IMPACT OF ALTERNATIVE DISPERSION MODEL VALIDATION METHODS:

A Case Study on the LNG Model Validation Database using DRIFT

Simon Gant, Simon Coldrick, Graham Tickle and Harvey Tucker

Harmo-17 Conference, 9-12 May 2016

Budapest, Hungary

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Regulation of LNG Facilities

- US Federal Regulation 49 CFR 193 on Liquefied Natural Gas (LNG) facilities
- NFPA 59A (2001) "Standard for the Production, Storage, and Handling of LNG"
- Applicants required to calculate size of exclusion zones, based on vapour cloud dispersion distance to ½ Lower Flammability Limit (LFL) for design spills
- Approved dispersion models (until 2011): DEGADIS, FEM3A
- Alternative dispersion models approved by US Pipelines and Hazardous Materials Safety Administration (PHMSA) using the NFPA LNG Model Evaluation Protocol

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LNG Model Evaluation Protocol

2007 ← LNG Model Evaluation Protocol (Ivings *et al.*, 2007)

2008 ← LNG Model Validation Database (Coldrick *et al.*, 2008)

2009 ← Review of LNG Source Models (Webber *et al.*, 2009)

2010 ← LNG Model Validation Database, Version 11 (Coldrick *et al.*, 2010)
PHMSA Advisory Bulletin PHMSA-2010-0226

2011 ← DEGADIS 2.1 Evaluation (FERC, 2011)
PHAST v6.6/6.7 Evaluation (PHMSA, 2011)
FLACS v9.1r2 Evaluation (PHMSA, 2011)

2012

2013

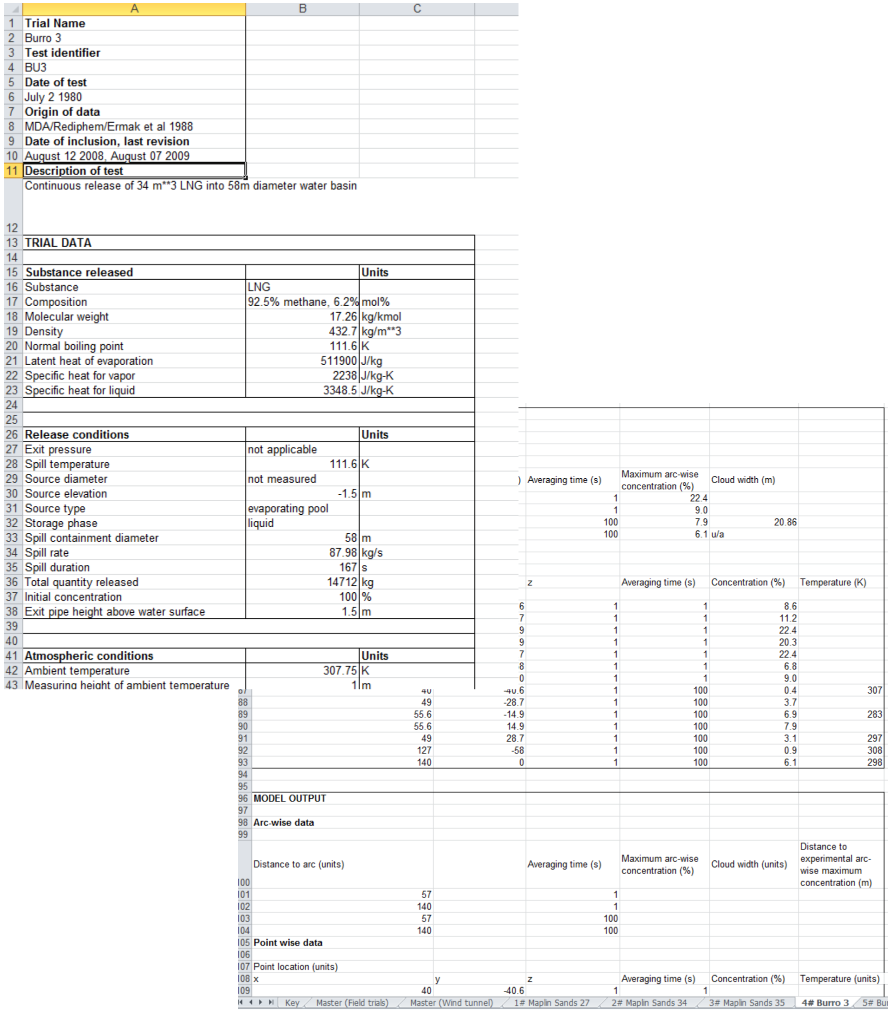
2014

2015

2016 ← LNG Model Validation Database, Version 12 (Stewart *et al.*, 2016)

LNG Model Validation Database

Trial Name	Sheet number in the Database	Trial number	Field (F) or Wind tunnel (WT)	Obstructed (O) or unobstructed (U)	Atmospheric stability	Substance released	Dispersion over water (W) or land (L)
Maplin Sands, 1980	1	27	F	U	C-D	LNG	W
	2	34			D		
	3	35			D		
Burro, 1980	4	3	F	U	B	LNG	L
	5	7			D		
	6	8			E		
	7	9			D		
Coyote, 1981	8	3	F	U	B-C	LNG	L
	9	5			C-D		
	10	6			D		
Falcon, 1987	11	1	F	O	G	LNG	L
	12	3			D		
	13	4			D-E		
Thorney Island 1982-4	14	45	F	U	E-F	Freon 12 & Nitrogen	L
	15	47			F		
CHRC, 2006	16	A	WT	U	D	Carbon Dioxide	L
	17	B		O	D		
	18	C		O	D		
BA-Hamburg	19	Unobstructed (DA0120)	WT	U	D	Sulfur Hexafluoride	L
	20	Unobstructed (DAT223)		U	D		
	21	Upwind fence (039051)		O	D		
	22	Upwind fence (039072)		O	D		
	23	Downwind fence (DA0501)		O	D		
	24	Downwind fence (DA0532)		O	D		
	25	Circular fence (039094/039095)		O	D		
	26	Circular fence (039097)		O	D		
	27	Slope (DAT647)		U	D		
	28	Slope (DAT631)		U	D		
	29	Slope (DAT632)		U	D		
	30	Slope (DAT637)		U	D		
BA-TNO	31	TUV01	WT	U	D	Sulfur Hexafluoride	L
	32	TUV02		O	D		
	33	FLS		U	D		



	A	B	C
1	**Trial Name**		
2	Burro 3		
3	**Test identifier**		
4	BU3		
5	**Date of test**		
6	July 2 1980		
7	**Origin of data**		
8	MDA/Rediphem/Ermak et al 1988		
9	**Date of inclusion, last revision**		
10	August 12 2008, August 07 2009		
11	**Description of test**		
12	Continuous release of 34 m**3 LNG into 58m diameter water basin		
13	**TRIAL DATA**		
14			
15	**Substance released**		**Units**
16	Substance	LNG	
17	Composition	92.5% methane, 6.2%	mol%
18	Molecular weight	17.26	kg/kmol
19	Density	432.7	kg/m**3
20	Normal boiling point	111.6	K
21	Latent heat of evaporation	511900	J/kg
22	Specific heat for vapor	2238	J/kg-K
23	Specific heat for liquid	3348.5	J/kg-K
24			
25			
26	**Release conditions**		**Units**
27	Exit pressure	not applicable	
28	Spill temperature	111.6	K
29	Source diameter	not measured	
30	Source elevation	-1.5	m
31	Source type	evaporating pool	
32	Storage phase	liquid	
33	Spill containment diameter	58	m
34	Spill rate	87.98	kg/s
35	Spill duration	167	s
36	Total quantity released	14712	kg
37	Initial concentration	100	%
38	Exit pipe height above water surface	1.5	m
39			
40			
41	**Atmospheric conditions**		**Units**
42	Ambient temperature	307.75	K
43	Measuring height of ambient temperature	1	m

Averaging time (s)	Maximum arc-wise concentration (%)	Cloud width (m)
1	22.4	
1	9.0	
100	7.9	20.86
100	6.1	u/a

z	Averaging time (s)	Concentration (%)	Temperature (K)
6	1	1	8.6
7	1	1	11.2
9	1	1	22.4
9	1	1	20.3
7	1	1	22.4
8	1	1	6.8
0	1	1	9.0

88	49	-28.7	1	100	3.7	
89	55.6	-14.9	1	100	6.9	283
90	55.6	14.9	1	100	7.9	
91	49	28.7	1	100	3.1	297
92	127	-58	1	100	0.9	308
93	140	0	1	100	6.1	298
94						
95						
96	**MODEL OUTPUT**					
97						
98	**Arc-wise data**					
99						
100	Distance to arc (units)		Averaging time (s)	Maximum arc-wise concentration (%)	Cloud width (units)	Distance to experimental arc-wise maximum concentration (m)
101	57		1			
102	140		1			
103	57		100			
104	140		100			
105	**Point wise data**					
106						
107	Point location (units)					
108	x	y	z	Averaging time (s)	Concentration (%)	Temperature (units)
109	40	-40.6	1	1		

Previous Evaluations

FLACS v9.1

PHAST v6.6/6.7

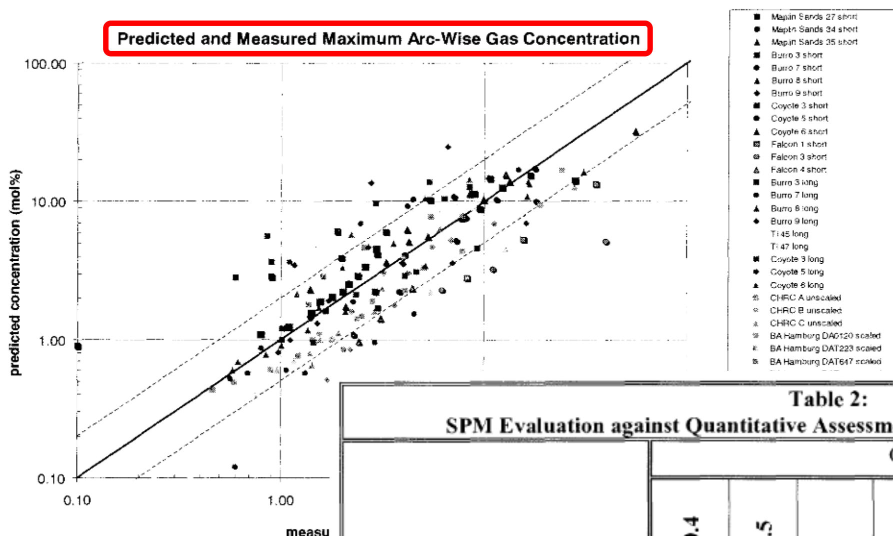
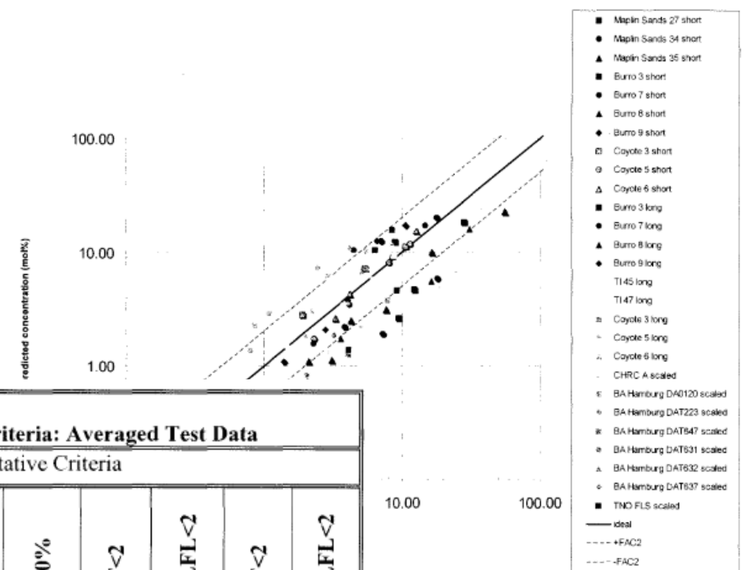


Figure 1 Predicted Co

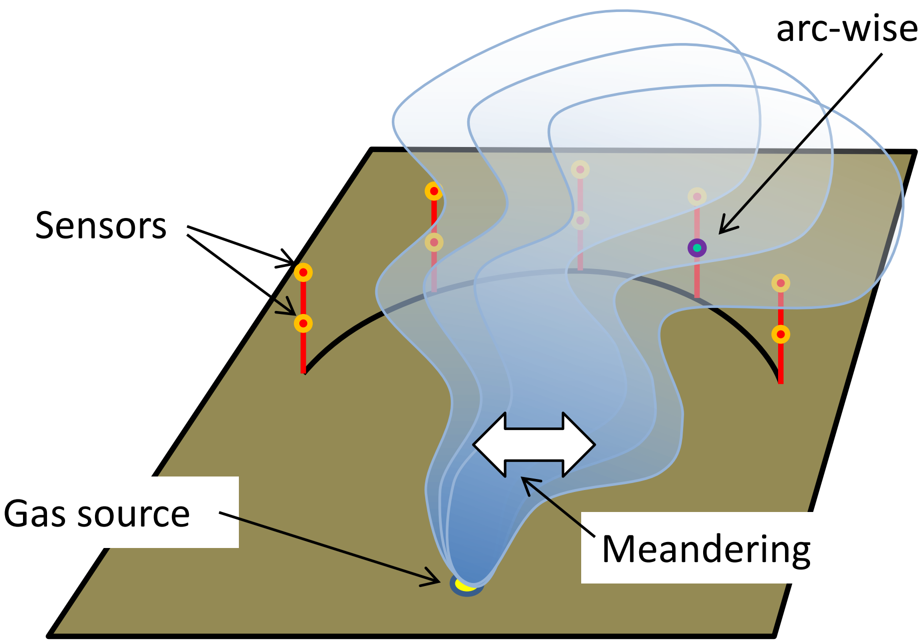


t Measured Concentration

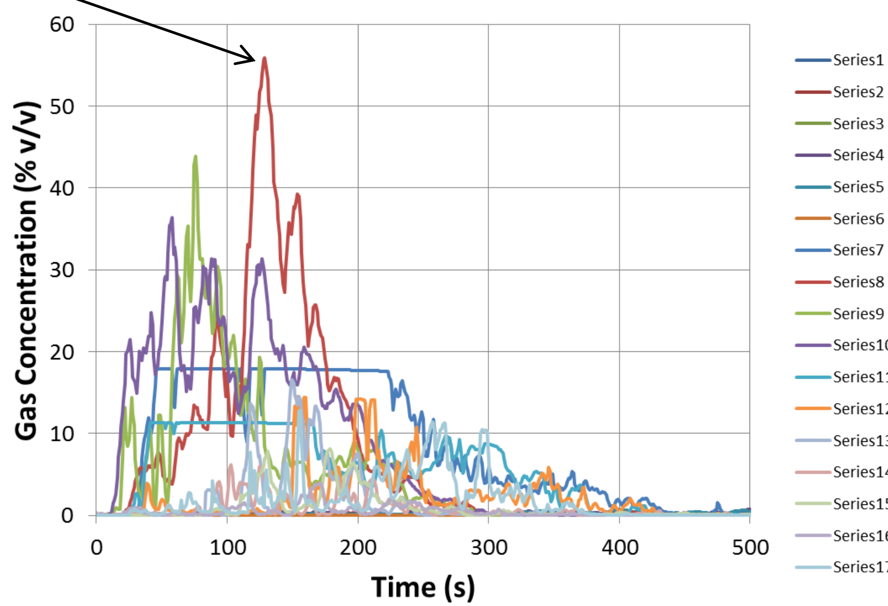
Table 2:
SPM Evaluation against Quantitative Assessment Criteria: Averaged Test Data

Data Set	Quantitative Criteria								
	-0.4<MRB<0.4	0.67< MG<1.5	MRSE<2.3	VG<3.3	FAC2 >50%	0.5<CSF<2	0.5< CSF_LFL<2	0.5<DSF<2	0.5< DSF_LFL<2
Maximum Arc-Wise Gas Concentration									
Maplin Sands 27 (short)	1.24	2.54	1.20	5.16	0%	0.64	0.38	N/A	N/A
Maplin Sands 34 (short)	1.10	3.45	1.21	4.70	0%	0.29	0.24	N/A	N/A
Maplin Sands 35 (short)	0.89	2.61	0.79	2.51	0%	0.38	0.38	N/A	N/A
Burro 3 (short)	0.06	1.06	0.14	1.15	100%	1.01	2.17	N/A	N/A

Maximum Arc-Wise Concentration

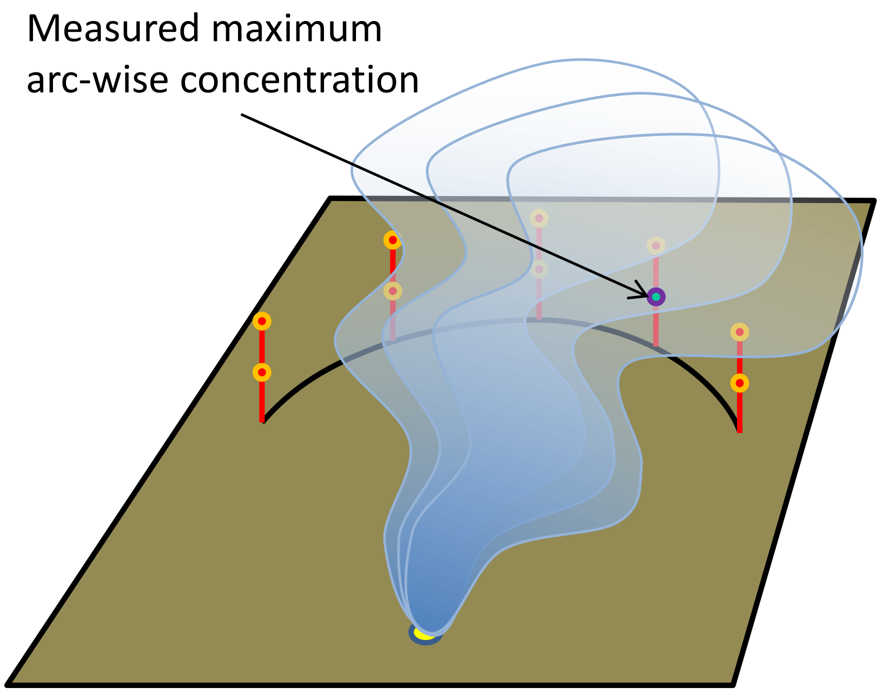


Experiments

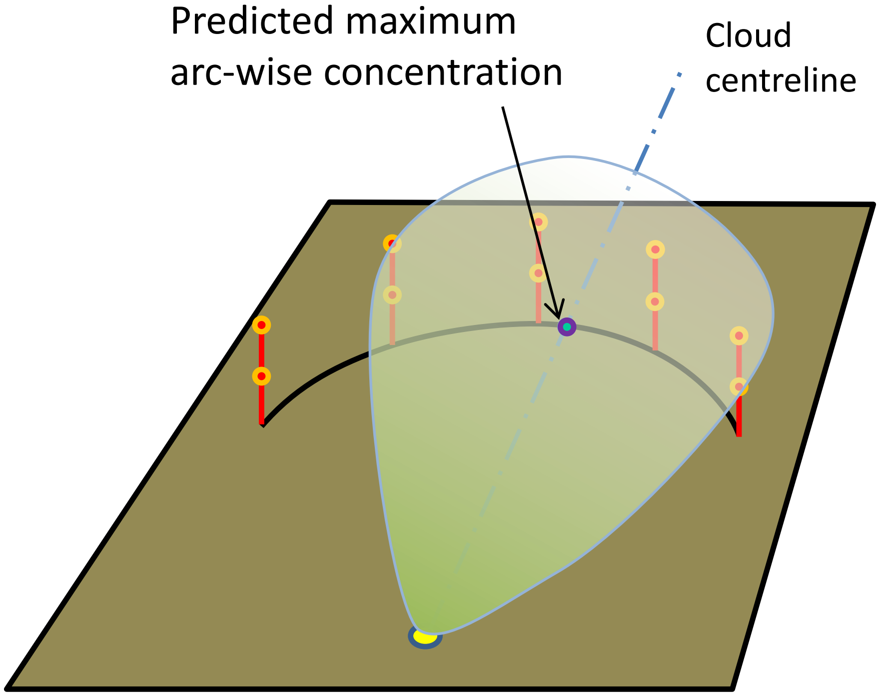


Example: Burro 8 sensors on arc at distance of 57 m

Maximum Arc-Wise Concentration



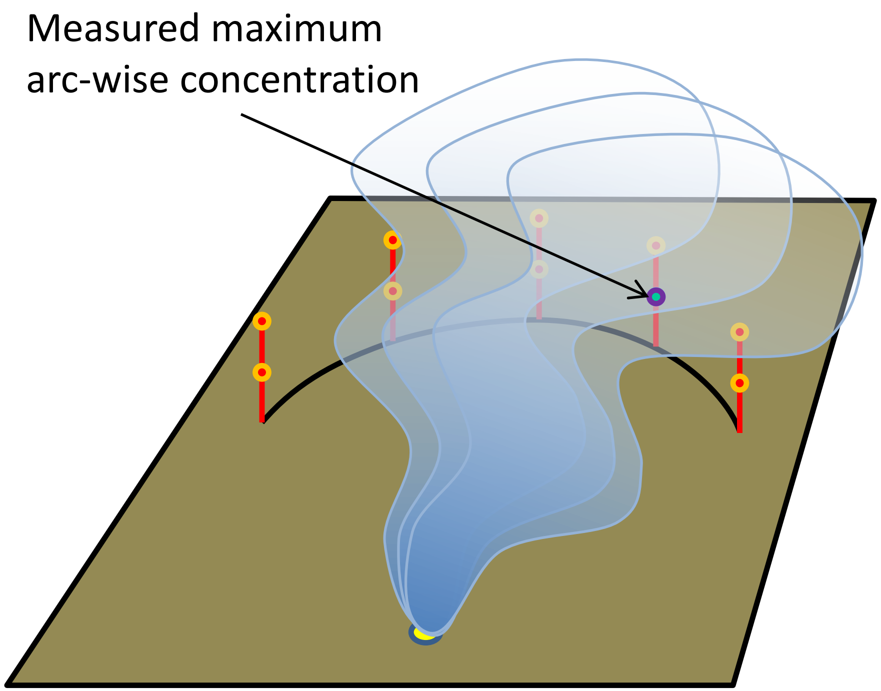
Experiments



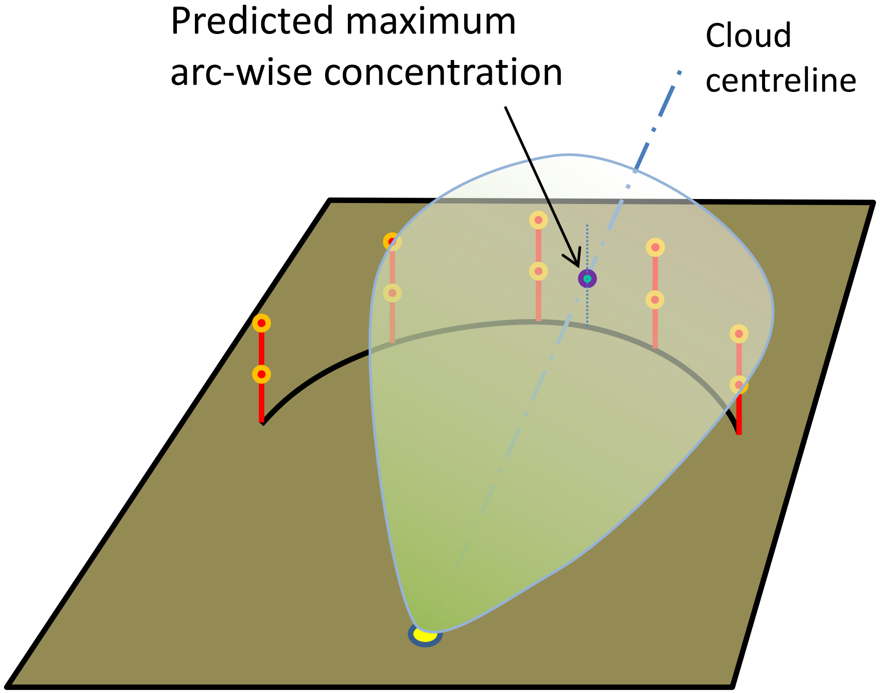
Model: Method 1

Maximum concentration at any circumferential position and at any height

Maximum Arc-Wise Concentration



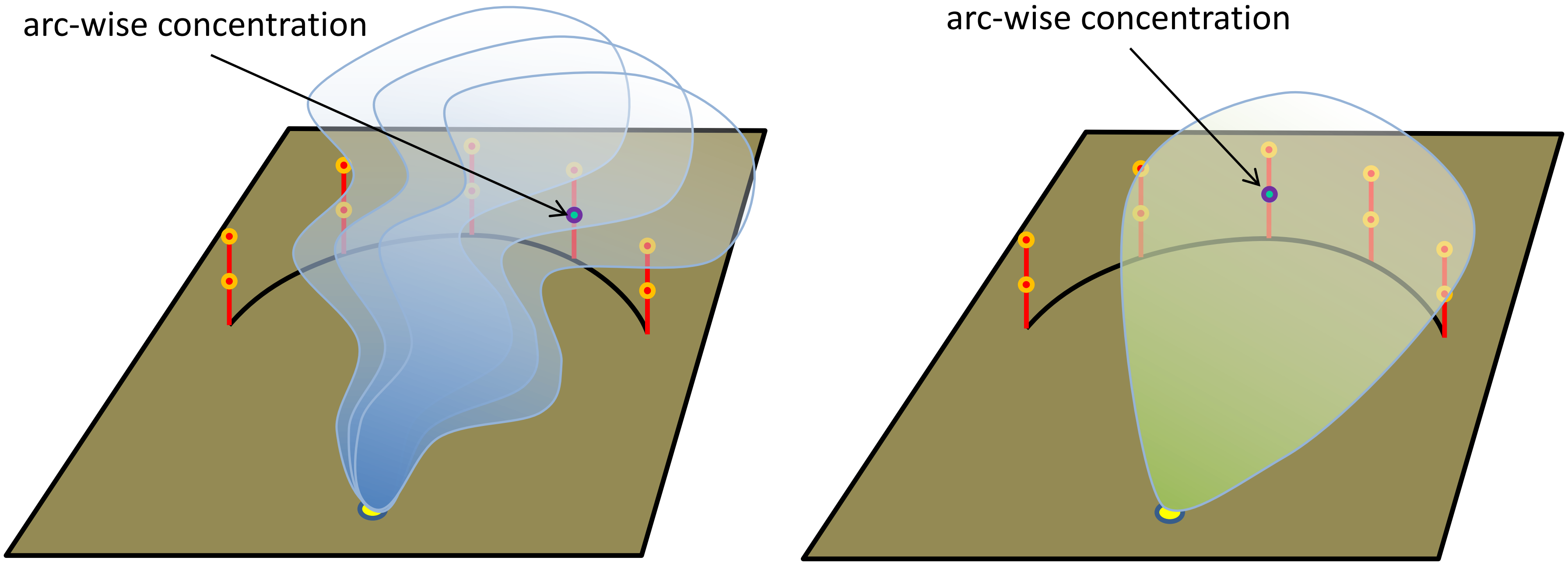
Experiments



Model: Method 2

Maximum concentration at any circumferential position and at height of lowest sensors

Maximum Arc-Wise Concentration



Experiments

Model: Method 3

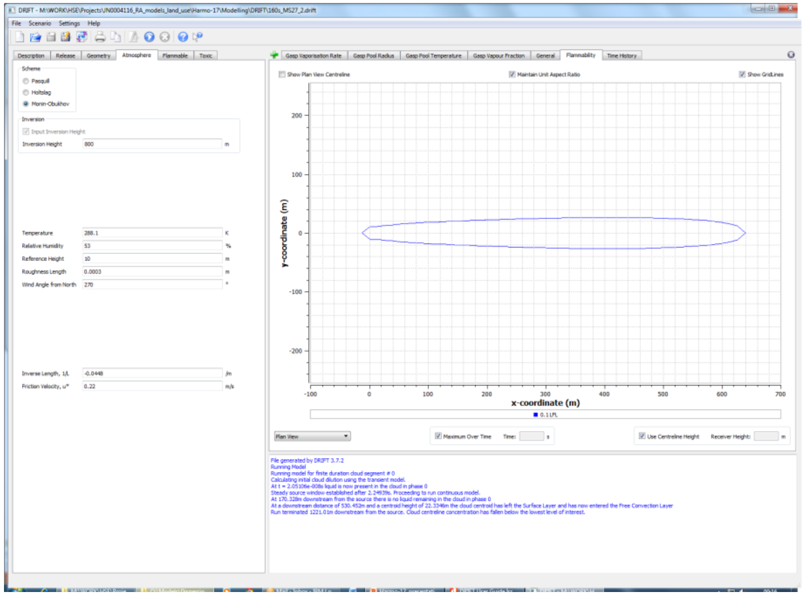
PHMSA-2010-0226 Advisory Bulletin "The maximum arc wise concentration should be based on the location of the experimental sensor data that produced the maximum arc wise concentration relative to the cloud centerline"

→ Maximum at any of the sensor positions

Aim & Methodology

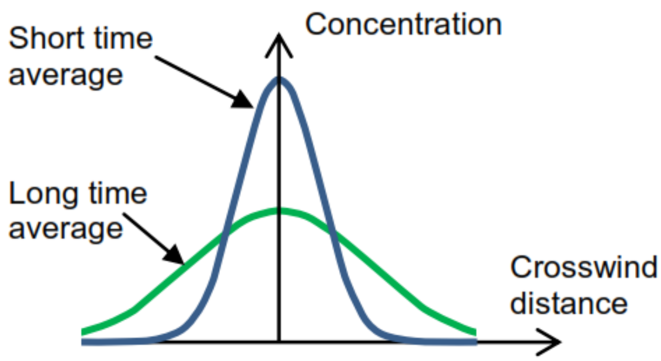
- **Aim**: To assess how Methods 1, 2 and 3 affect the results for the field-scale experiments in the LNG MEP
  - Does it matter which method is used?

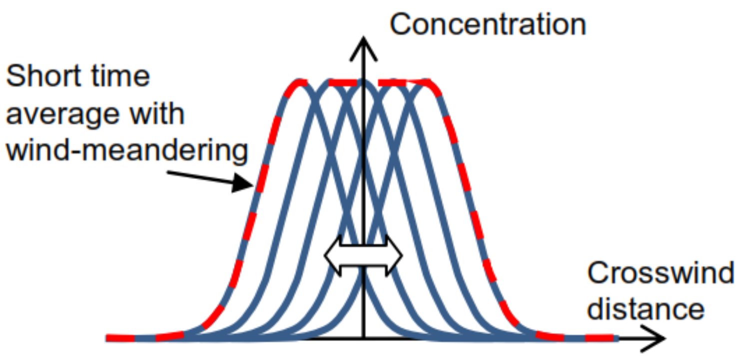
- **Methodology**: DRIFT integral dispersion model

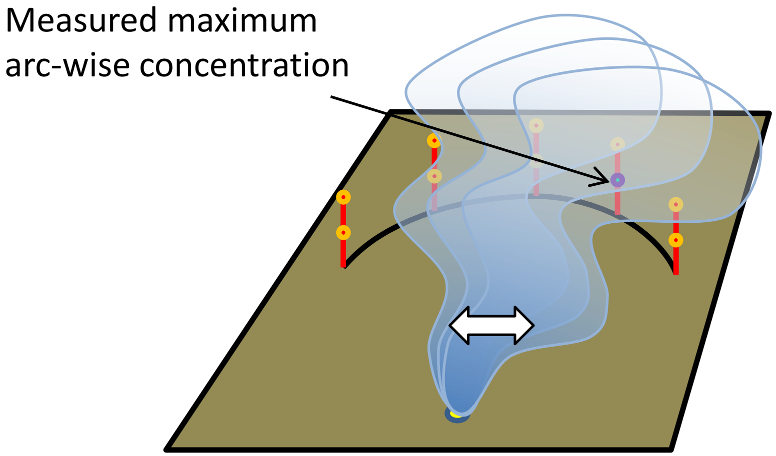


  - Developed by ESR Technology
  - Dense/passive/buoyant dispersion
  - GASP pool evaporation model

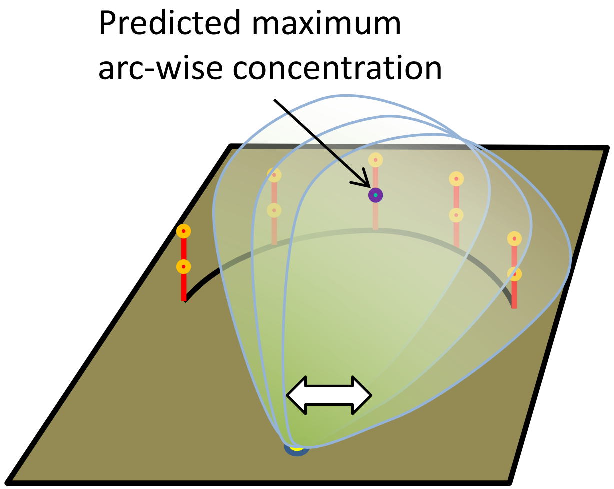
Plume Meander (Method 3a)





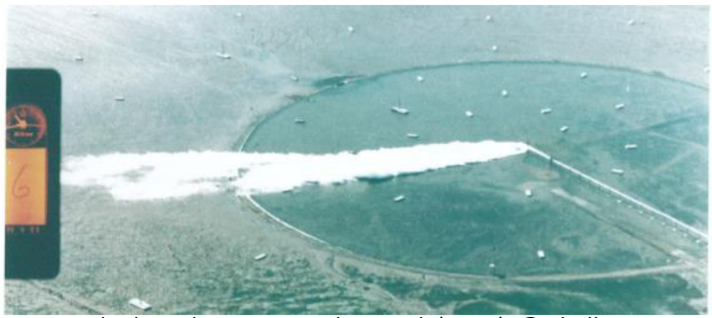


Experiments

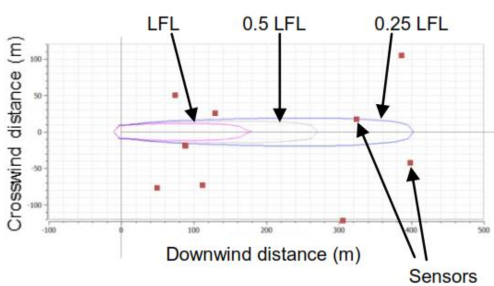


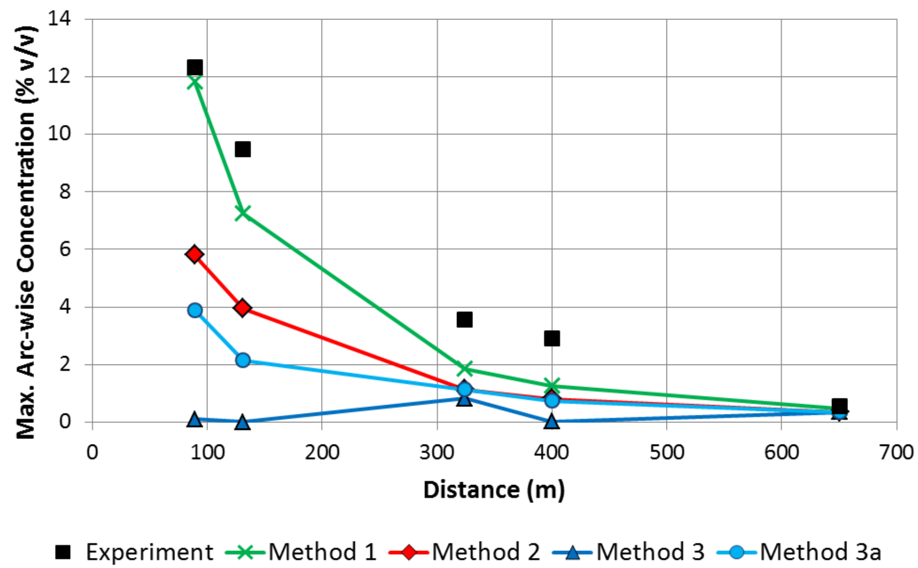
Model: Method 3a

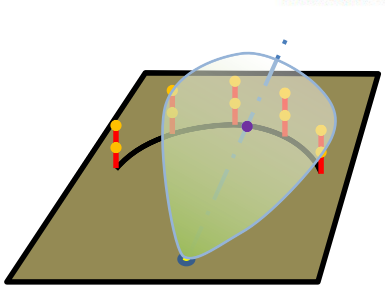
Results: Maplin Sands 27



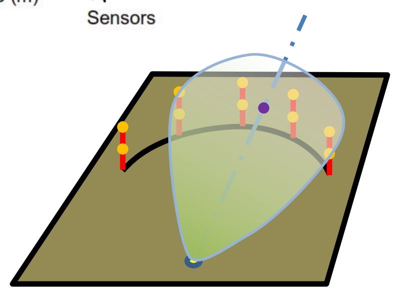
From: Colenbrander, Evans and Puttock (1984), © Shell



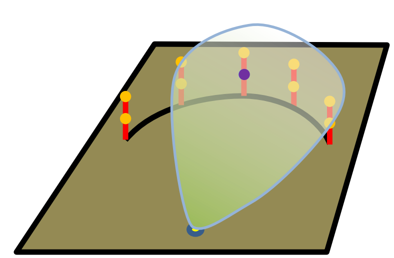




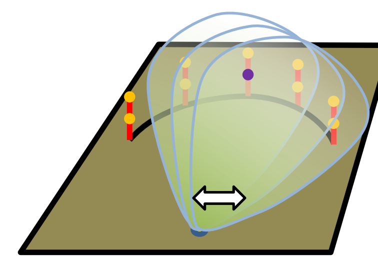
Method 1: Max. anywhere



Method 2: Max. at lowest sensor height

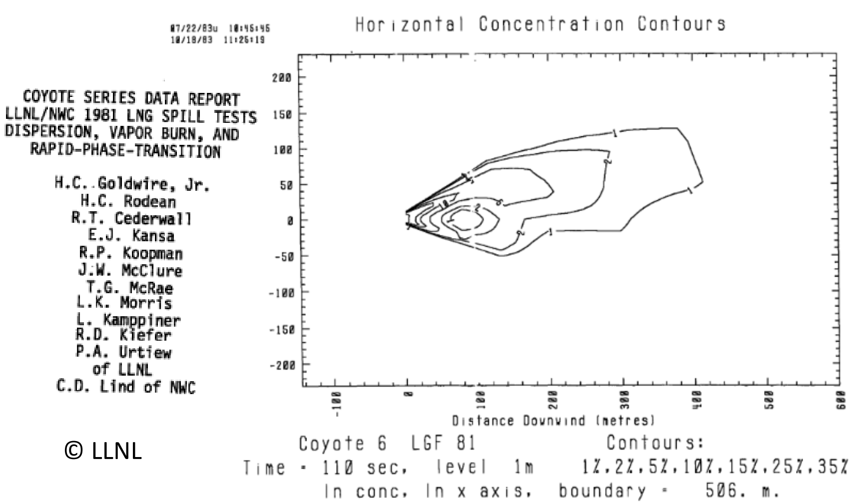


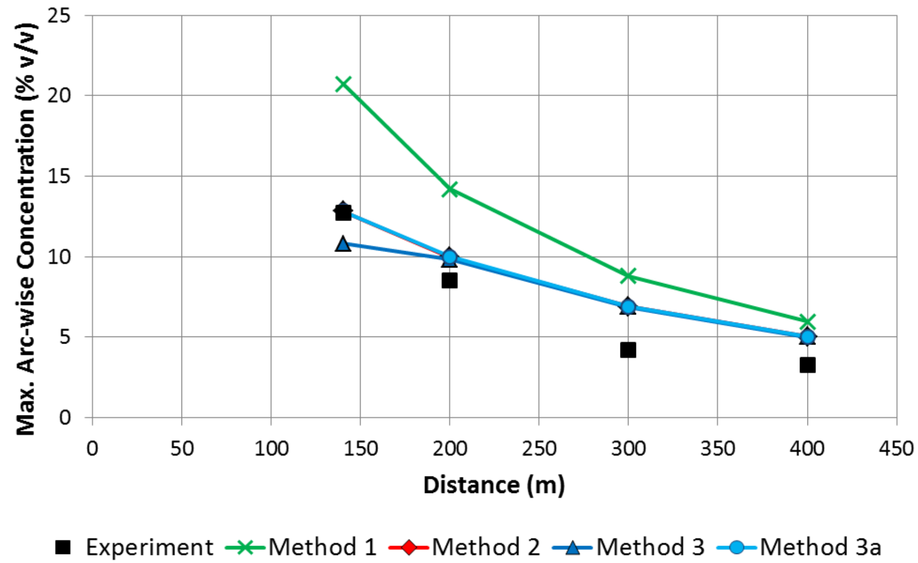
Method 3: Max. at sensor positions

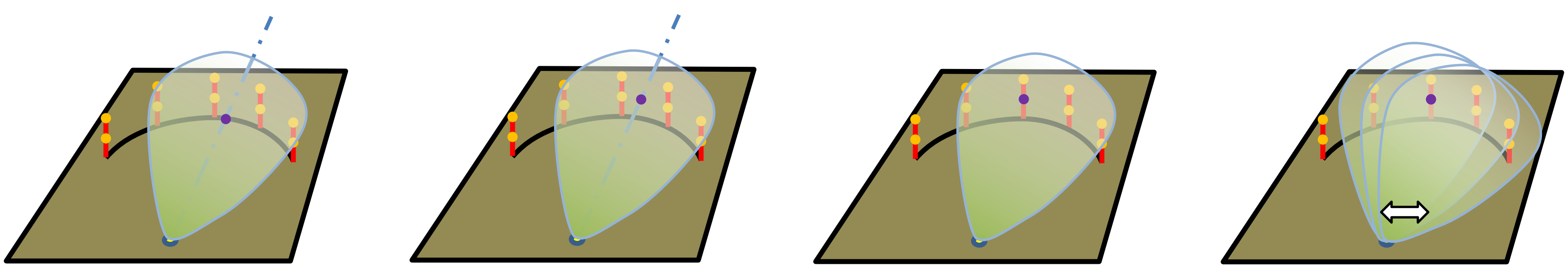


Method 3a: Wind meandering

Results: Coyote 6







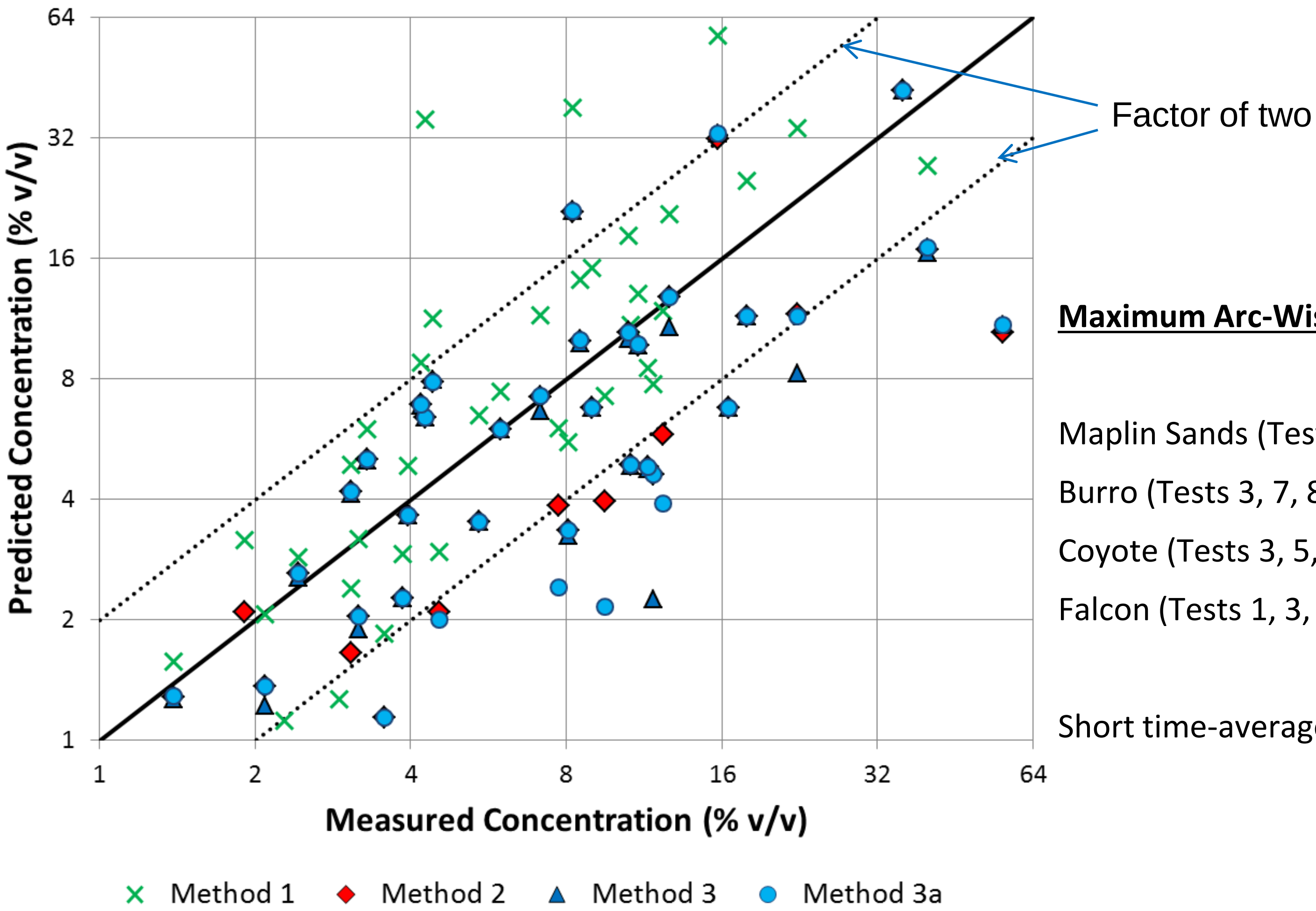
Method 1: Max. anywhere

Method 2: Max. at lowest sensor height

Method 3: Max. at sensor positions

Method 3a: Wind meandering

Results: Overall



Maximum Arc-Wise Concentrations

Maplin Sands (Tests 27, 34, 35)

Burro (Tests 3, 7, 8, 9)

Coyote (Tests 3, 5, 6)

Falcon (Tests 1, 3, 4)

Short time-averaged concentrations

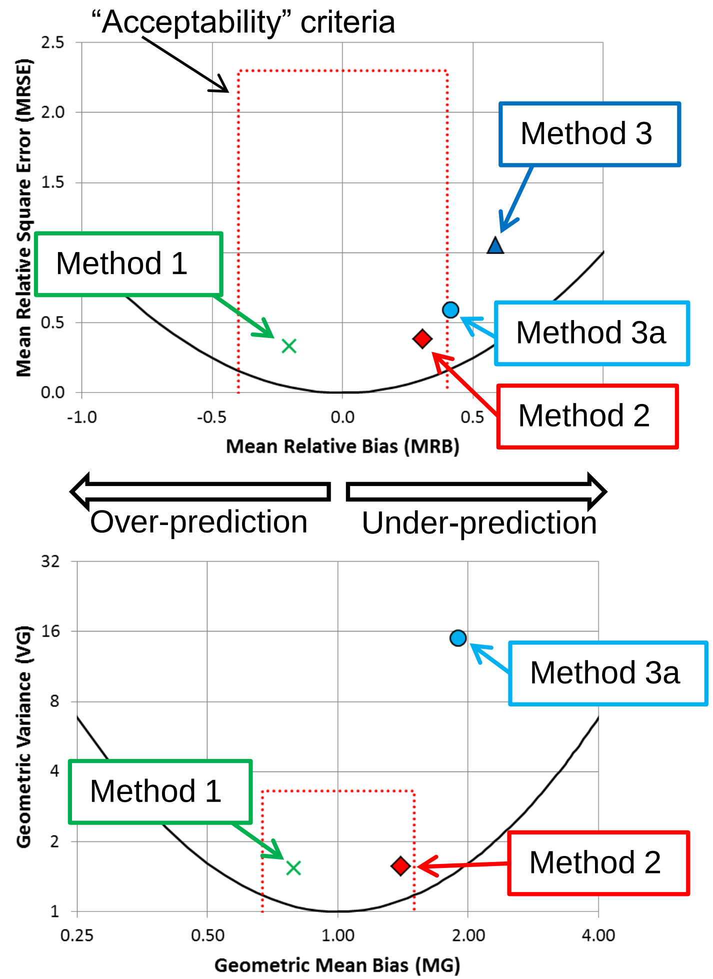
Results: Overall

	Method 1	Method 2	Method 3	Method 3a
Mean Relative Bias, MRB	-0.21	0.31	0.59	0.41
Mean Relative Square Error, MRSE	0.34	0.38	1.1	0.59
Geometric Mean Bias, MG	0.79	1.4	6.6	1.9
Geometric Variance, VG	1.5	1.6	2e13	15
Factor of Two	78%	61%	54%	56%

$$MRB = \left\langle \frac{C_m - C_p}{\frac{1}{2}(C_p + C_m)} \right\rangle \qquad MRSE = \left\langle \frac{(C_p - C_m)^2}{\frac{1}{4}(C_p + C_m)^2} \right\rangle$$

$$MG = exp\left\langle \ln\left(\frac{C_m}{C_p}\right) \right\rangle \qquad VG = exp\left\langle \left[\ln\left(\frac{C_m}{C_p}\right)\right]^2 \right\rangle$$

C_m = measured concentration $\qquad C_p$ = predicted concentration



Conclusions

- Choice of method for maximum arc-wise concentrations is important
- Depending on the choice of method, a model may be found to under/over-predict the measurements on average
- Method 3 (used by PHMSA) is more likely to indicate that a model under-predicts on average than other methods for max. arc-wise concentration
  - This is a precautionary approach given uncertainties in ensemble mean concentrations (it will tend to make the ½ LFL exclusion zone larger)
  - It accounts for the strong vertical gradient in concentration near the ground
  - It accounts for sensors not being aligned to arcs in some experiments
  - It encourages development of plume meandering models
- Further work is needed to investigate the plume meandering model in DRIFT and the sensitivity of results to the cloud height in the near-field

Acknowledgements

We would like to thank the following for their support in producing this work:

- Julie Halliday (PHMSA)
- Simon Rose (Oak Ridge National Laboratory)
- Andrew Kohout (Federal Energy Regulatory Commission)
- PHMSA
- Shell
- LLNL

(PHMSA, Shell, LLNL:) For permission to use their material

This publication and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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