Review of modelling methods for restricted and horizontal stacks

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Background

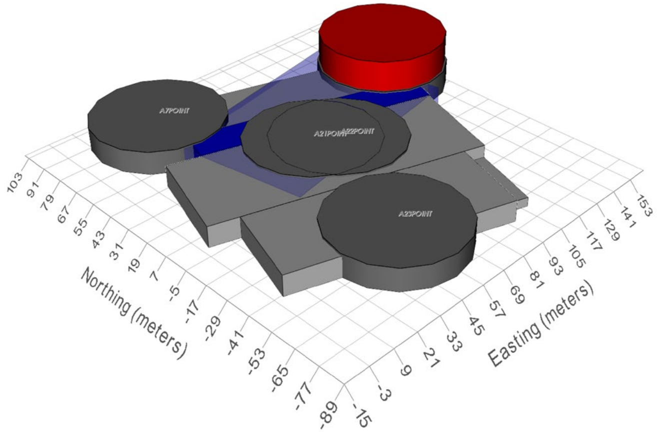
- Capped and horizontal stacks do not represent best available techniques (BAT) for most regulated industries
- Capped and horizontal stacks are often associated with older medium combustion plant (MCP) which are being brought into UK regulation
- Consultants use a variety of methods to model capped and horizontal sources
- Review was requested by the Environment Agency's (EA) Environment and Business directorate
- Review focusses on the dispersion models that are most commonly used in UK regulation: ADMS and AERMOD

Aims

- Identify the recommended methods for each model for reasonable worst-case predictions and consistency across air quality assessments (AQA)
- Investigate the limitations and modelling uncertainties associated with each method
- Reminder of the EA’s guidance on estimating model uncertainty and sensitivity analysis

Summary of methods often used

- Pseudo point sources in ADMS with non-zero vertical momentum (efflux velocity reduced to 0.1-0.001 m/s)
- Plume buoyancy not conserved
- Plume buoyancy conserved using an effective stack diameter to preserve volumetric flow
- Stack-induced downwash typically not switched off
- ADMS jet sources for horizontal stacks



Vertical momentum

- AERMOD – US EPA Model Clearinghouse Memo 93-II-09 velocity of 0.001 m/s
- ADMS – velocity set to 'non-zero'
- Proposed Guideline for Air Dispersion Modelling (2003, now withdrawn) – velocity set to between 0.1-0.01 m/s
- TG16 (2016) – velocity of <1 m/s or as low as 0.1 m/s
- EA MCP Screening Tool guidance – divide the velocity by 1000 e.g. 20 m/s / 1000 = 0.02 m/s

Plume buoyancy

- Models use volumetric flowrates and efflux temperature to calculate buoyant plume rise
- When reducing the efflux velocity to non-zero, actual volumetric flowrate must be maintained to preserve thermal buoyancy
- An ‘effective’ stack diameter should be calculated to maintain volumetric flowrate

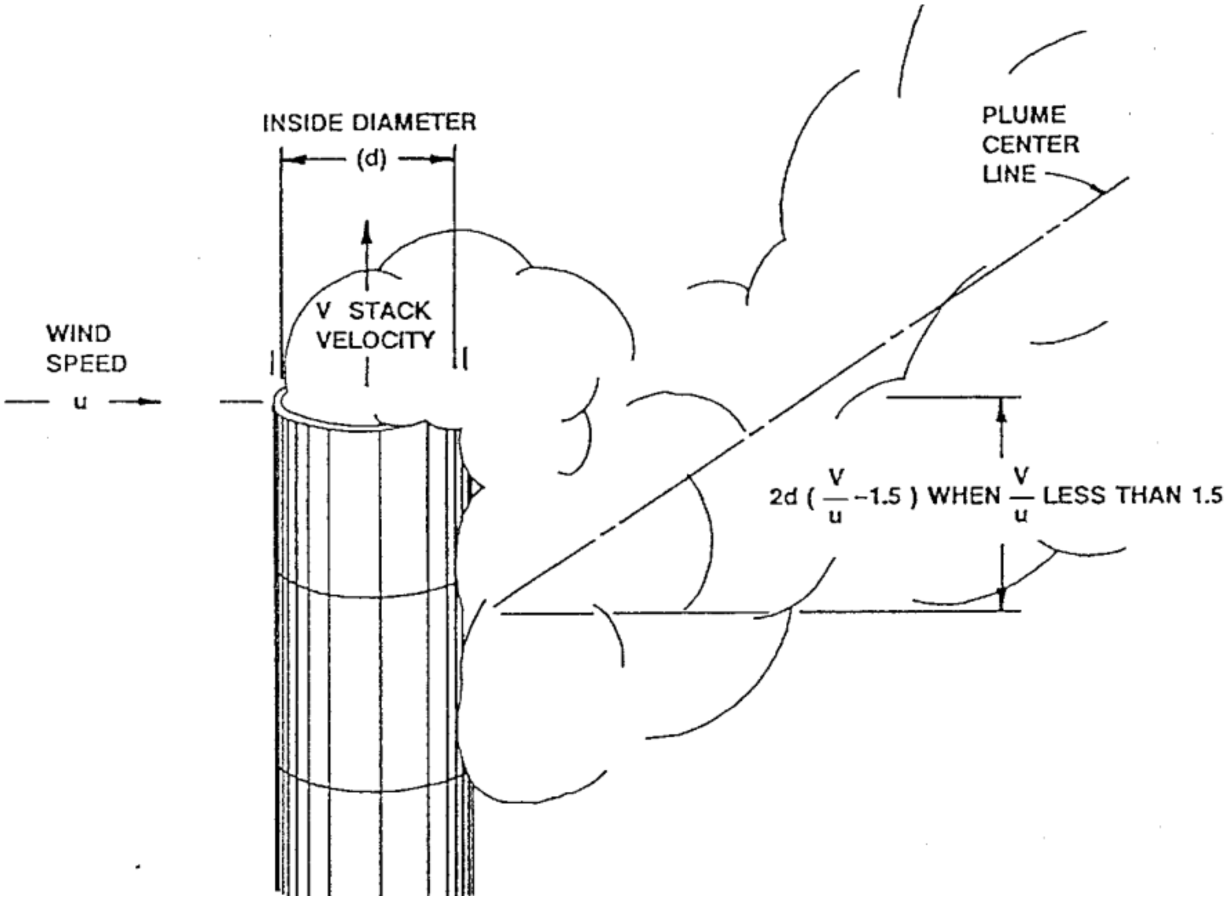
$$\boldsymbol{Effective\ diameter = 2 * \sqrt{\frac{\left(\frac{actual\ volumetric\ flowrate}{reduced\ efflux\ velocity}\right)}{\pi}}}$$

Stack-induced downwash

- Stack-induced downwash is an algorithm used by both ADMS and AERMOD to simulate the potential reduction in the effective height of release from stack-top cross wind turbulence
- Downwash is assumed when stack-top horizontal wind speed exceeds two thirds the stack efflux velocity
- Effective height of the stack reduced by up to three times the stack diameter depending on the ratio between wind speed and efflux velocity. If wind speed exceeds two-thirds of efflux velocity:

$$\boldsymbol{Stack\ height\ reduction = 2 * stack\ diameter * \left(\frac{efflux\ velocity}{wind\ speed} - 1.5\right)}$$

Stack-induced downwash



Trinity Consultants Breeze AERMOD training material

AERMOD stack options

- Capped point sources – when capped stacks are subject to building downwash, AERMOD doubles the actual stack diameter, divides the actual efflux velocity by four and sets the plume trajectory to horizontal
- Horizontal point sources – when horizontal stacks are subject to building downwash, AERMOD sets the plume trajectory to horizontal
- For both capped and horizontal sources, the direction of release is aligned with the wind direction for each met hour
- Stack-induced downwash is not modelled for capped or horizontal stack options

Methodology

- ADMS 6
- Breeze AERMOD 11 (22112 executable)
- Lakes AERMOD 11.2 (22112 executable)
- Real world case studies of regulated industrial facilities with restricted or horizontal stacks
- Tested sensitivity to a range of methods used by consultants and compared the results
- Tested sensitivity to a range of model input data and model options, e.g. source terms, meteorology and building configurations

Model inputs

Site	Industry Type	Source Types	Number of Buildings	Building Height Range	Number of Stacks	Stack Height Range	Stack Diameter	Efflux Velocity	Stack Temperature
				m		m	m	m/s	°C
1	Food and drink	Natural gas ovens with low clearance vertical capped stacks on top of buildings	9	8.1-21	4	12-14	0.3-0.5	1.84-5.23	130-250
2	Food and drink	Natural gas ovens with low clearance vertical capped stacks and horizontal stacks on top of buildings	1	10	5	11	0.5	15	250
3	Sewage treatment	Diesel engines with low clearance horizontal stacks on top of buildings	5	3.65-14.1	4	4.24	0.5	32.1	400

Sensitivity

Model	Source type / Method	Stack-induced downwash	Stack Diameter (actual/ effective*)	Stack Height	Stack Temperature	Efflux Velocity
			m	m	°C	m/s
ADMS	Pseudo Point	On / Off	10.1-76*	4.24-40	25-400	0.001-1
AERMOD	Pseudo Point	On / Off	10.1-76*	4.24-40	25-400	0.001-1
AERMOD	Horizontal	Off	0.3-0.5	4.24-40	25-400	1.84-50
AERMOD	Capped	Off	0.3-0.5	4.24-40	25-400	1.84-50

Case study 3 – ADMS jet sources

Source type	Stack Height	Stack diameter	Efflux velocity	Angle 1 (pitch angle)	Angle 2 (release direction)	Stack Temperature
	m	m	m/s	°	°	°C
Jet	4.24	0.42	32.1	0	000	25-400
Jet	4.24	0.42	32.1	0	045	25-400
Jet	4.24	0.42	32.1	0	090	25-400
Jet	4.24	0.42	32.1	0	135	25-400
Jet	4.24	0.42	32.1	0	180	25-400
Jet	4.24	0.42	32.1	0	225	25-400
Jet	4.24	0.42	32.1	0	270	25-400
Jet	4.24	0.42	32.1	0	315	25-400

Results

- Example from case study 1, ADMS point sources vs AERMOD capped sources
- 1-hour 100th percentile results
- No clear trends on which model predicts higher in like-for-like scenarios
- Results between models in like-for-like scenarios can vary significantly

ADMS predicts higher
AERMOD predicts higher

Case study 1 - 100th %ile 1-hour					
		Source			
Receptor	Approx. distance from stack	1	2	3	4
1	97	-125%	-45%	50%	22%
2	192	38%	32%	-6%	-22%
3	248	50%	53%	39%	7%
4	312	61%	59%	41%	-5%
5	354	63%	58%	33%	-29%
6	368	72%	67%	64%	21%
7	354	76%	69%	65%	35%
8	362	73%	75%	61%	63%
9	385	57%	45%	38%	34%
10	425	30%	45%	-24%	36%
11	173	-12%	24%	58%	54%
12	132	-33%	-21%	54%	52%
13	105	-176%	-35%	43%	41%
14	158	-14%	27%	49%	31%
15	139	7%	37%	64%	47%
16	157	38%	37%	66%	52%
17	251	34%	61%	57%	39%
18	667	62%	54%	38%	8%
19	773	28%	-20%	16%	47%
20	625	74%	61%	53%	35%
21	727	78%	71%	65%	53%
22	672	62%	54%	59%	57%

Results – vertical momentum

- Annual and 100th percentile results
- Significant reduction in predictions from 0.001 m/s to 0.01 m/s
- In certain situations, increasing efflux velocity can increase predictions
- Velocity of 0.001 m/s is generally worst-case but could be over-predicting

Annual				
		Velocity (m/s)		
Receptor	Direction from stack	0.001 vs 0.01	0.01 vs 0.1	0.1 vs 1
1	E	14%	3%	-1%
2	W	-14%	0%	-1%
3	N	-11%	-1%	-1%
4	S	-37%	-4%	-1%
5	SW	1%	1%	-1%
6	SE	-34%	-2%	-1%
7	NE	-22%	-2%	-2%
8	NW	-17%	-2%	-1%
100th %ile 1-hour				
1	E	-39%	9%	-2%
2	W	-34%	4%	-2%
3	N	-50%	2%	-1%
4	S	-56%	4%	-2%
5	SW	-20%	3%	-2%
6	SE	-38%	5%	-2%
7	NE	-57%	4%	-2%
8	NW	-39%	4%	-1%

Increasing velocity predicts higher
Decreasing velocity predicts higher

Results – plume buoyancy

- Results from case study 1 looking at differences between buoyant and non-buoyant sources
- Annual average concentrations
- For all sources and receptors, conserving plume buoyancy decreased predictions

Case study 1 - Annual					
		Source			
Receptor	Approx. distance from stack	1	2	3	4
1	97	-43%	-38%	-42%	-48%
2	192	-35%	-32%	-29%	-24%
3	248	-39%	-36%	-33%	-24%
4	312	-42%	-38%	-33%	-29%
5	354	-44%	-41%	-35%	-29%
6	368	-46%	-44%	-40%	-31%
7	354	-45%	-42%	-41%	-29%
8	362	-46%	-43%	-42%	-30%
9	385	-44%	-41%	-39%	-27%
10	425	-36%	-34%	-30%	-33%
11	173	-58%	-59%	-61%	-63%
12	132	-55%	-53%	-56%	-59%
13	105	-50%	-43%	-48%	-52%
14	158	-39%	-37%	-39%	-43%
15	139	-32%	-29%	-33%	-41%
16	157	-30%	-28%	-32%	-41%
17	251	-33%	-32%	-33%	-39%
18	667	-40%	-33%	-26%	-27%
19	773	-34%	-29%	-21%	-25%
20	625	-48%	-41%	-31%	-34%

Buoyancy predicts lower
Buoyancy predicts higher

Results – stack-induced downwash

- Example from case study 3 – ADMS point sources with stack-induced downwash on vs off
- Annual results from the four sources at 15 m stack height
- Stack-induced downwash can lead to large over-estimations in predictions
- Receptors 15-21 are within 100 m of sources, others are further away

Case study 3 - Annual					
		Source			
Receptor	Approx. distance from stack	1	2	3	4
1	66	-96%	-93%	-90%	-86%
2	124	-81%	-78%	-75%	-72%
3	192	-46%	-44%	-43%	-42%
4	519	-47%	-47%	-47%	-47%
5	325	-39%	-38%	-37%	-36%
6	283	-59%	-59%	-59%	-59%
7	442	-29%	-29%	-29%	-28%
8	474	-21%	-21%	-22%	-22%
9	552	-25%	-26%	-26%	-26%
10	842	-10%	-10%	-10%	-10%
11	140	-62%	-60%	-59%	-57%
12	599	-21%	-21%	-22%	-22%
13	275	-72%	-74%	-76%	-78%
14	369	-40%	-41%	-43%	-44%
15	136	-99%	-99%	-99%	-99%
16	80	-99%	-98%	-96%	-93%
17	95	-99%	-99%	-99%	-97%
18	108	-100%	-99%	-99%	-99%
19	127	-99%	-99%	-99%	-99%
20	145	-99%	-99%	-99%	-99%
21	114	-97%	-97%	-96%	-95%

On predicts higher
Off predicts higher

Results – case study 1

ADMS predicts higher
AERMOD predicts higher

Case study 1 - Annual					
		Method			
Receptor	Approx. distance from stack	ADMS Point	AERMOD Point	AERMOD Capped	AERMOD Horizontal
1	97	113.8	52.4	105.6	106.2
2	192	46.1	30.0	42.7	42.9
3	248	33.2	22.4	32.4	32.8
4	312	22.9	17.9	23.9	24.0
5	354	14.7	13.5	18.0	17.9
6	368	6.8	9.2	12.6	12.6
7	354	5.0	8.4	11.8	11.7
8	362	3.7	6.3	8.6	8.5
9	385	3.0	4.3	5.4	5.2
10	425	2.4	3.7	4.5	4.4
11	173	15.5	15.6	29.8	30.9
12	132	30.3	23.3	45.6	46.0
13	105	69.9	41.7	85.5	85.4
14	158	51.2	32.0	49.3	49.7
15	139	51.9	33.1	53.8	54.6
16	157	43.3	29.6	46.8	47.3
17	251	21.9	19.5	26.7	26.8
18	667	1.0	1.4	1.7	1.6
19	773	0.8	1.2	1.4	1.3
20	625	3.1	3.5	4.2	4.2
21	727	2.0	3.1	4.6	4.6
22	672	4.5	5.2	7.5	7.4

Case study 1 - 100th %ile 1-hour					
		Method			
Receptor	Approx. distance from stack	ADMS Point	AERMOD Point	AERMOD Capped	AERMOD Horizontal
1	97	1330.0	479.6	1224.1	1198.9
2	192	672.0	368.5	893.0	922.3
3	248	444.0	358.5	835.6	865.5
4	312	365.0	370.6	719.4	747.3
5	354	382.0	359.3	629.9	638.9
6	368	343.0	421.2	814.3	858.6
7	354	453.0	487.2	1178.0	1241.7
8	362	315.0	501.9	1125.3	1173.5
9	385	418.0	447.1	789.1	801.3
10	425	376.0	270.8	409.6	415.9
11	173	771.0	289.3	841.8	945.6
12	132	889.0	437.3	1114.8	1074.7
13	105	1280.0	443.1	980.8	968.3
14	158	793.0	425.8	864.6	890.1
15	139	780.0	347.7	1123.5	1323.0
16	157	552.0	390.1	940.6	1096.0
17	251	334.0	379.8	838.4	867.8
18	667	279.0	308.6	536.2	545.5
19	773	249.0	212.3	308.9	311.1
20	625	291.0	309.9	569.4	599.6
21	727	207.0	191.6	505.2	551.9
22	672	227.0	222.5	425.4	451.5

Results – case study 3

ADMS predicts higher
AERMOD predicts higher

Case study 3 - Annual					
		Method			
Receptor	Approx. distance from stack	ADMS Point	AERMOD Point	AERMOD Capped	AERMOD Horizontal
1	66	29.9	19.5	28.7	30.0
2	124	13.7	9.3	11.6	12.1
3	192	8.1	6.3	6.7	6.4
4	519	3.1	1.9	2.1	1.9
5	325	4.9	3.7	3.8	3.7
6	283	4.7	3.0	3.2	3.0
7	442	3.4	2.6	2.6	2.6
8	474	7.8	7.7	7.7	7.7
9	552	6.1	5.4	5.5	5.4
10	842	3.2	2.7	2.7	2.7
11	140	8.1	5.6	6.2	5.9
12	599	2.4	2.2	2.2	2.2
13	275	13.5	8.8	10.4	9.6
14	369	12.0	12.2	12.7	12.3
15	136	43.0	13.0	24.7	35.8
16	80	36.1	19.0	30.3	36.2
17	95	42.9	16.9	29.7	41.5
18	108	45.7	14.5	27.1	38.0
19	127	45.1	13.0	25.0	37.1
20	145	41.9	13.3	25.1	36.9
21	114	29.0	11.8	19.7	26.9

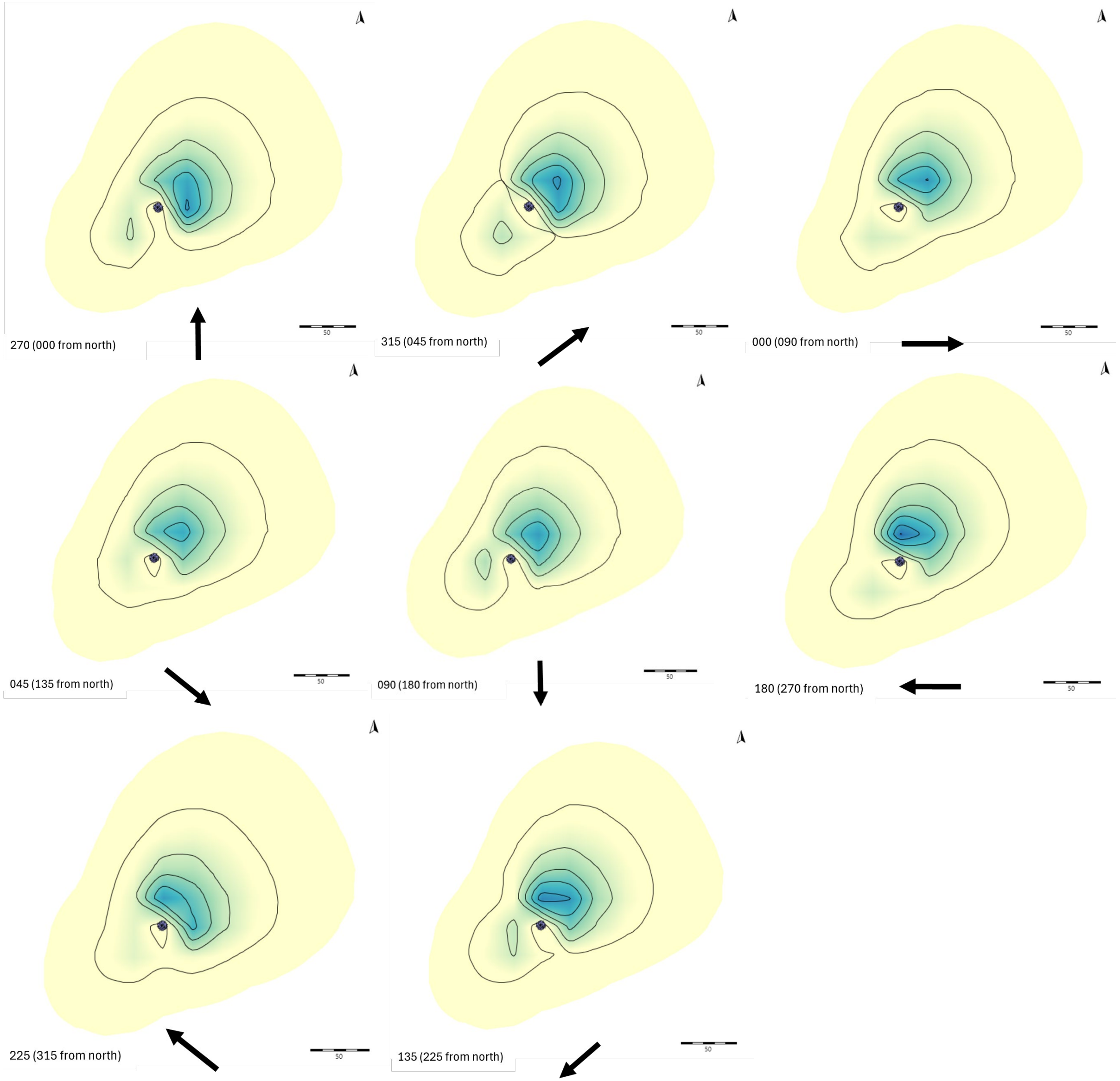
Case study 3 - 100th %ile 1-hour					
		Method			
Receptor	Approx. distance from stack	ADMS Point	AERMOD Point	AERMOD Capped	AERMOD Horizontal
1	66	796.6	439.2	415.6	466.7
2	124	267.3	257.1	259.8	292.5
3	192	243.6	133.4	141.1	134.3
4	519	134.7	83.8	86.0	83.8
5	325	177.4	93.2	96.0	93.2
6	283	160.7	138.7	142.0	138.7
7	442	134.1	60.0	63.5	60.0
8	474	93.7	103.1	106.9	103.1
9	552	92.4	85.9	88.3	86.0
10	842	62.7	47.8	50.3	47.8
11	140	497.8	163.7	171.7	169.3
12	599	68.2	61.4	63.4	61.4
13	275	313.1	234.4	248.9	239.0
14	369	173.2	158.7	164.2	159.0
15	136	1117.2	575.3	585.0	2431.7
16	80	971.5	501.8	483.0	951.8
17	95	1401.7	579.1	502.5	1658.5
18	108	1267.0	586.8	512.0	1933.3
19	127	1481.7	585.3	598.3	3346.9
20	145	952.4	535.6	527.8	2587.1
21	114	590.7	462.3	433.2	2544.7

Results – ADMS jet sources

Point sources predict higher
Jet sources predict higher

- ADMS point sources vs ADMS jet sources with building module switched off
- Results are generally quite similar for this scenario
- Annual results are within 20% and 1-hour 100th percentile results are within 30%
- Directionality of jet sources could affect dispersion

Case study 3 - Annual					
		Source			
Receptor	Approx. distance from stack	1	2	3	4
1	66	-8%	-4%	0%	2%
2	124	3%	3%	3%	4%
3	192	7%	8%	8%	8%
4	519	20%	19%	19%	19%
5	325	9%	9%	9%	9%
6	283	11%	11%	11%	11%
7	442	14%	14%	14%	14%
8	474	14%	14%	14%	15%
9	552	17%	17%	17%	17%
10	842	13%	13%	13%	13%
11	140	17%	17%	17%	17%
12	599	14%	15%	15%	15%
13	275	17%	17%	17%	16%
14	369	20%	20%	21%	21%
15	136	0%	-4%	-9%	-13%
16	80	-16%	-12%	-7%	-3%
17	95	-21%	-20%	-16%	-11%
18	108	-15%	-19%	-19%	-16%
19	127	-4%	-9%	-14%	-17%
20	145	2%	-1%	-5%	-9%
21	114	-4%	-6%	-7%	-7%


270 (000 from north)
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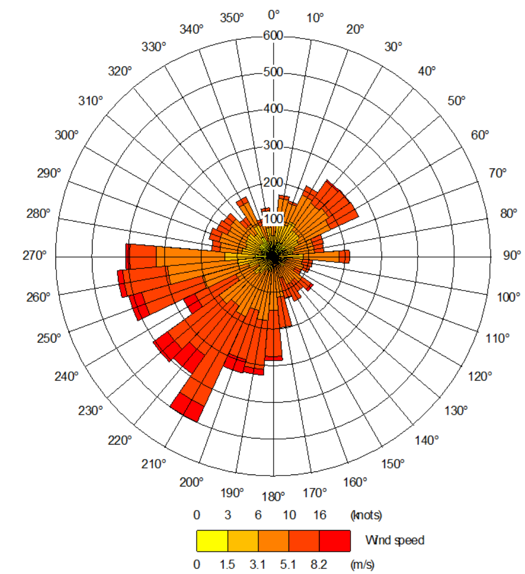
180 (270 from north)
225 (315 from north)
135 (225 from north)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310°
320°
330°
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500
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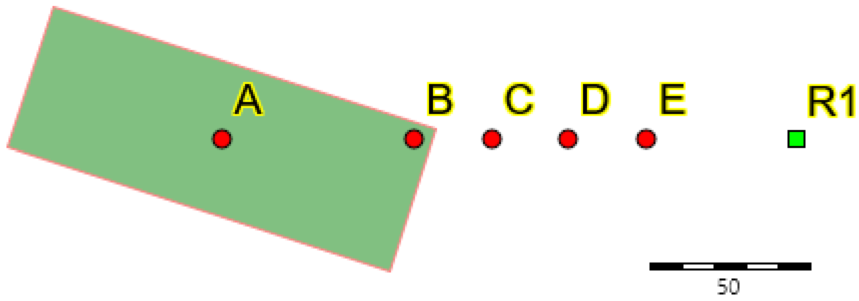
0 3 6 10 16 (knots)
Wind speed
0 1.5 3.1 5.1 8.2 (m/s)

Results – offsetting source location

		Source				
Averaging time	Model	A	B	C	D	E
1-hour 100th	ADMS	65.9	97.6	106.6	122.0	161.4
1-hour 100th	AERMOD	155.0	66.8	26.9	19.6	22.3



- ADMS – source proximity has a greater affect on predictions
- AERMOD – building downwash has a greater affect on predictions

Model uncertainties

Estimate model uncertainty

You must show that you have estimated the level of uncertainty in your predictions.

Look at evaluation or validation documents for examples of the differences between measured values and those estimated by models.

Where these documents indicate levels of uncertainty that might affect your conclusions, you need to consider running another model to check the differences between models.

You must justify your input data and assumptions. You will need to carry out sensitivity analysis to deal with uncertainty and variability in your input data.

Your conclusions must show that you have taken the uncertainty of predictions into account.

- Environmental permitting: air dispersion modelling reports - GOV.UK (www.gov.uk)

Recommended method - ADMS

- Use the point source option in ADMS
- Reduce efflux velocity to non-zero (0.001-0.1 m/s) to remove non-buoyant vertical momentum
- For buoyant sources, calculate an ‘effective’ stack diameter to maintain correct actual volumetric flowrate to preserve plume buoyancy.
- Turn stack-induced downwash off using .aai file although the US EPA method suggests that the user could manually apply the effects of stack-induced downwash
- Stack-induced downwash and plume buoyancy have the greatest potential to affect results

Recommended method - AERMOD

- Use the capped and horizontal source options
- You could manually reduce the height of a stack in the model to apply the effects of stack-induced downwash

- For any model, where the uncertainties and limitations associated with the recommended methods could affect conclusions, consider sensitivity to an alternative model

Questions