	FT 931 retardant	432–1430	34–45	1–7
Marana	Constant flow	Water; PC LV, PC MV and PC HV	0; 152–1300	38–78	0.5–4

ENV4-CT98-0729), which was financed by the European Commission. These experiments were conducted in order to analyse the effect of product viscosity on ground distribution (Giroud *et al*. 2002). The second set of data resulted from drop tests conducted in October 2005 at Marana, Arizona, in the US (see Fig. 1*b*). The specific data used in the present paper were part of the systematic real-scale drop tests that have been conducted since the 1970s by the USDA-FS with the main purpose of comparing ground deposition response to changes in product rheology. For additional information on these tests, see Amorim (2008).

In both tests, a converted CDF-S2F Turbo Firecat aircraft, converted by Conair Aviation (Marseille, France), was used, although with differences in the type of delivery system. The French aircraft carried a maximum of 3030 L of product distributed by four similar compartments that were opened at once (1×4 salvo drop), releasing the entire capacity of the tank. In contrast, the US aircraft carried ~4500 L and was equipped with a constant flow gating system, with two doors that controlled the flow rate and volume released.

In the experiments conducted in Marseille, a gum-thickened Fire Trol (FT) 931 retardant (an ammonium polyphosphate solution (BIOGEMA S.A., Asnieres, France)) was used. In order to obtain different viscosities, the fraction of gum added to the solution was varied accordingly. In Marana, Phos-Chek (PC) retardant (originally produced by Monsanto Co. and currently manufactured by ICL Performance Products, St Louis, MO, USA) with a wide range of viscosities was used, as well as water. LV, MV and HV indicate low-, medium- and high-viscosity products respectively. G is for guar gum and X is for xanthan thickener. The LV-G and MV-G were dilutions of HV-G, which is PC D75. MV-X and HV-X were from products that had been evaluated but not marketed. The wide range of conditions tested is shown in Table 1.

Unlike the Marseille tests in which no measured flow rate values were available (therefore requiring calculation with ADM's discharge module), reliable data on instantaneous flow rate were collected in Marana with an on-board data acquisition system. The implications of using the model's discharge module to compensate for not having measured flow rate values in the case of Marseille drops will be evaluated in the following section. Meteorological parameters (wind direction and velocity, air temperature and humidity) were continuously monitored during both tests using a meteorological mast located near the grid. Samples of the retardant loaded into the tank were taken in order to measure the viscosity of the product with a Brookfield viscometer (Middleboro, MA, USA). Elasticity values were not measured during the field experiments. Digital video cameras were used to provide frontal and lateral images of the dropping sequence.

Table 2 shows the parameters used as input data by ADM according to the following categories: product characteristics, flight parameters and meteorological conditions. The drops are ordered by increasing viscosity. Note that the relative wind direction is the angle in geometric coordinates between the aircraft trajectory (0°) and the wind, indicating the direction to which the wind is blowing relative to the grid orientation.

Each drop trial was categorised according to the criteria shown in Table 3. The classification of viscosity is based on

Table 2. Drop parameters for Marseille 2000 and Marana 2005 drop tests

Product	Drop number	Product viscosity (cP)	Product density (kg m^{-3})	Volume (m^3)	Average flow rate (m^3 s^{-1})	Drop height (m)	Drop speed (m s^{-1})	Wind velocity (m s^{-1})	Relative wind direction (°)
Marseille drop tests									
Fire Trol 931	S4 L1	432	±1000	2.80	±2.80	42.9	±60	1	294
	S4 L3	432		2.60	±2.60	34.1		1	12
	S3 L1	637		2.62	±2.62	41.2		7	214
	S3 L2	720		3.01	±3.01	39.0		7	224
	S6 L3	1060		2.81	±2.81	45.9		6	159
	S6 L1	1260		2.73	±2.73	35.5		4	107
	S6 L2	1430		2.98	±2.98	44.7		4	144
Marana drop tests									
Water	M128	1	1000	4.60	1.22	59.44	68.42	2.68	210
	M134	1	1000	4.64	2.04	60.66	67.90	2.68	135
	M183	1	1000	4.59	2.11	88.09	66.36	1.79	130
PC LV-G	M114	152	1033	4.57	1.15	72.54	69.44	2.68	120
	M112	214	1032	4.60	2.08	37.19	63.79	2.68	120
PC MV-X	M120	700	1052	4.62	2.23	57.91	70.99	1.79	210
PC MV-G	M110	750	1051	4.62	2.12	54.86	65.84	2.68	125
	M109	800	1055	4.55	1.18	65.84	65.84	3.58	110
PC HV-X	M119	1250	1078	4.59	1.17	59.44	66.87	0.89	0
	M117	1300	1075	4.63	2.05	77.72	70.99	0.45	20
	M118	1300	1075	4.64	2.12	60.96	66.36	0.89	50

Table 3. Criteria for drop classification based on viscosity, drop height, wind velocity and relative wind direction

Viscosity (cP)		Drop height (m)		Wind velocity (m s^{-1})		Relative wind direction (°)	
Water-like	<60	Low	<45	Calm	0–0.2	Headwind	135–224
Low	60–249	Medium	45–69	Light air	0.3–1.5	Left crosswind	225–314
Medium	250–999	High	≥70	Light breeze	1.6–3.3	Tailwind	315–44
High	≥1000			Gentle breeze	3.4–5.4	Right crosswind	45–134
				Moderate breeze	5.5–7.9		

the protocols currently in use by worldwide fire agencies (Vandersall 1994). The drop height was classified from low to high according to the range of values typical for Europe and the US (e.g. Vandersall 1994). The relative wind direction uses typical aeronautics terminology. Following these criteria, drop trials are classified in Table 4.

As can be seen in Table 4, data are widespread along the different product viscosities, drop heights and meteorological conditions, although in the Marana data, a tendency for right-crosswind drops with light breezes is noticeable. Compared with Marseille, and following the usual procedure in the US, the product was released from much higher altitudes, exceeding 70 m in three cases; two of the high-altitude drops used water or a low-viscosity product.

Measurement of the spatial distribution of the ground concentration of product was made applying the 'cup-and-grid' method, in which the weight of product in each cup is registered after complete deposition (see Fig. 2) and an interpolation method is used after to estimate the values between consecutive cups (Suter 2000; Giroud *et al*. 2002; Lovellette 2004). The spatial distribution of the product concentrations at ground level was obtained in Marseille using a 160×60-m^2 grid of cups with 10×5-m^2 resolution, whereas in Marana, the grid was 613×105 m^2, with a maximum resolution in the centre of 4.6×4.6 m^2.

The post-processing of the measured ground concentration of product involves the analysis of several metrics of interest, of which the most important are the line length and the area of each iso-concentration contour (defining different ranges of concentration or coverage levels). For the Marana drops, the following minimum threshold concentrations were defined for each level: 0.25, 0.75, 1.5, 2.5, 3.5, 5.5, 7.5 and 9.5 gpc[A], according to the usual procedure of the USDA-FS. For the Marseille tests, the minimum values per class of concentration used were the following: 0.5, 0.8, 1, 1.5, 2, 3 and 4 L m^{-2}.

[A]1 gpc corresponds to 1 gallon (US) per 100 square feet (~0.4 L m^{-2}). This is the unit currently used by the USDA Forest Service for representing the ground concentration of firefighting products.

Table 4. Classification of Marseille and Marana drop trials based on the predefined criteria

	Viscosity				Drop height			Wind velocity					Relative wind direction			
	No viscosity	Low	Medium	High	Low	Medium	High	Calm	Light air	Light breeze	Gentle breeze	Moderate breeze	Headwind	Left crosswind	Tailwind	Right crosswind
Marseille drop tests																
S4 L1			•		•				•					•		
S4 L3			•		•				•						•	
S3 L1			•		•							•	•			
S3 L2			•		•							•	•			
S6 L3				•		•						•	•			
S6 L1				•	•						•					•
S6 L2				•	•						•		•			
Marana drop tests																
M128	•					•				•			•			
M134	•					•				•			•			
M183	•						•			•						•
M114		•					•			•						•
M112		•			•					•						•
M120			•			•				•			•			
M110			•			•				•						•
M109			•			•					•					•
M119				•		•			•					•		
M117				•			•		•					•		
M118				•		•			•							•

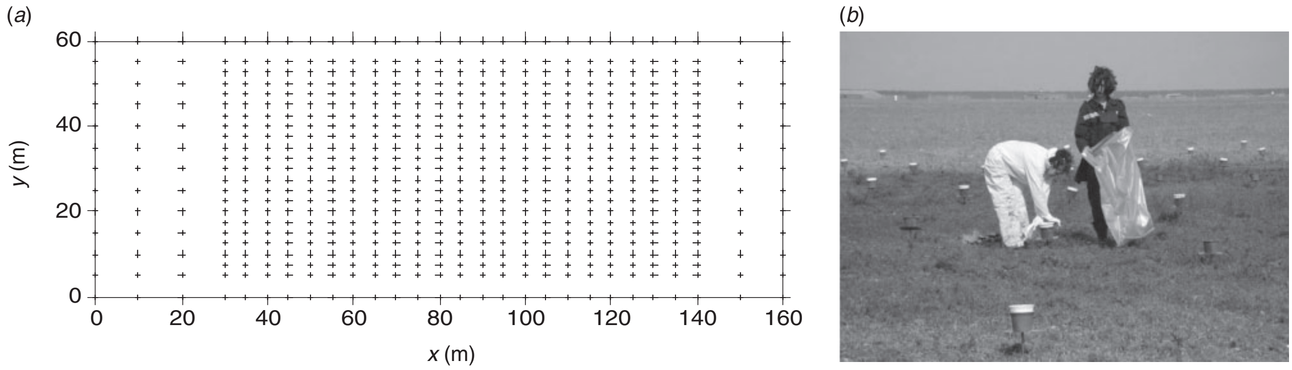

Fig. 2. Cup grid setting (*a*) and cup collection (*b*) during the Marseille aerial drops (Giroud *et al*. 2002).

As the coarse measuring grid is usually a source of error in the determination of line lengths and areas, a kriging interpolation method was applied in the determination of the concentration values between two consecutive measurement cups.

The model evaluation procedure involved a three-stage process:

- visual comparison of ground pattern shape per contour area;
- calculation of a set of statistical parameters on the computed and measured values of line length and area per coverage level;
- comparison of the variation of volume of product deposited along the *x* axis.

In terms of statistical analysis of the modelling results, and although there is not an accepted criterion defined for the evaluation of aerial drop model performance, a 10% value for the modulus of the percentage error has been used as a quality requirement by the USDA-FS for this type of application. This analysis was complemented with the calculation of a set of metrics commonly applied on the evaluation of numerical model performance (Abramowitz and Stegun 1972; ASTM International 2000; Chang and Hanna 2005).

Validation of the Aerial Drop Model

Fig. 3 shows the comparison of ground patterns obtained by simulation and measurement for the different Marseille drops.

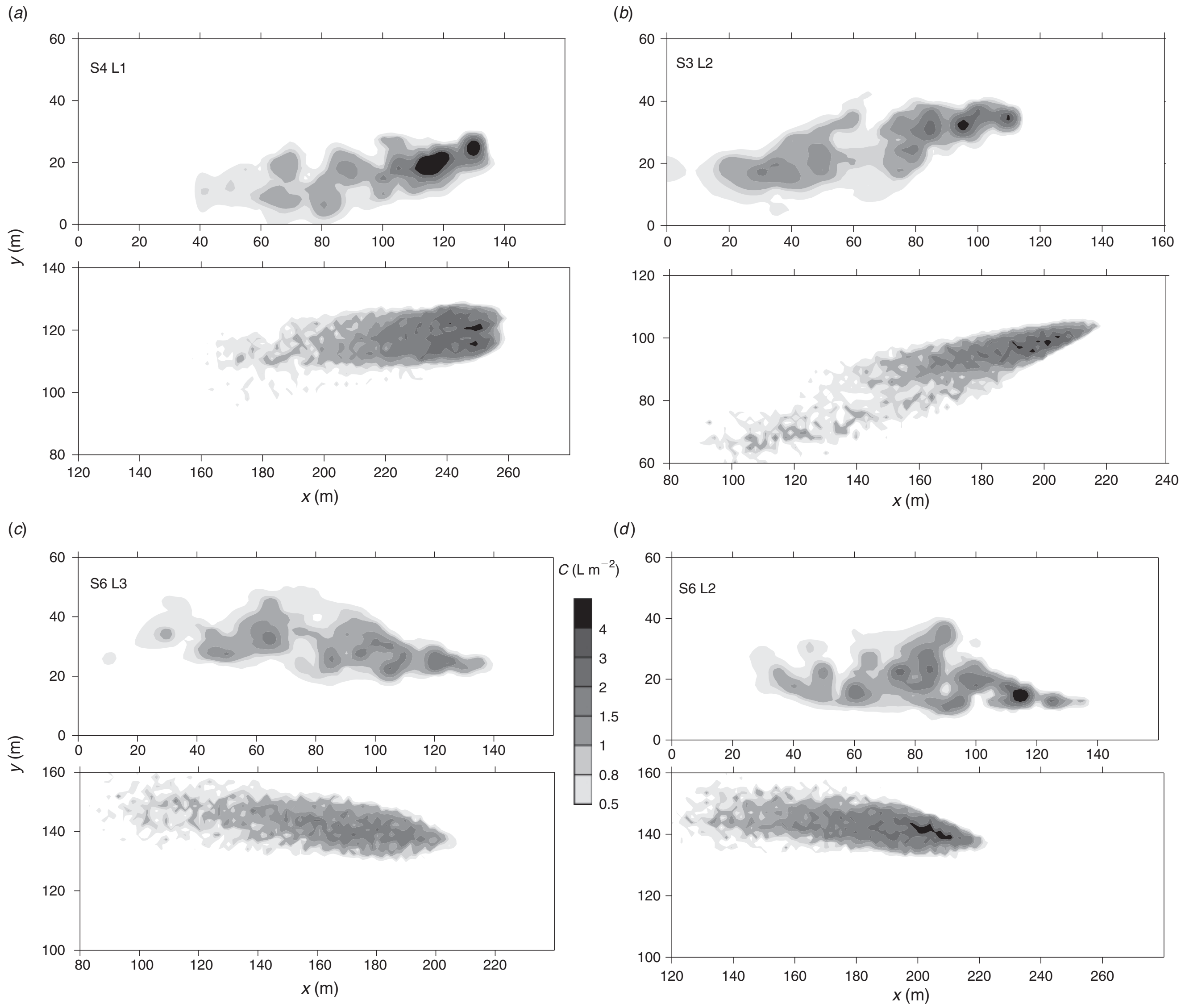

Fig. 3. Comparison between the measured (top image) and simulated (bottom image) ground patterns of product concentration for the Marseille drop tests. Two examples for each class of viscosity (medium and high) were selected. Note that the positions of the pattern in the grid are not comparable. *C*, product concentration at ground (L m^{-2}).

The position of the aircraft at the instant of release was not registered, which is why the locations of the modelled and measured patterns in the grid are not comparable. Generally speaking, ADM provides a good representation of the spatial distribution of product for all the classes of concentrations considered, showing the typical accumulation of product at the front of the pattern, which is a characteristic of patterns from conventional delivery systems. For additional results obtained in the validation process, see Amorim (2008).

The contours shown in the images in Fig. 3*a* and *b* are specific for medium-viscosity products. In particular for the case in Fig. 3*a* the model underestimates the accumulation of product at the front of the pattern for the higher concentration level, which can be related to some inaccuracy resulting from the estimation with ADM's discharge module of the flow rate of product exiting from the tank (instead of using more reliable measured data).

The patterns shown in Fig. 3*b*, *c* and *d* show a distinct behaviour of the liquid, evidenced by the narrow configuration (particularly evident in the two last contours), with a lower pattern width at the front and an increased total length, which is mainly a result of the headwind conditions. From the comparison, ADM demonstrates the capability to deal with this wind-flow-induced effect. The model was also capable of simulating the characteristics of the patterns observed with higher-viscosity products, as shown in Fig. 3*c* and *d*.

In the case of Marana drops, the ground pattern contours are given in Fig. 4. Note that, as in Marseille, the location of the pattern given by measurement and by the model for each drop is again not comparable.

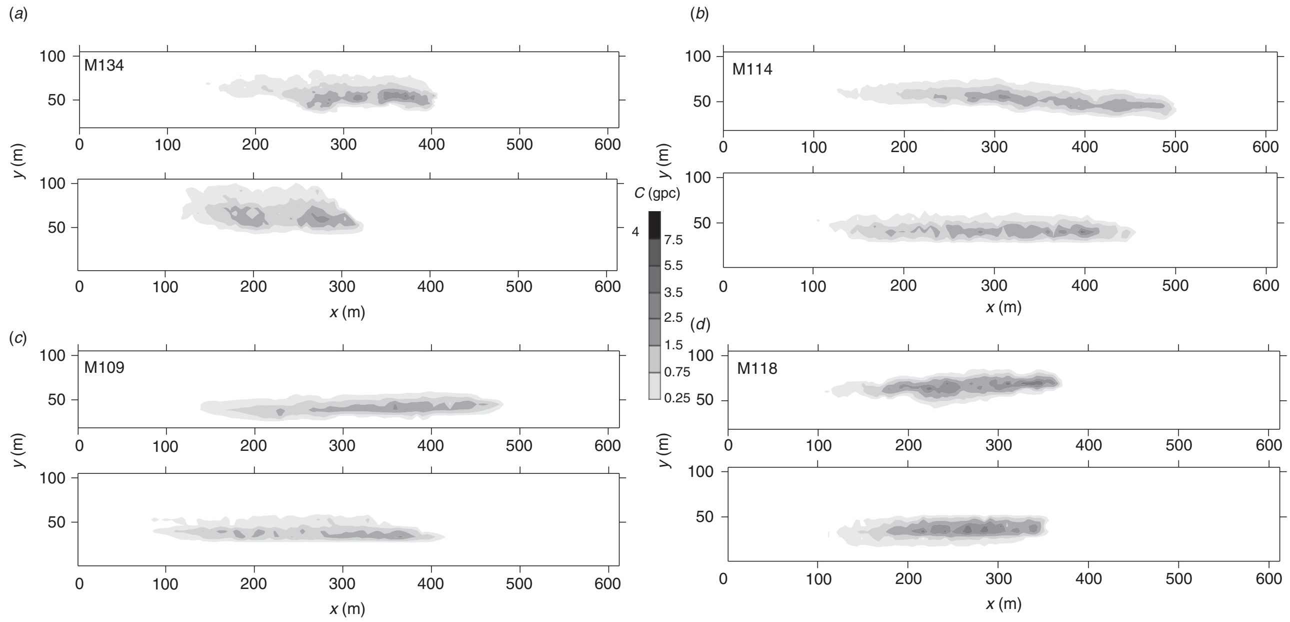

Fig. 4. Comparison between the measured (top image) and simulated (bottom image) ground patterns of product concentration for the Marana drop tests. One example for each class of viscosity (water, low, medium and high) was selected. Note that the positions of the pattern in the grid are not comparable. *C*, product concentration at ground (gpc).

Table 5. Statistical analysis of the pattern length values estimated by the Aerial Drop Model (ADM) for each coverage level
NMSE, *r*, *FB* and *FAC2* are unitless. See Appendix for definitions

Product	Drop number	*NMSE*	*r*	*d* (m)	*MG* (m)	*VG* (m^2)	*FB*	*FAC2*
Marseille drop tests								
Fire Trol 931	S4 L1	0.010	0.987	1.571	1.19	1.32	0.029	0.857
	S4 L3	0.011	0.987	−0.571	1.15	1.38	−0.011	0.857
	S3 L1	0.032	0.972	5.143	1.39	1.75	0.092	0.857
	S3 L2	0.020	0.983	4.714	1.19	1.09	0.077	1.000
	S6 L3	0.008	0.993	3.167	1.26	1.23	0.045	0.833
	S6 L1	0.010	0.996	−4.000	0.92	1.03	−0.080	1.000
	S6 L2	0.013	0.992	5.000	1.11	1.03	0.077	1.000
Marana drop tests								
Water	M128	0.012	0.993	0.381	0.92	1.02	0.002	1.000
	M134	0.024	0.990	12.375	1.79	3.25	0.102	0.800
	M183	0.020	0.972	3.658	1.05	1.03	0.026	1.000
PC LV	M114	0.005	0.998	9.144	0.99	1.01	0.039	1.000
	M112	0.029	0.984	5.639	1.55	3.94	0.047	0.875
PC MV	M120	0.013	0.987	−4.115	1.04	1.05	−0.029	1.000
	M110	0.005	0.999	−9.144	0.68	1.89	−0.063	0.833
	M109	0.004	0.998	−3.414	1.92	9.22	−0.018	0.800
PC HV	M119	0.020	0.981	−2.804	1.06	1.21	−0.014	0.800
	M117	0.003	0.993	−1.000	0.98	1.00	−0.002	1.000
	M118	0.027	0.990	20.117	1.09	1.07	0.119	1.000

An example of a contour obtained from a water drop is shown in Fig. 4*a*. In general, the model captures the main aspects that influence the final ground pattern. There is, however, an underestimation tendency on the line length for the first coverage level (i.e. concentration values above 0.75 gpc) that, as expected, also influences the accuracy of the estimation of area occupied by this concentration class range, which was also observed in drops M128 and M183 (not shown).

The spatial distribution of concentrations at ground for a low-viscosity PC product is given in Fig. 4*b*. There is acceptable

Table 6. Averaged statistical parameters for the evaluation of ground pattern length simulation
NMSE, *r*, *FB* and *FAC2* are unitless. See Appendix for definitions

	Data	μ (m)	σ (m)	*NMSE*	*r*	*d* (m)	*MG* (m)	*VG* (m^2)	*FB*	*FAC2*
Marseille	Measured	58.80	36.40	0.000	1.000	0.00	1.00	1.00	0.000	1.000
	ADM	56.70	36.50	0.010	0.983	2.12	1.16	1.24	0.037	0.917
Marana	Measured	161.86	107.79	0.000	1.000	0.00	1.00	1.00	0.000	1.000
	ADM	159.22	102.01	0.010	0.986	2.65	1.16	1.82	0.017	0.911

Table 7. Statistical analysis of the pattern area values estimated by the Aerial Drop Model (ADM) for each coverage level
NMSE, *r*, *FB* and *FAC2* are unitless. See Appendix for definitions

Product	Drop number	*NMSE*	*r*	*d* (m^2)	*MG* (m^2)	*VG* (m^4)	*FB*	*FAC2*
Marseille drop tests								
Fire Trol 931	S4 L1	0.029	0.986	−65.71	1.04	1.68	−0.096	0.857
	S4 L3	0.021	0.986	−28.71	1.33	2.66	−0.047	0.857
	S3 L1	0.024	0.990	32.50	1.25	1.22	0.055	0.857
	S3 L2	0.015	0.999	60.14	1.04	1.02	0.080	1.000
	S6 L3	0.004	0.998	−0.50	1.08	1.10	−0.001	1.000
	S6 L1	0.011	0.993	−5.00	1.00	1.05	−0.008	1.000
	S6 L2	0.011	0.995	26.71	0.97	1.08	0.036	1.000
Marana drop tests								
Water	M128	0.008	0.999	−66.98	0.96	1.03	−0.022	1.000
	M134	0.006	0.999	169.72	1.91	2.53	0.067	0.600
	M183	0.063	0.999	588.7	1.41	1.18	0.182	1.000
PC LV	M114	0.035	0.994	307.11	0.98	1.02	0.077	1.000
	M112	0.392	0.980	477.07	1.33	1.71	0.310	0.750
PC MV	M120	0.030	0.990	−243.28	0.99	1.04	−0.102	1.000
	M110	0.014	0.997	5.84	0.72	3.36	0.003	0.833
	M109	0.018	0.998	−164.72	1.52	2.71	−0.058	0.800
PC HV	M119	0.058	0.998	353.35	0.84	1.20	0.124	0.800
	M117	0.007	0.998	−124.51	1.04	1.11	−0.041	1.000
	M118	0.009	0.998	92.64	1.00	1.01	0.033	1.000

agreement between modelled and measured contours, although the tendency for ADM to underestimate the line lengths for the lower coverage levels, i.e. for values lower than 1.5 gpc, remains. As a result of the lower height, drop M114 (Fig. 4*b*) is characterised by a much higher maximum concentration, reaching the highest coverage level. This wide distribution of product across all the levels is also present in the modelling results, although ADM tends to underpredict the area covered, which leads to an increased error when compared with measurements (as will be seen in Table 7).

The comparison between measurements and modelling results for a medium-viscosity product is shown in Fig. 4*c*, whereas Fig. 4*d* shows the model outputs for a higher-viscosity trial. In general, the model showed a good capacity for dealing with the conditions simulated, as shown by the generally good agreement between the shapes of the experimental and simulated patterns for each contour level.

In all the drops, the line lengths per coverage level were validated using statistical metrics for modelling evaluation. The results are presented in Table 5 (see the Appendix for a definition of the various parameters). There is some fluctuation in the normalised mean squared error (*NMSE*) value, although a relation with viscosity is not obvious. Nevertheless, all the *NMSE* values are clearly within the expected accuracy. As pointed out in the analysis of the ground pattern contours for the Marana drops, there is a tendency for the model to underestimate the line length values for low-viscosity products, and the opposite occurs for medium-viscosity retardants. For higher viscosities, there is no definite trend in the results. Table 6 presents the mean statistical metrics for the entire datasets of measured and simulated pattern length values.

From the statistical parameters given in Table 6, it is possible to conclude that the model exhibits generally good performance for both experiments, as indicated by the averaged *NMSE* of 0.01, which is independent from viscosity, as analysed in Table 5. Both the mean (μ) and standard deviation (σ) of the computed dataset are in close agreement with the measured values, notwithstanding the slight tendency for underestimating the length of the ground patterns, as shown also by the positive value of the mean bias *d*. Apparently, there is no immediate relation between the tendency of the model to under- or overestimate the lengths of the contours per class of

Table 8. Averaged statistical parameters for the evaluation of ground pattern area simulation
NMSE, *r*, *FB* and *FAC2* are unitless

	Data	μ (m^2)	Σ (m^2)	*NMSE*	*r*	*d* (m^2)	*MG* (m^2)	*VG* (m^4)	*FB*	*FAC2*
Marseille	Measured	694.96	635.82	0.000	1.000	0.00	1.00	1.00	0.000	1.000
	ADM	692.11	621.73	0.020	0.991	2.84	1.09	1.32	0.004	0.938
Marana	Measured	2717.1	2713.6	0.000	1.000	0.00	1.00	1.00	0.000	1.000
	ADM	2588.3	2587.2	0.040	0.981	128.77	1.11	1.52	0.049	0.877

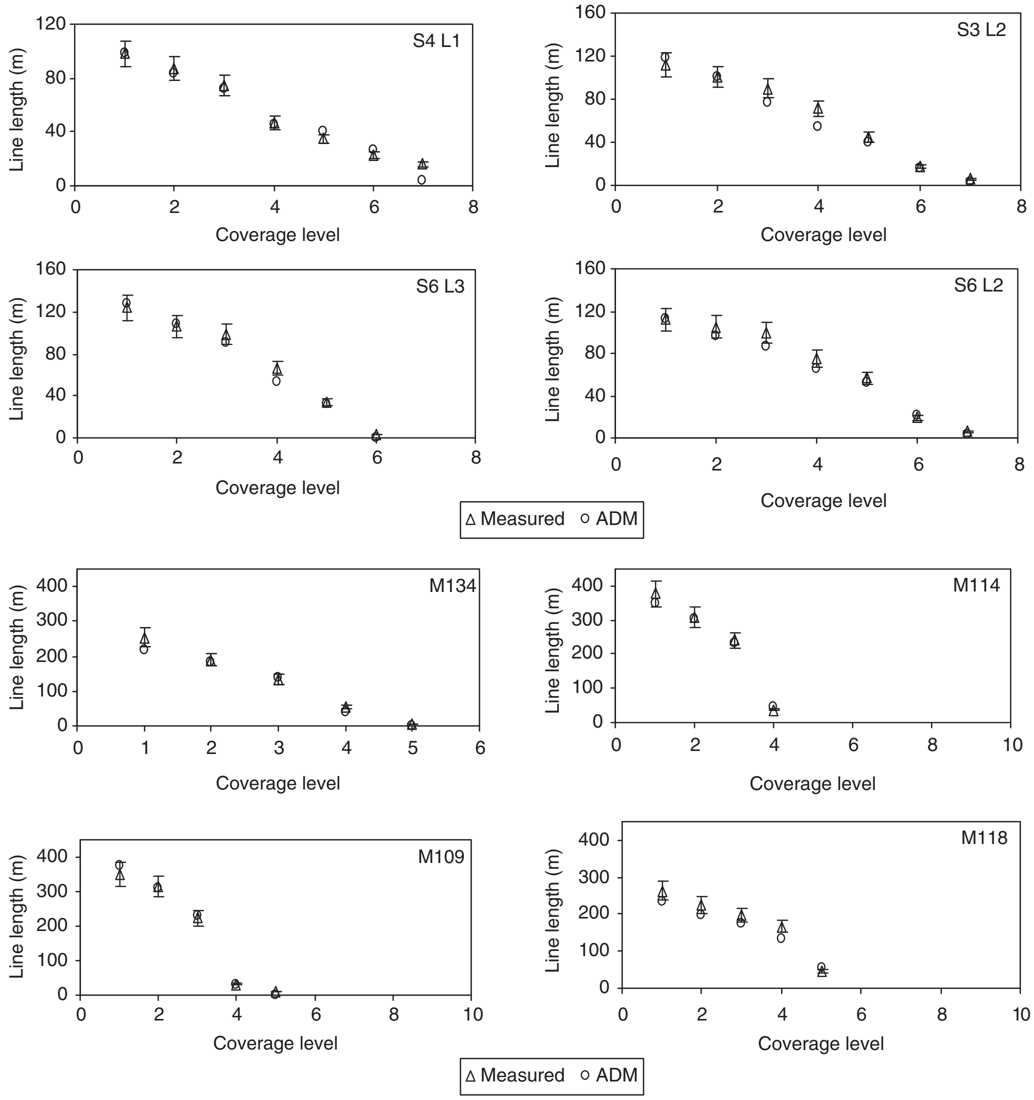

Fig. 5. Comparison between modelled and measured line lengths per coverage level. Vertical error bars indicate a relative error of ±0.1. For the Marseille drops, the numbers on the *x* axis represent the seven coverage levels considered: 0.5, 0.8, 1, 1.5, 2, 3 and 4 L m^{-2}. In the case of the Marana drops, the represented coverage levels are: 0.25, 0.75, 1.5, 2.5, 3.5, 5.5, 7.5 and 9.5 gpc. Note that the scale indicates the order of each coverage level and not the respective concentration.

concentration and the meteorological conditions, although it can be inferred that the model always underestimated lengths in headwind drops.

The modelling outputs were also statistically evaluated in terms of the area occupied by each coverage level. The results are presented in Table 5. Although the good correlation between model and measurement is maintained, there is an increase of the *NMSE*, in particular for the low-viscosity drops, in which, in accordance with the line length analysis, a slight tendency for underestimation is observed.

The overall good accuracy of ADM results in terms of area occupied by each concentration contour is reinforced by the

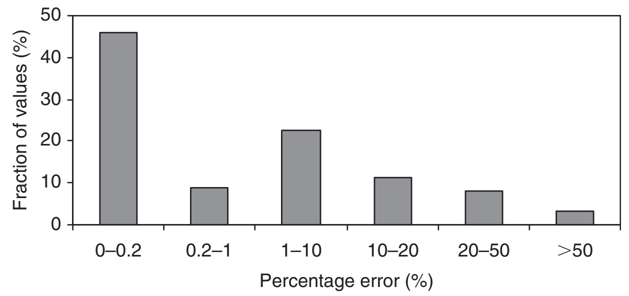

Fig. 6. Percentage error of the computed line lengths for the complete dataset of Marseille and Marana drop tests.

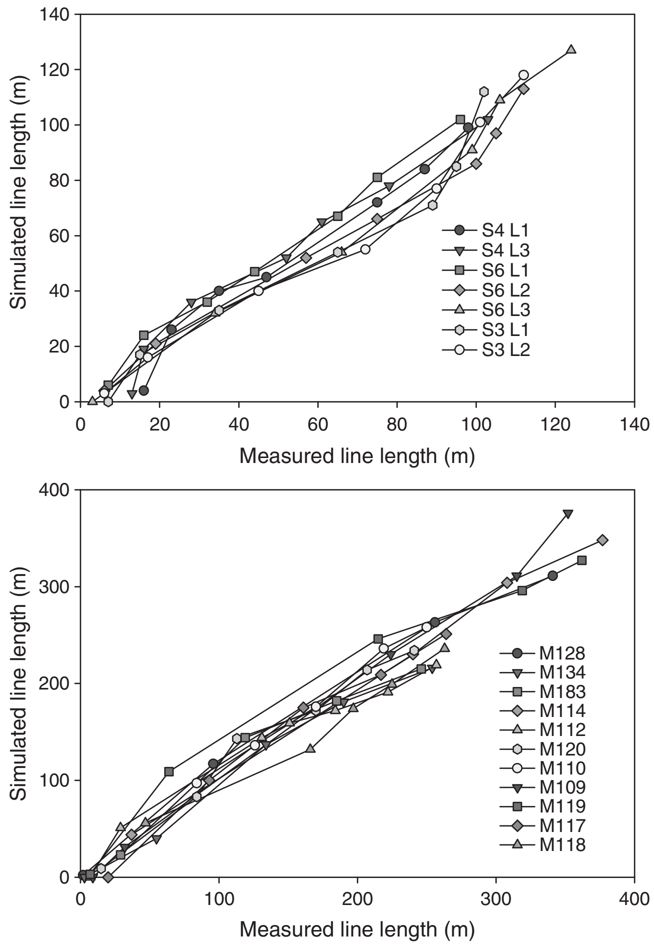

Fig. 7. Regression analysis of the measured and simulated line lengths for the Marseille and Marana drops.

analysis of the overall statistical metrics presented in Table 8. For the Marseille drops, the model maintains a very low *NMSE* and a good linear correlation between predicted and observed values, demonstrating that the slight tendency of underestimation ($d = 2.84$) of the ground pattern area does not have a significant effect on general accuracy. These conclusions are strengthened by the analysis of the factor of 2 (*FAC2*) parameter, which shows that nearly 94% of the data are within a factor of 2 of the observations. In the case of the Marana tests, and comparing with the values shown in Table 6, there is, in fact, an increase in the error, resulting from the underprediction referred to previously. Nevertheless, nearly 90% of the results, a value similar to the one obtained in the line length validation, are within a factor of 2 of observations.

Additionally, Fig. 5 shows the comparison between modelled and measured line lengths per coverage level. The appropriate statistical parameter for this analysis is the percentage error (δx), which is equal to 100% times the relative error, i.e. 100% times the difference between the observed and the computed values normalised by the latter (Abramowitz and Stegun 1972). The performance goal of the model is to guarantee that, for each level, $|\delta x| < 10\%$. This criterion is fulfilled in most of the Marseille drops, although ADM has some difficulty in coping with the apparently higher line length for mid-range coverage levels (in the range between 3 and 4 L m^{-2}) in S3 L1, S3 L2, S6 L3 and S6 L2 drops. In the case of the Marana experiments, an overall tendency of ADM to keep within the required 10% error was observed. As shown, there is in general a good compromise between computed and experimental data for the entire range of coverage levels, and in contrast to the Marseille drops, there is no underestimation of line length values for mid-levels.

The percentage error for the entire dataset (partly shown in Fig. 5) is given in Fig. 6. It is shown that 78% of the computed values fulfil this data-quality criterion. In fact, the error associated with the simulation of the pattern length in each concentration level is lower than 0.2 in 46% of the estimations.

In Fig. 7, the regression lines for the comparative analysis between measured and simulated line lengths per coverage level are shown. The underestimation of the length of mid-range coverage level contours is visible in some of the Marseille simulations. Nevertheless, there is a good correlation between measured and simulated values.

An additional indication of the spatial variation of the volume deposited at ground is given by the representation along the x axis of the cumulative volume $V_x (= \sum_y V(y))$. The various graphs in Fig. 8 show, for each drop, the comparison between the computed and measured V_x values. The position of the curves on the x axis was adjusted in order to give the best fit (note that the position of the aircraft during the experiments is unknown, and therefore the position of the patterns in the grid cannot be compared). In general, ADM is capable of showing a distribution similar to the one measured, although in drops S3 L1 (not shown) and S3 L2, there is a tendency to overestimate the asymmetry. However, an underestimation of the maximum value of V_x was found in all cases except for S3 L1. The degree of underestimation varies between 3% (S6 L3) and 27% (S6 L2) of the corresponding maximum volume (with a mean value of 16%).

As can be seen, owing to the time evolution of the flow rate of product in the outflow from the aircraft tanks, the distribution of volumes on the x axis is right-skewed, which is in fact a characteristic of conventional delivery systems. In some cases, as in drops S4 L1, S4 L3 and S6 L1, the distribution is highly skewed to the right, showing that a significant amount of product deposits in the last third of the total length of the pattern.

The same analysis was applied over the Marana results. Note that, for better comparison with the Marseille drops, the length and volume units were converted to metres and litres

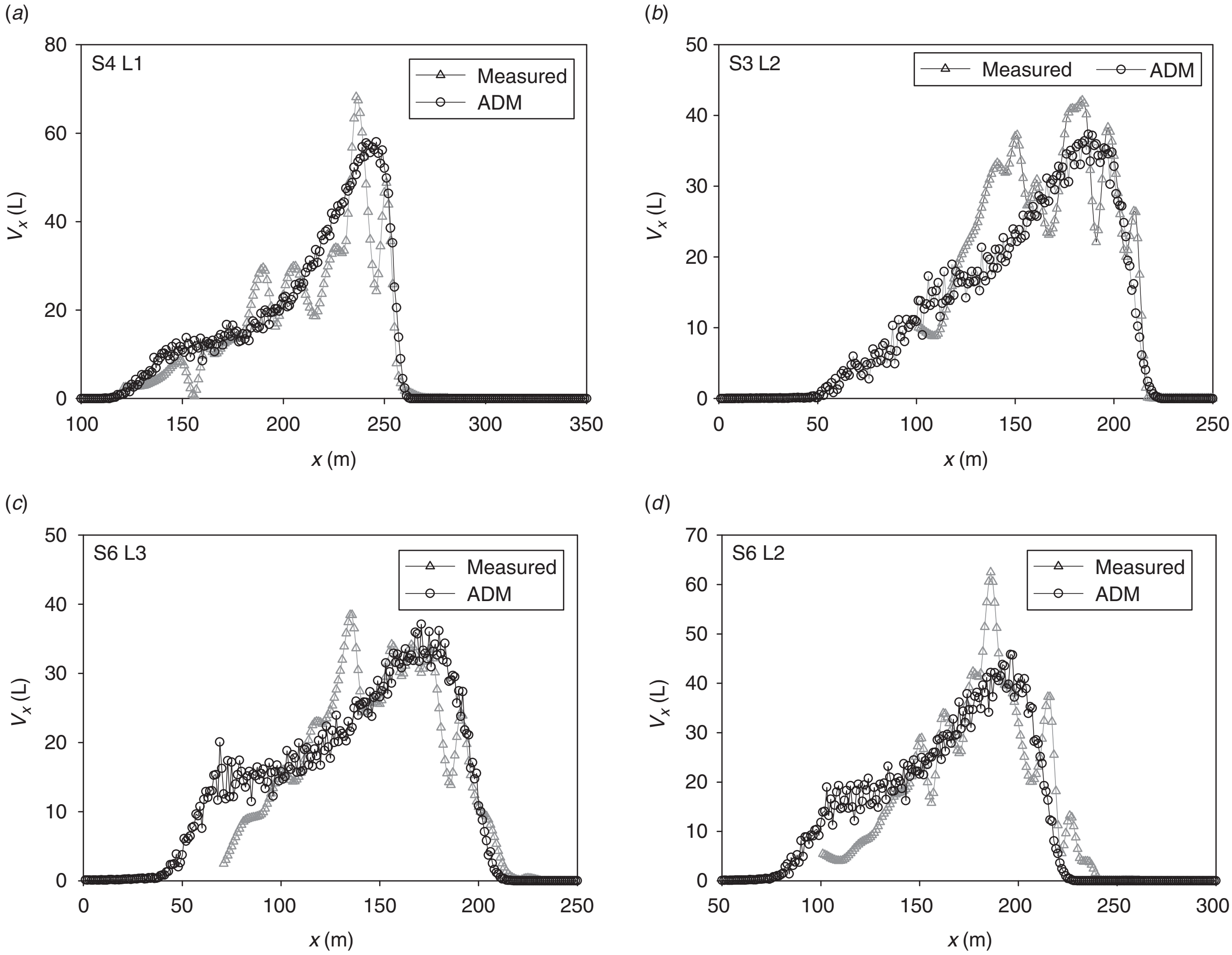

Fig. 8. Comparison between modelled and measured values of cumulative volume (V_x) deposited along the x axis for the Marseille drops.

respectively. V_x results are given in Fig. 9. As expected for a constant-flow delivery system, the distributions are almost symmetric in the majority of the drops, although with some right-skewness that results from the time taken for the flow rate of liquid exiting the tank to attain the maximum (and nearly constant) value. The total length of the ground patterns is considerably higher than in Marseille because of the higher volume of product dropped and the approximately constant flow rate at the exit (longer dropping times). By comparison with the measured values, the agreement can be considered very good, stressing the importance of having a detailed knowledge of the flow rate variation with time. Again, there is some tendency of ADM to underestimate the peak value of V_x, which varies between 4% of the maximum volume in M114 and 18% in M110 (not shown in Fig. 9), with an average value of 12%.

The difficulty found in having a good estimate of the maximum value of V_x in Marseille decreases in importance with the higher symmetry that characterises the volume distributions in Marana drops. Nevertheless, in both cases the modelled results are, in general, very close to the measured values.

In Fig. 10, the *NMSE* for the statistical comparison between the modelled and measured lengths and areas of each coverage level are presented. The averaged *NMSE* for the computed contour lengths is 0.015, whereas the *NMSE* for the simulated areas occupied by each level increases to 0.046. The averaged Pearson correlation coefficients (not shown) are 0.989 in both cases. The accuracy of the simulations shows no strong relation with the corresponding viscosity, although better results are obtained in the range from 700 to 1100 cP. Except for one case, there is a decreasing trend in the *NMSE* for the simulated pattern area with increasing viscosity.

In conclusion, the statistical validation has shown that, in general, the results are in good agreement with observations. This conclusion is particularly important given the wide range of input conditions and the difficulty in simulating the complex dynamical behaviour of firefighting products (especially retardants) in the atmosphere while maintaining the operational characteristics of the model.

Conclusions

The comparison between the simulated and observed spatial distribution of liquid concentration at ground revealed that ADM has some flexibility in dealing with the variation of the

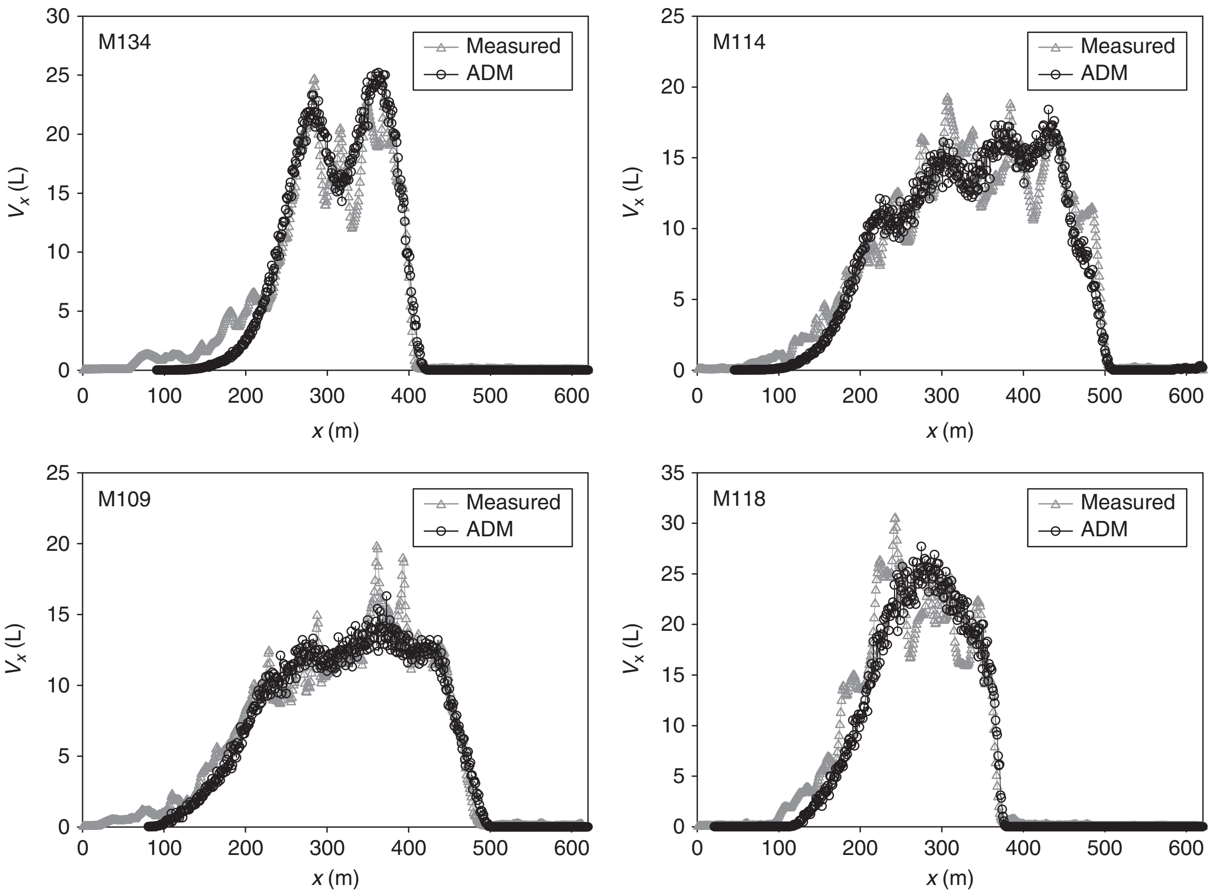

Fig. 9. Comparison between modelled and measured values of cumulative volume deposited along the *x* axis for the Marana drops.

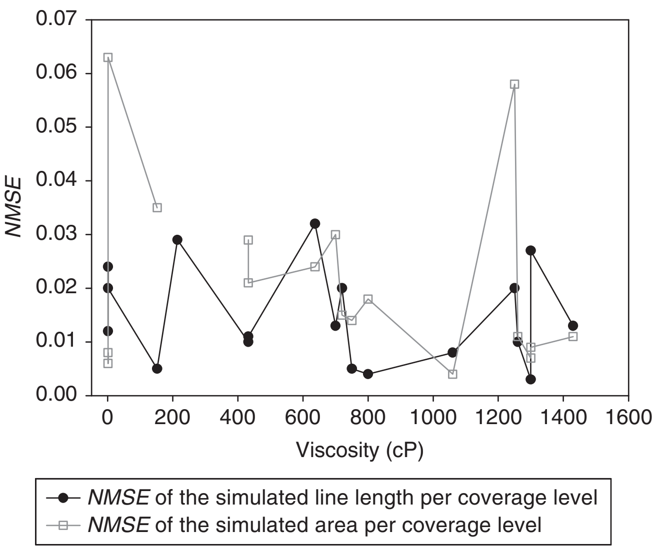

Fig. 10. Normalised mean squared error (*NMSE*) of the simulated length and area for each ground coverage level, considering the entire range of viscosities tested. Note that three distinct products (water, Fire-Trol (FT) and Phos-Check (PC)) are considered in the graphical representation. The higher *NMSE* (0.392) of the simulated area for the M112 drop (214 cP) was omitted in order to allow an easier interpretation of results.

input conditions without compromising the accuracy of the results. The wide range of viscosities tested showed that the computational code is suitable for the numerical representation of the aerodynamic breakup of the bulk liquid and the following deposition of the spray cloud. In particular, the computed ground pattern contours showed the features observed in the tests, namely a ground concentration profile that starts at the tail of the pattern with a light concentration, which is produced during the first instants after door-opening and increases with the increase in flow rate until the effective portion of the pattern (i.e. for concentrations above $0.8\,\mathrm{L\,m^{-2}}$) is attained. The higher concentrations at the front of the pattern, with a typical elliptic contour, are particularly visible in conventional delivery systems like the one used in Marseille. With a constant-flow delivery system, as in the Marana tests, there is a decrease in the maximum concentration attained, due to a more efficient ground distribution of product. This distinctive behaviour of the product as a function of the delivery system has been captured by ADM in the majority of the situations.

In the case of low-viscosity products (agent viscosity, $\mu_L < 214$ cP), a tendency to underestimate the contour length was found. However, this behaviour was observed mainly for concentrations in the pattern lower than $0.6\,\mathrm{L\,m^{-2}}$ (1.5 gpc). As the minimum retardant application rate required to stop a fire (despite variations in fire characteristics, meteorological conditions and vegetation) has been defined as 0.8 L m^{-2} (2 gpc) by fire agencies in the US (George and Blakely 1973) and Europe (Giroud *et al*. 2002), the underprediction referred to above does not compromise the ability of the model to simulate the operationally effective portion of the pattern.

In fact, the statistical validation of the results in terms of the computed length and area for several concentration ranges (coverage levels) indicated generally good model performance, in particular given the wide range of input conditions assessed. The model agreement is actually within the statistical uncertainty of the cup-and-grid sampling method. A total of 78% of the computed line lengths per coverage level are within a 10% error in general, with an average *NMSE* of 0.01 and a Pearson correlation coefficient above 0.9 in both Marseille and Marana drop trials. The accuracy of the simulated areas per level decreases to an average *NMSE* of 0.02 and 0.04 for the two drop trials respectively, although the good correlation remains. In all cases, nearly 90% of the results were within a factor of 2 of observations. Also, the averaged mean geometric bias (*MG*) was between 1.1 (for area) and 1.2 (for line length). It should be mentioned that, in spite of the higher level of uncertainty in the Marseille input data, the performance of the model in the simulation of line lengths in Marseille and Marana is similar, and it is even better for Marseille in the computation of pattern areas. It can be concluded that the discharge module used in the simulation of Marseille drops to compensate for the lack of measured flow rates led to good results, especially when considering the known difficulty of describing the unsteady outflow of liquid from a tank in conventional discharge systems.

Although the methodology for dealing with the complex process of liquid breakup is specifically suited for fluids exhibiting Newtonian behaviour, a decrease in the accuracy of results due to the viscoelastic behaviour of PC products, when compared with FT (which are non-elastic in nature) and, in the extreme, with water, was not observed. Based on the statistical evaluation of modelling results, the operational tool is capable of numerically describing on a simplified basis the phenomena occurring during breakup and deposition without prejudice to general performance. Nevertheless, research on the effect of the non-Newtonian characteristics of retardants on breakup time and droplet sizes is important, especially for determining if there are specific drop parameters (such as aircraft speed) where non-Newtonian behaviour could cause the model's performance to degrade. The development of numerical approaches that could encompass the response of viscosity to shear rate would allow an increase in the understanding of fluid behaviour, particularly for those products showing elastic properties, in order to provide an extended capability to adequately address differences in rheological properties, which are particularly relevant for the evaluation of the performance of new fire-chemical formulations. However, this will require that in future real-scale drop tests, elasticity, which is known to be an important factor in droplet formation during the aerodynamic breakup of viscoelastic agents, is measured on a regular basis. In the present study cases, the viscosity data from Marana and Marseille tests were measured only with a Brookfield viscometer, which does not provide the needed information on elasticity.

In conclusion, the validation process confirmed that the ADM model can be applied in predicting with good accuracy the ground patterns of firefighting agents dropped by fixed-wing aircraft over the tested range of drop conditions. The operational characteristics of the tool, and the good performance obtained, allow it to be used in the optimisation of firefighting operations, in the improvement of aerial delivery performance, as a complementary method to expensive and time-consuming drop testing, and in training and demonstration activities with pilots, aerial resource coordinators, civil protection personnel and on-the-ground firefighters.

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Appendix. Nomenclature used in this paper

- C, product concentration at ground (L m^{-2} or gpc)
- d, average bias $\left(d = \bar{d}_i = \overline{M_i - S_i}\right)$ (m or m^2)
- $FAC2$, factor of two: fraction of data that satisfy $0.5 \leq \frac{S_i}{M_i} \leq 2.0$ (unitless)
- FB, fractional bias $\left(FB = \frac{\sum_i (M_i - S_i)}{0.5 \cdot \sum_i (M_i + S_i)}\right)$ (unitless)
- MG, mean geometric bias $(MG = \exp(\overline{\ln M_i} - \overline{\ln S_i}))$ (m or m^2)
- M_i, ith measured value (unitless)
- $NMSE$, normalised mean squared error $\left(NMSE = \frac{\overline{(M_i - S_i)^2}}{\bar{M}\,\bar{S}}\right)$ (unitless)
- r, Pearson correlation coefficient $\left(r = \frac{\sum (M_i - \bar{M})(S_i - \bar{S})}{\left[\sum (M_i - \bar{M})^2 \cdot \sum (S_i - \bar{S})^2\right]^{1/2}}\right)$ (unitless)
- S_i, ith simulated value (unitless)
- VG, geometric variance $(VG = \exp[\overline{(\ln M_i - \ln S_i)^2}])$ (m^2 or m^4)
- x, position in the pattern (m)
- V_x, cumulative volume deposited along the x axis (L)
- $V(y)$, volume deposited in a given cell (L)
- δx, percentage error $\left(\delta x = \left(\frac{M_i - S_i}{M_i}\right) \times 100\right)$ (%)
- μ, mean value (m or m^2)
- μ_L, dynamic viscosity (cP)
- σ, standard deviation (m or m^2)