Building Downwash - Development

EPA RSL Workshop

U.S. EPA / OAQPS / Air Quality Modeling Group

Monday, June 21, 2021

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Building Downwash - Development

- **Purpose/Goal:** Improve PRIME building downwash algorithm in AERMOD for circumstances in which AERMOD has been shown to either underpredict or overpredict ground-level concentrations.
- **Internal Collaboration:** EPA's Office of Research and Development (ORD)
- **External Collaboration:** PRIME2 Advisory Subcommittee (PRIME2) within the Atmospheric Modeling and Meteorology (APM) Committee of the Air and Waste Management Association (A&WMA)
- **AERMOD v.19191: 6** new **alpha** options; **3** developed by **ORD** and **3** developed by **A&WMA (PRIME2)**
  - ORDUEFF: *Height of effective wind speed calculation*
  - ORDTURB: *Maximum vertical turbulence intensity*
  - ORDCAV: *Cavity discontinuity*
  - AWMAUEFF: *Height of effective wind speed calculation* (similar but different from ORDUEFF)
  - AWMAUTURB: *Enhanced turbulence and velocity deficit calculations*
  - STREAMLINE: *Enhanced turbulence and velocity deficit calculations for streamlined buildings*

Building Downwash - Development

- **BPIPPRM v.19191_DRFT: Experimental/research only**
  - Reduced building/tier footprint when building is angled to the wind
  - Modified for rectangular buildings/tiers only, single building/tier configurations
  - Limited testing to date
- **AERMOD v.21112: 2** new **alpha** options developed by **A&WMA**
  - AWMAUTURBHX: *Enhanced turbulence and velocity deficit calculations w/distance-based plume rise*
  - AWMAENTRAIN: *Modified Beta entrainment constant*
- With a few exceptions, downwash alpha options can be used individually or in combination with others
- Exceptions:
  - ORDUEFF **or** AWMAUEFF *(cannot be used together)*
  - AWMAUTURB **or** AWMAUTURBHX *(cannot be used together)*
  - STREAMLINE requires **either** AWMAUTURB **or** AWMAUTURBHX

Building Downwash – Next Steps

- Current effort to evaluate individual options and combinations of options, with using BPIPPRM v.04274 and v.19191_DRFT
- Databases – AGA, Alaska, Bowline, DAEC, EOCR, Milestone, Balko
- Started with AERMOD v.19191
- Rerun with AERMOD v.21112 and integrate recent options
- Assess results - propose one or a combination of options as a regulatory update to PRIME
- Further assessment of BPIPPRM and building characterization
  - ORD proposed changes in 19191_DRFT affect only rectangular buildings/tiers
  - Limited testing to date
  - Need to look at how changes could apply more broadly to non-rectangular buildings and more complex site configurations

Building Downwash – Eval DBs

Database	Availability	Short Description	Previous Evaluation
American Gas Association Study (AGA) (Engineering Science, 1980)	SCRAM	Texas and Kansas; rural, flat, highly buoyant releases from 1 to 2.5 times building height; sampler arrays from 50 to 200m; 10m met tower	AERMOD: Perry et al., 2005
Alaska (Guenther et al., 1990)	SCRAM	Alaska; Isolated, very flat; buoyant release at 39m; building height of 34m; samplers in seven arcs from 50m to 3,000m; 33m met tower (wind, temp, velocity variance); primarily stable to very stable conditions; SF6 release.	PRIME: Schulman et al., 2000; AERMOD: Perry et al., 2005
Balko (Pipeline Research Council International)	ORD	Oklahoma; relatively flat with gently rolling terrain which slopes mainly from east to west,; mostly isolated without major roadways or other sources within 3 miles; 4 stacks height varies from 25ft to 68ft; buoyant releases; three natural gas-fired reciprocating internal combustion engines and one emergency generator; emission varies based on customer demand; 8 buildings at the site which vary in height from 14ft to 62ft; on site met with measurements of winds, temperature, solar radiation, humidity, pressure, and rainfall; 4 monitoring locations around emission sources measure NO, NO2 and NOx (Ozone monitor 112+ miles away).	None identified
Bowline (Schulman et al., 1986)	SCRAM	New York; locally flat; buoyant twin stacks; 87m release; dominant building height 65m; SO2 samplers at 250m and 850m; 100m met tower (wind & temp); full year of data.	PRIME: Schulman et al., 2000; AERMOD: Perry et al., 2005
Duane Arnold Energy Center (DAEC) (Thuillier and Mancuso, 1980)	SCRAM	Terrain variations up to 30m (Iowa); rooftop non-buoyant releases at 46m and 24m plus ground-level releases; samplers on arcs at 300m and 1,000m; 50m met tower (mostly light wind; convective conditions).	AERMOD: Perry et al., 2005
Experimental Organic Cooled Reactor (EOCR) (Start et al., 1981)	SCRAM	Idaho; terrain variation <10m; nonbuoyant releases at 30m, 25m, and near ground level; building height 25m; sampling arcs at seven distances from 50 to 1,600m; wide range of stabilities and wind speeds; many stable	AERMOD: Perry et al., 2005
Millstone (Bowers and Anderson, 1981)	SCRAM	Coastal Connecticut; terrain variation <10m; nonbuoyant releases at 48m and 29m; building height 45m; sampling on arcs from 350m to 1,500m; 43m met tower (wind and temp: mostly high winds and onshore flow); releases of SF6 and CF3BR.	AERMOD: Perry et al., 2005

Petersen Research and Consulting, LLC

Enhanced Building Downwash and Plume Rise Alpha Options in AERMOD 21112

2021 Regional, State, and Local (RSL)
Dispersion Modelers' Workshop.
June 21, 2021, Virtual

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Acknowledgements

The continued advancements to the building downwash predictions in AERMOD would not be possible without the financial support of the American Petroleum Institute's Air Modeling Group.

Outline

- Background
- PRIME2 Alpha Options
- PRIME Plume Rise Enhancements

  AWMAENTRAIN Option
- PRIME2 Enhanced Turbulence and Velocity Deficit

  AWMAUTURBHX Option
- Model Evaluation
- Conclusions

Background On PRIME2 Alpha Options

- 2017: Petersen and Guerra published a paper documenting flaws in current PRIME theory (Journal of Air &Waste Management Association).
- 2017/2018: Industry Group funded a research study and new building wake equations were developed.
- 2018: Journal Article published documenting PRIME2 equations (Petersen and Guerra. Journal of Wind Engineering & Industrial Aerodynamics).
- 2018/2020: Collaboration between EPA and AWMA PRIME2 committee to develop an implementation plan.
- 2019: PRIME2 Alpha options included in AERMOD 19191.
- 2020: API funded additional research to improve the plume rise in PRIME and to enhance the PRIME2 downwash theory.
- 2021: New Alpha options included in AERMOD 21112.

PRIME2 Alpha Options in AERMOD 21112

- ***Keyword: AWMADWNW***
- ***Parameters***
  - **AWMAUeff:** controls the height for which the wind speed is calculated for the main plume concentration. Plume height is used for this calculation.
  - ***AWMAUTURB (Old PRIME2):*** enables enhanced calculations of turbulence and wind speed
  - **AWMAUTURBHX (New PRIME2):** enables enhanced calculations of turbulence and wind speed using the PRIME plume rise versus x for all calculations.
  - **AWMAENTRAIN:** enables the use of a new entrainment constant (Beta = 0.35) in the PRIME plume rise calculation.
  - ***STREAMLINE:*** defines the set of constants for modeling all structures as streamlined.

ORD Alpha Options in AERMOD 21112

- ***Keyword: ORD_DWNW***
- ***Parameters:***
  - ***ORDUEFF:*** controls the heights for which the wind speed is calculated for the main plume concentrations. Average between plume height and receptor height recommended in ORD version. Default is current method in AERMOD, stack height wind speed.
  - ***ORDTURB:*** adjusts the vertical turbulence intensity (wiz0 in the PRIME code) from 0.06 to 0.07.
  - ***ORDCAV:*** modifies the cavity calculations: ***Used for PRIME2***.

PRIME PLUME RISE ENHANCMENTS

AWMAENTRAIN Parameter

PRIME Plume Rise Model

- Numerical solution to the basic equations for conservation of mass, energy and momentum.
- To solve the equations, entrainment constants ***(Alpha and Beta)*** are needed.
- ***Alpha and Beta*** values have a significant affect on predicted plume rise.

Reasons For Plume Rise Assessment

- PRIME2 has shown a tendency to overpredict concentrations for the Bowline Point and Alaska North Slope field databases.
- If PRIME is underestimating plume rise, this could explain the PRIME2 overprediction tendency.
- PRIME plume rise algorithm never tested against field and/or wind tunnel observations for building wake situations.

Plume Rise Databases

- EPA data base (Huber/Snyder).
  - Based on vertical concentration profiles for various stack heights to building height ratios.
  - All information is documented in a peer reviewed paper.

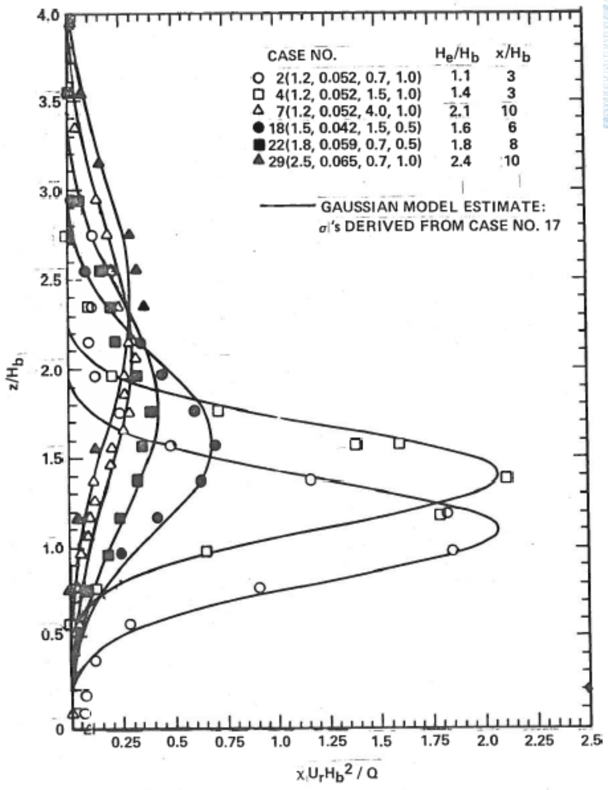


Figure 10. Vertical concentration profiles for isolated stack. In this and following legends, H_e/H_b identifies the presumed effective stack height as determined from analysis of vertical concentration profiles at position, x/H_b (see table 3).

- CPP Wind Tunnel Data Base.
  - Based on plume visualizations.
  - Four cases were selected.
  - Building heights varied from 30 to 42 m.
  - Stack height = 48.2 m.

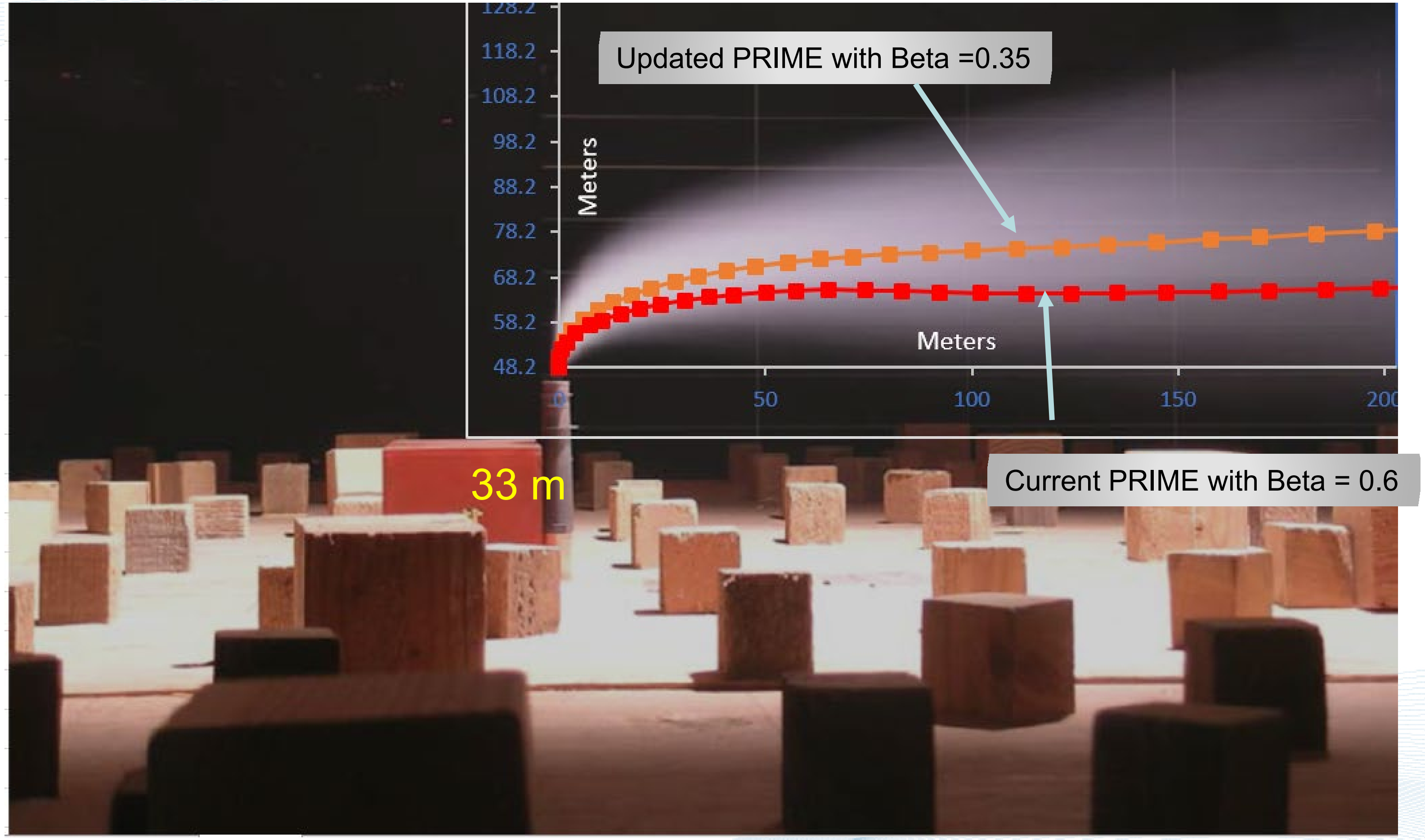
Methodology

- Source and meteorological inputs for each case were developed.
- AERMOD_v19191 was run for each case and predicted plume rise values were obtained from the diagnostic file.
- Observed and predicted plume rise values were then compared.
- PRIME entrainment constants, Alpha (A) and Beta (B) were varied as follows to obtain better agreement with observations.
  - Case 1: Current AERMOD: Alpha = A= 0.11; Beta = B= 0.6
  - Case 2: Alpha = A= 0.06; Beta =B = 0.6
  - Case 3: Alpha = A = 0.06; Beta=B = 0.3
  - ***Case 4: Alpha = A= 0.11; Beta = B= 0.35 > Performed Best, Recommended***
  - Case 5: Alpha = A= 0.11; Beta = B= 0.45

Typical Result

Mirant Data Base: Hs = 48.2 m; Hb = 33 m; Hs/Hb = 1.46

Current PRIME Underestimates Plume Rise; Modified PRIME Better



Old PRIME2 Wake Equations
AWMAUTURB Parameter

- PRIME2 enhanced turbulence and velocity deficit are calculated using minimum of final momentum plume or a representative PRIME plume rise.

New PRIME2 Wake Equation
AWMAUTURBHX Parameter

- PRIME plume rise is used at each X distance to calculate the PRIME2 enhanced turbulence and velocity deficit.

Model Evaluation

Model Runs

1. **P2** (19191 PRIME2) uses ***AWMAUTURB, AWMAUEFF, and ORDCAV*** parameters.
2. **P2HX**: Same as P2 but uses plume rise versus x for all enhanced calculations. Uses ***AWMAUTURBHX, AWMAUEFF, and ORDCAV*** parameters.
3. **P2HXB**: same as P2HX but adds the ***AWMAENTRAIN*** parameter.
4. **P**: 19191 AERMOD/PRIME.

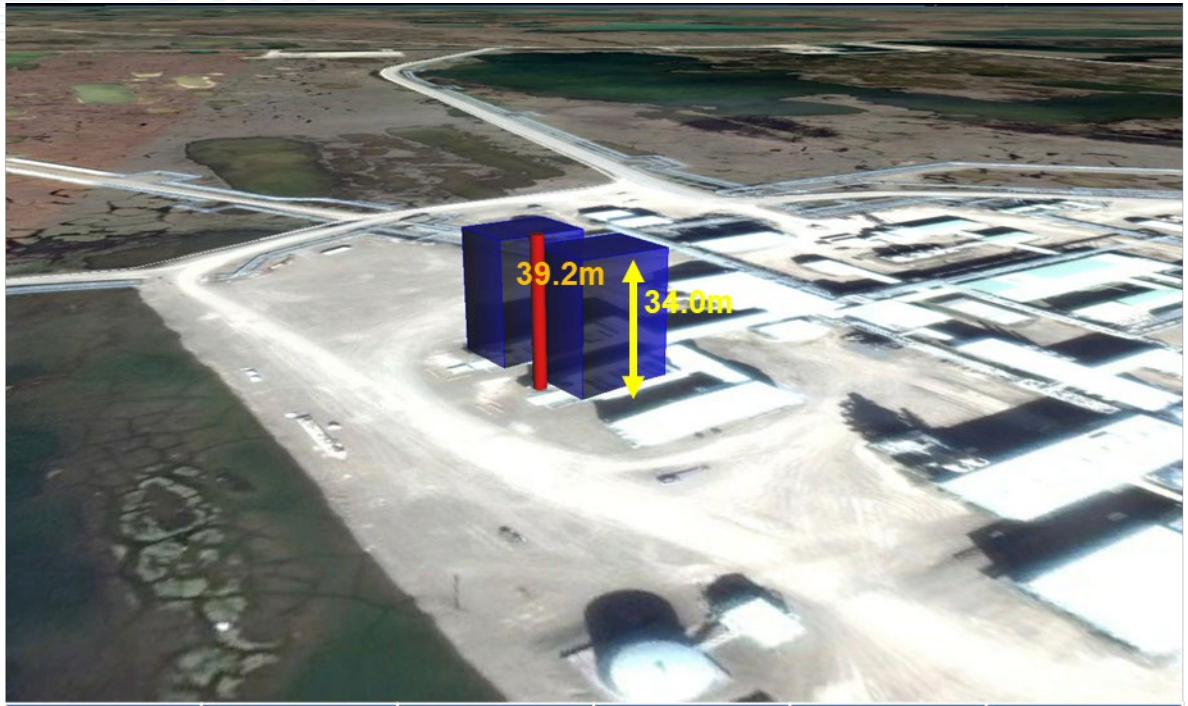
Databases & Evaluation

Model Performance Measures

- RHC: the Robust Hight Concentration. Represents a smoothed estimate of the highest concentration based on an exponential fit to the top 25 concentrations.
- Q-Q plot:

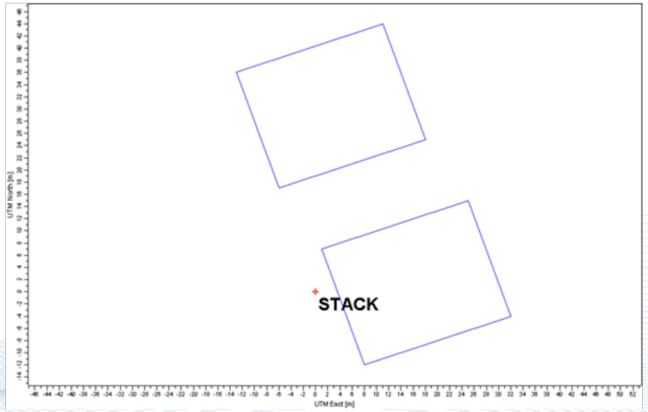
  Plots that are created by sorting by rank (highest to lowest) the predicted and observed concentrations for a set of predictions and observations that are initially paired in space and time. The sorted list of predicted and observed concentrations are then plotted by rank. They are no longer paired in space and time.

Alaska North Slope

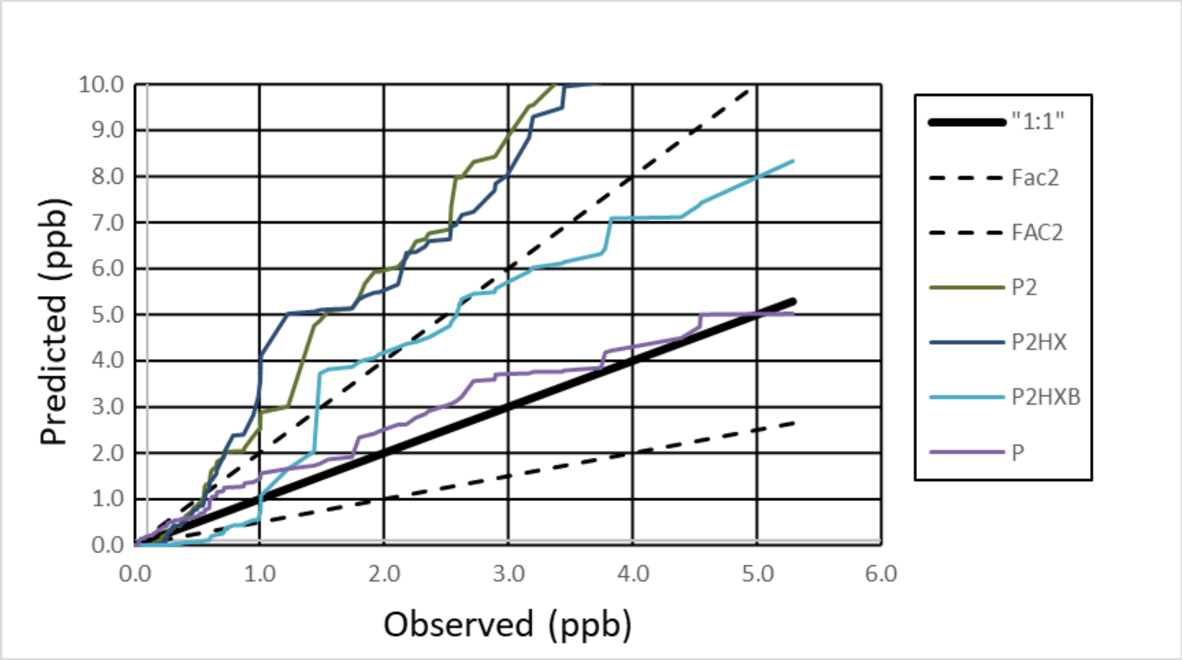


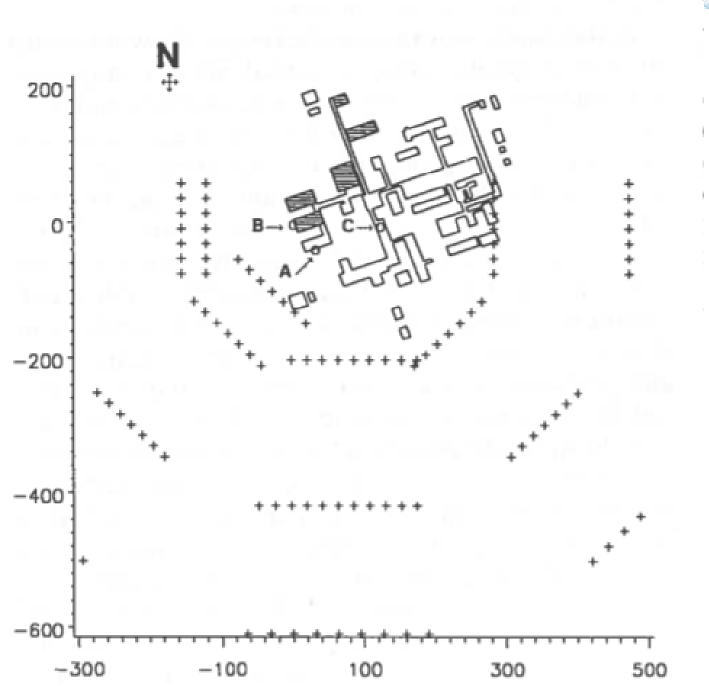
	Q (g/s)	Hs (m)	Ts (K)	Vs (m/s)	Ds (m)
STACK	1	39.2	554-584	17-21	3.66

- Buoyant , SF6 Source
- 33m met tower
- Met data include: ws, wd, temp, sigma-theta, and sigma-w
- 7 arcs of recs from 50m to 3,000m
- 44 hours during light hours (0900-1600)
- Stability conditions generally neutral or slightly stable
- Wind speeds at 33-m level
    - Less than 6 m/s for one test
    - Between 6 and 15 m/s for four tests
    - More than 15 m/s during three tests



Alaska North Slope





Model Scenario	RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/RHC_{obs}
P2	19.3	6.3	3.04
P2HX	19.4	6.3	3.05
P2HXB	10.1	6.3	1.59
P	**6.7**	**6.3**	**1.06**

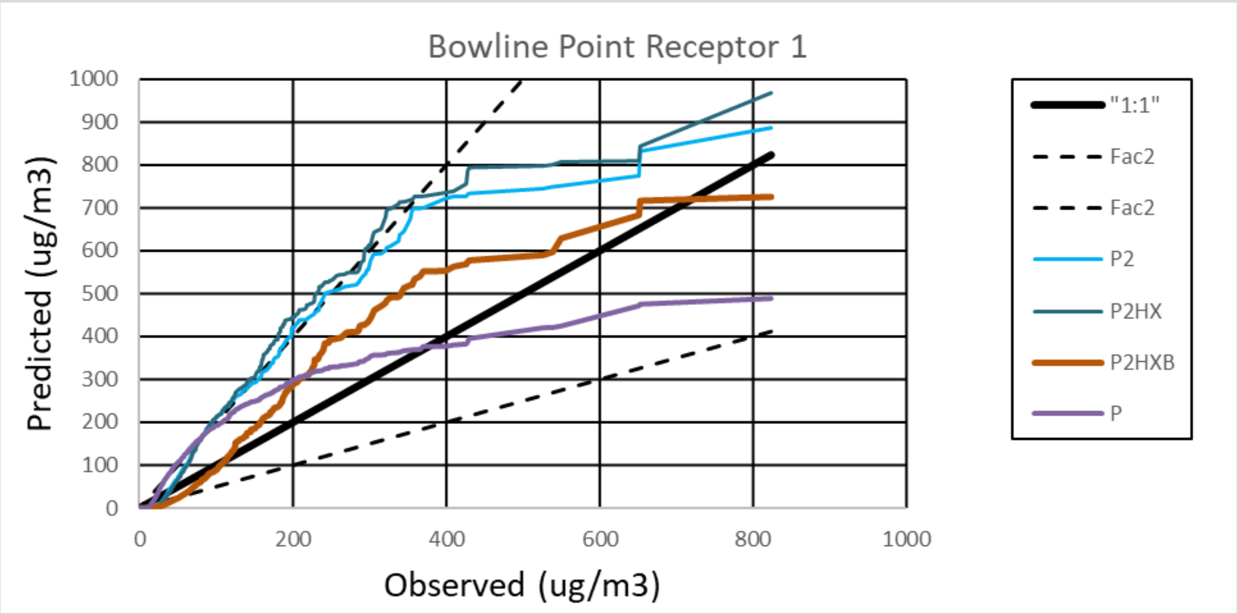
Best Agreement

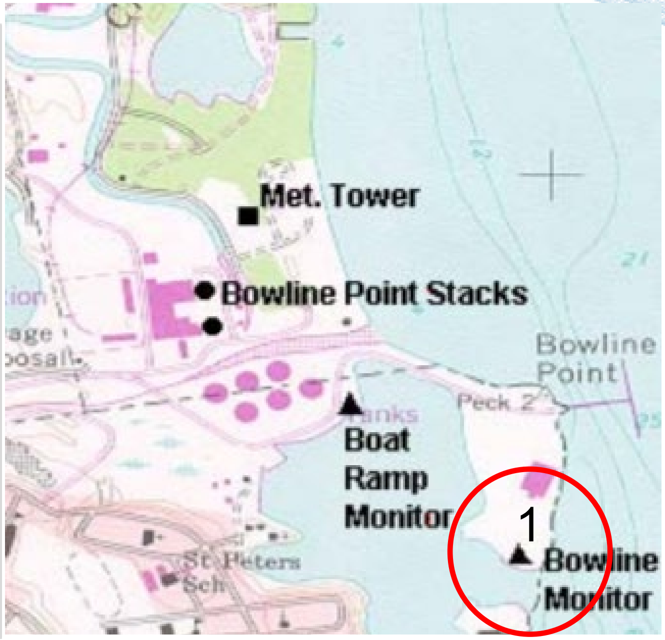
Bowline Point

- Buoyant , SO2 Source
- Hudson River Valley, New York
- 100m met tower
- No turbulence data
- Even split between stable and unstable hours
- Hourly emissions data
- Full year of data
- 4-Receptors (Recs 1 and 3 used)

	Q (g/s)	Hs (m)	Ts (K)	Vs (m/s)	Ds (m)
STACK	0 - 449.3	86.87	358 - 409	7.9 – 30.9	5.72

Bowline Point Receptor 1: X = 848m

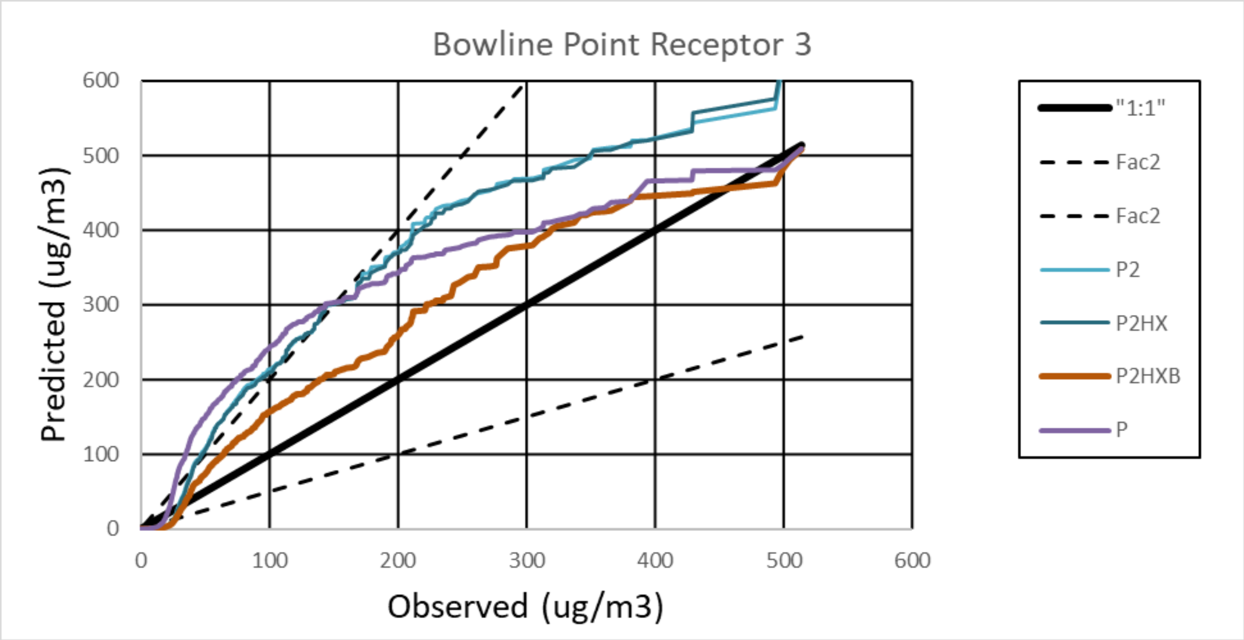


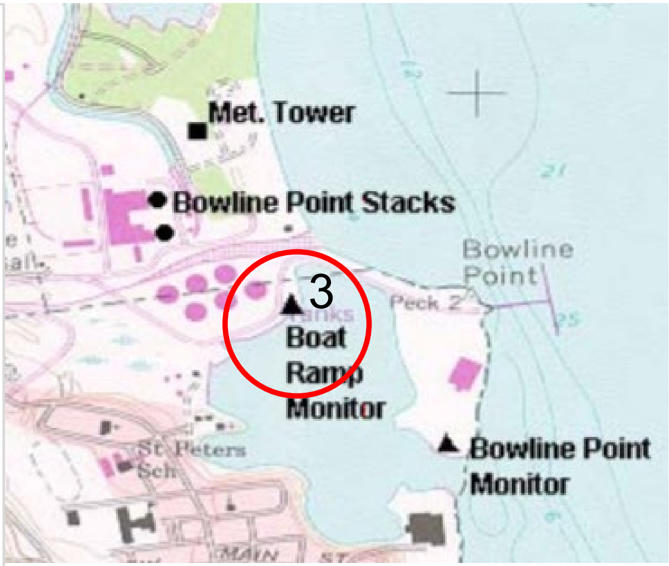


Model Scenario	RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/RHC_{obs}
P2	1001.1	742.6	1.35
P2HX	1085.2	742.6	1.46
P2HXB	**839.4**	**742.6**	**1.13**
P	480.9	742.6	0.65

Best Agreement

Bowline Point Receptor 3: X=376m



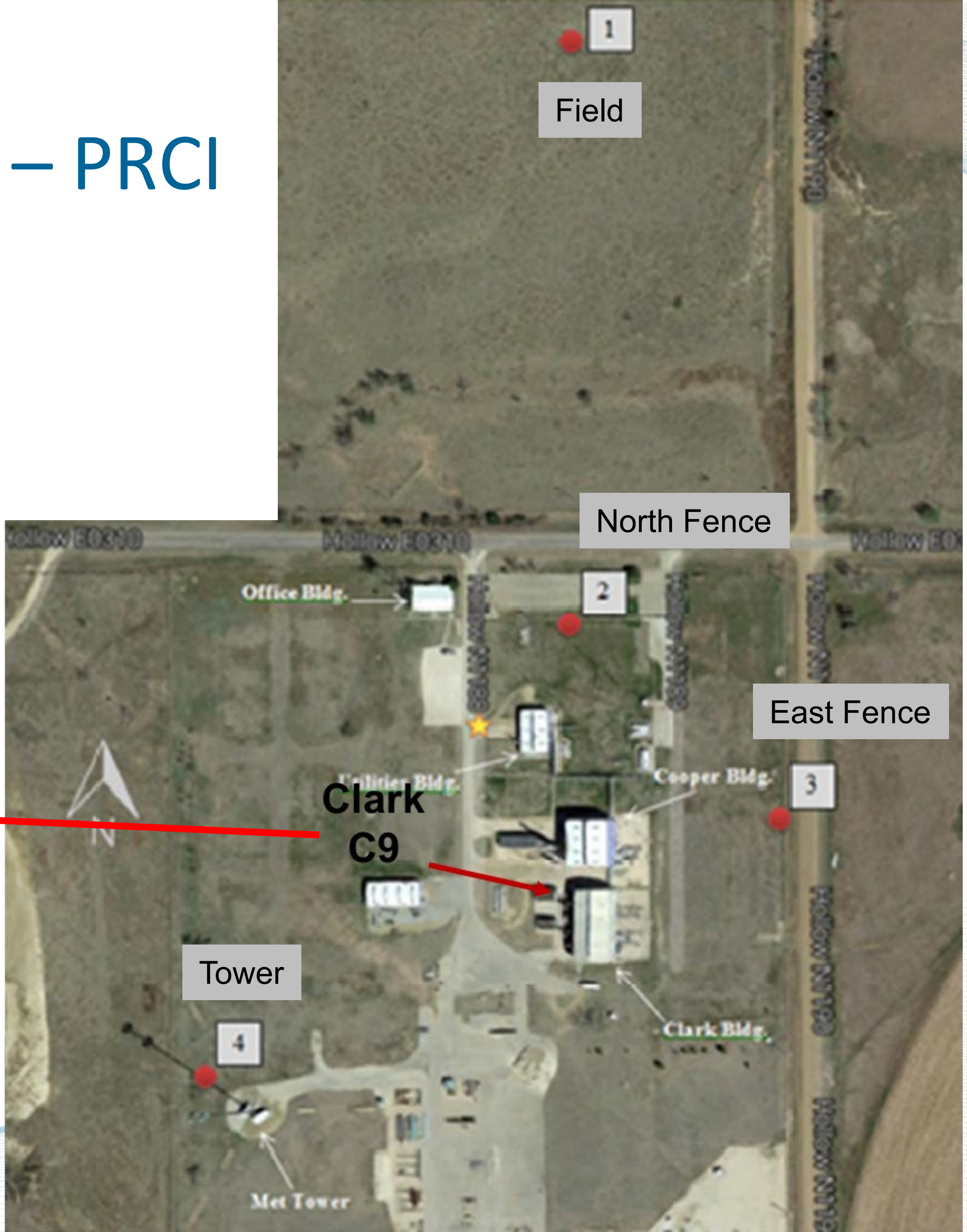


Model Scenario	RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/RHC_{obs}
P2	646.2	596.1	1.08
P2HX	663.2	596.1	1.11
P2HXB	**563.7**	**596.1**	**0.94**
P	547.7	596.1	0.92

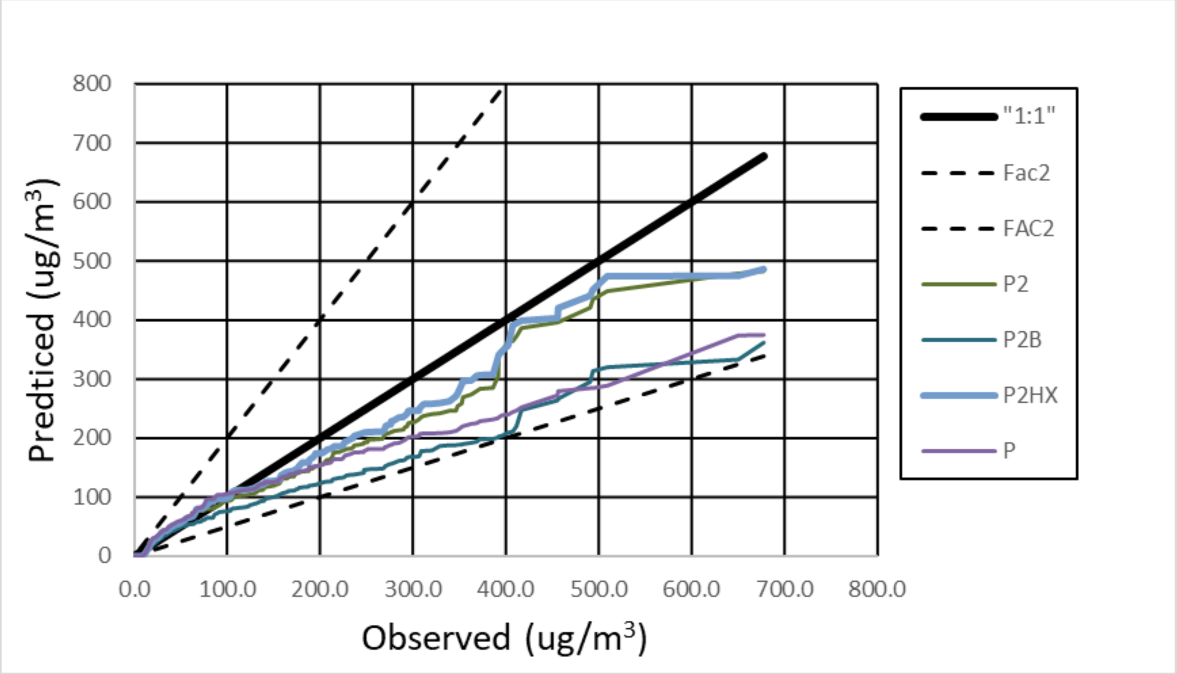
Best Agreement

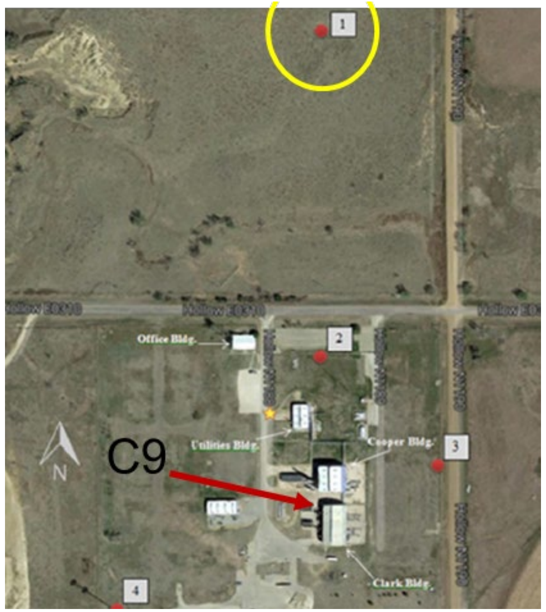
Balko, OK
Compressor Station – PRCI

Stack: C9
Hs = 10.5 m
Hb = 11.3 to 13.5 m



PRCI Receptor 1 (Field): X = 425 m

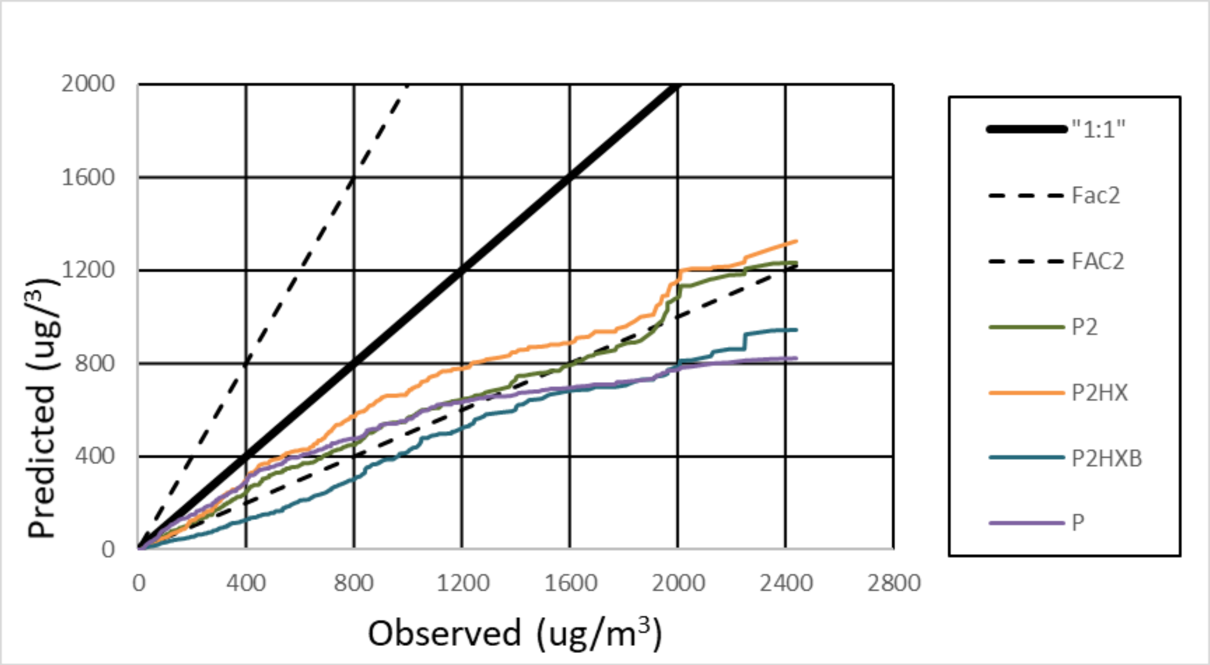




Model Scenario	RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/RHC_{obs}
P2	599.4	697.5	0.86
P2HX	**610.0**	**697.5**	**0.87**
P2HXB	387.2	697.5	0.56
P	361.7	697.5	0.52

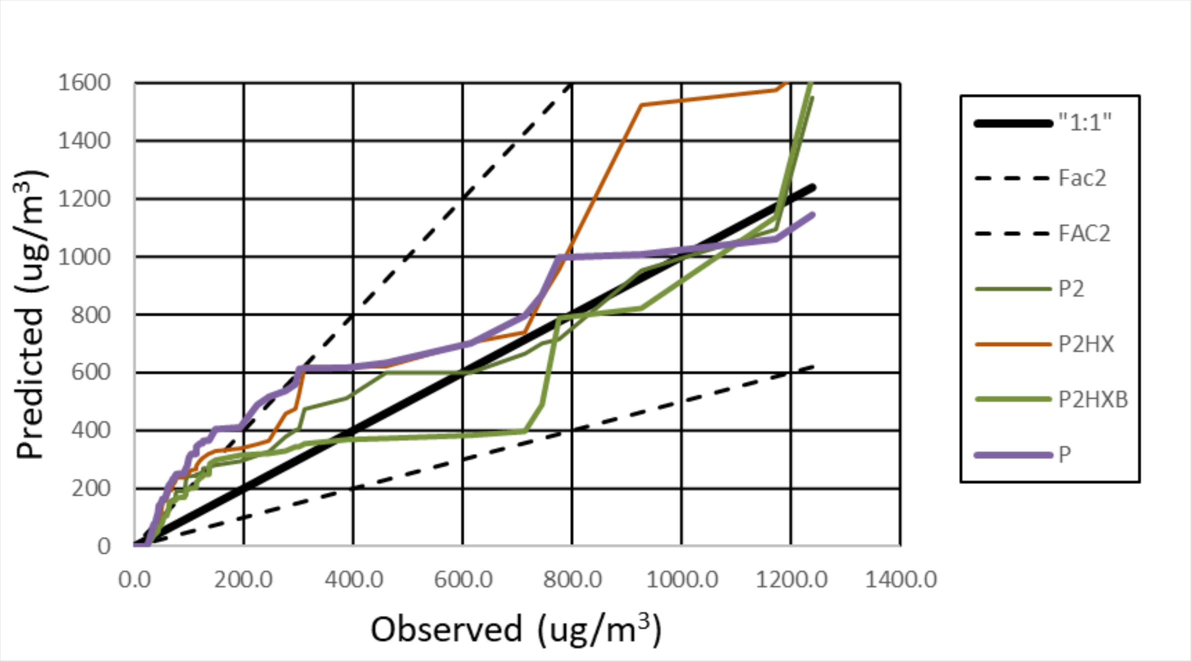
Best Agreement

PRCI: Receptor 2 (North Fence): X = 140m



Model Scenario	RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/RHC_{obs}
P2	1549.6	2617.6	0.59
P2HX	**1595.2**	**2617.6**	**0.61**
P2HXB	1033.7	2617.6	0.39
P	906.5	2617.6	0.35
Best Agreement			

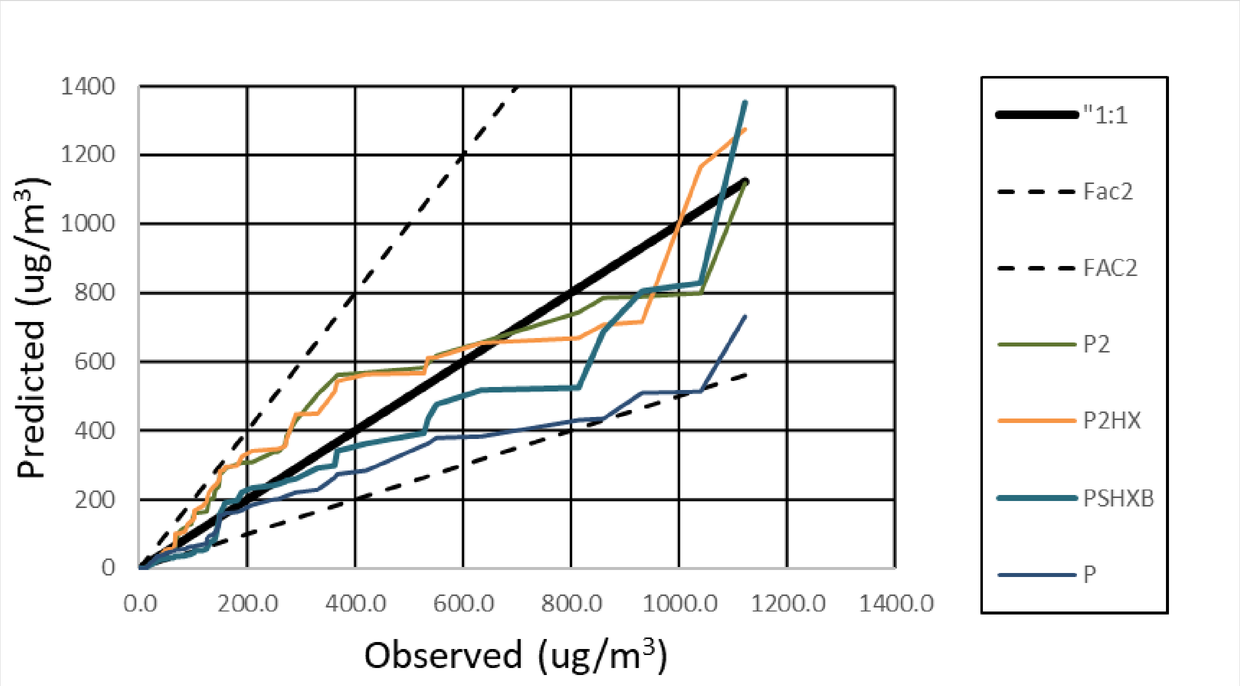
PRCI: Receptor 3 (East Fence): X= 101m



Model Scenario	RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/RHC_{obs}
P2	1156.1	1197.5	0.97
P2HX	1529.6	1197.5	1.28
P2HXB	**1168.9**	**1197.5**	**0.98**
P	1600.1	1197.5	1.34

Best Agreement

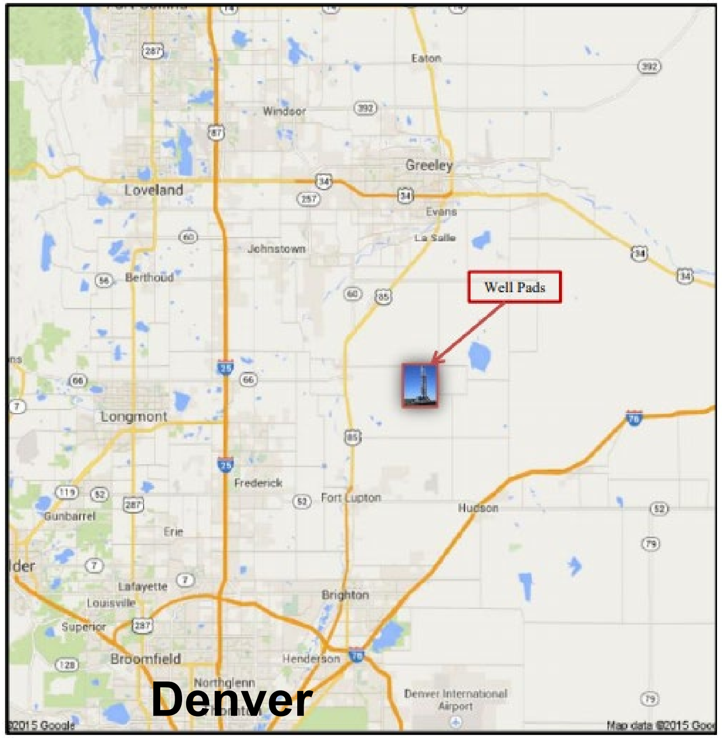
PRCI Receptor 4 (Tower): X=188m

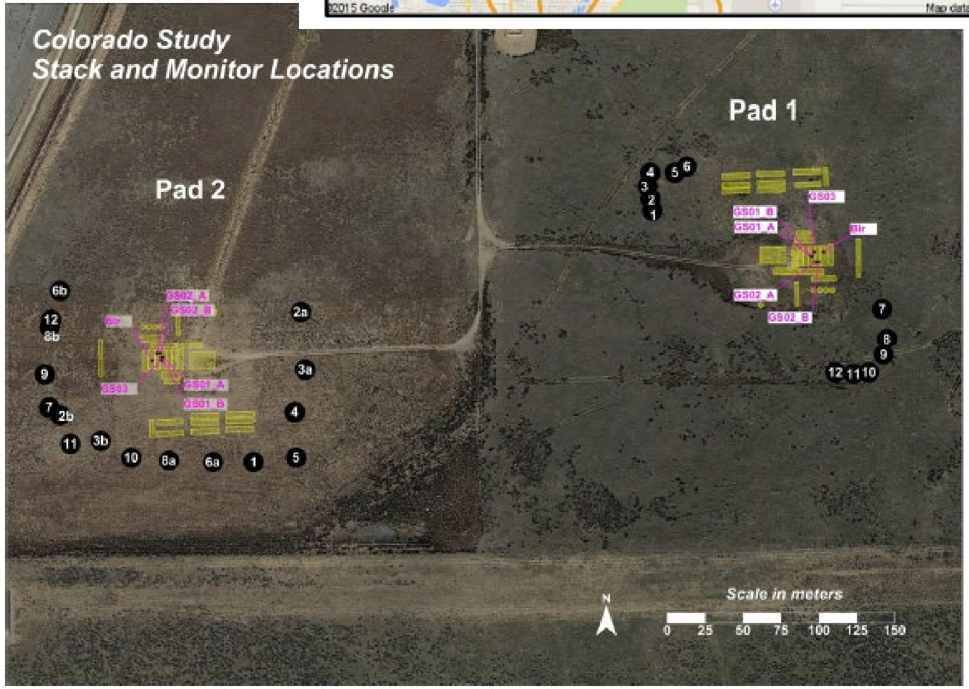


Model Scenario	RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/RHC_{obs}
P2	1179.7	1216.4	0.97
P2HX	**1207.2**	**1216.4**	**0.99**
PSHXB	1036.8	1216.4	0.85
P	678.4	1216.4	0.56
Best Agreement			

Denver Julesburg Drill Rig Study

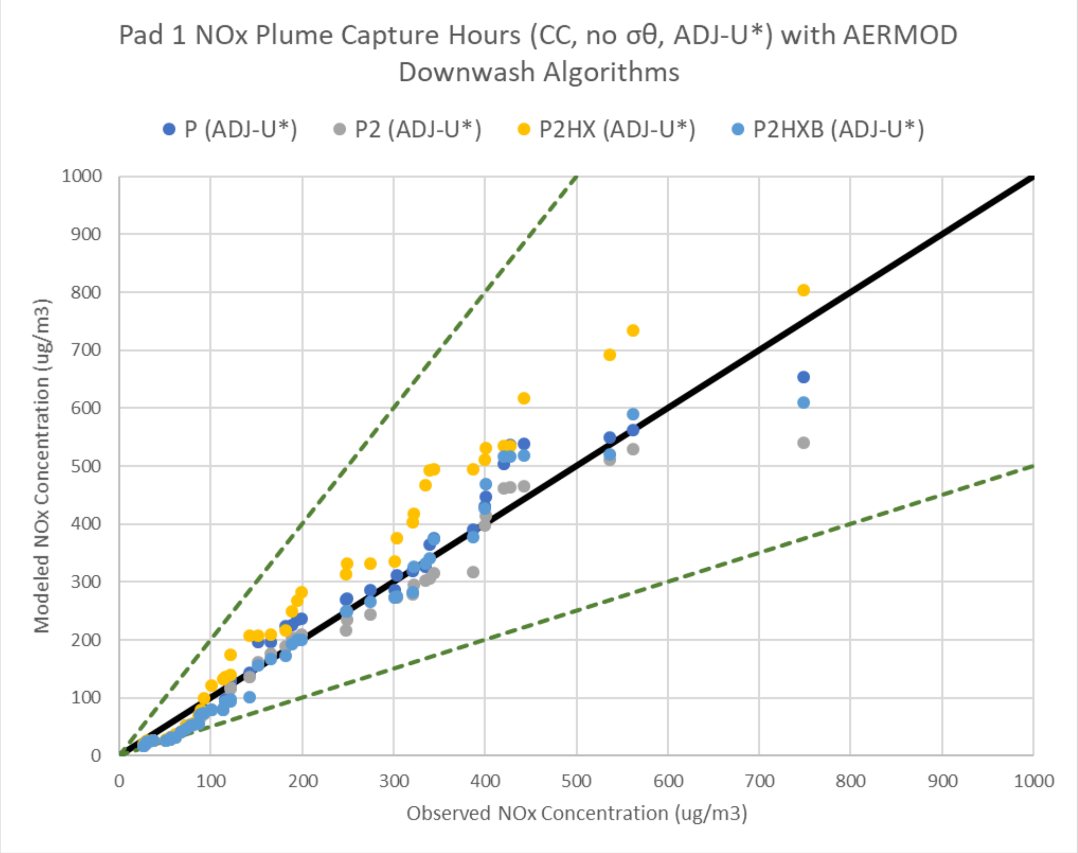
- Located north-northeast of Denver, CO.
- October 10 – November 16, 2014.
- Adjacent well pads
  - (Pad 1, Pad 2).
- 12 Ambient AQ monitors.
- CEMS were used to measure exhaust level at six stack sources (5 generators, 1 boilers) on the drill rig.





Colorado Pad 1:

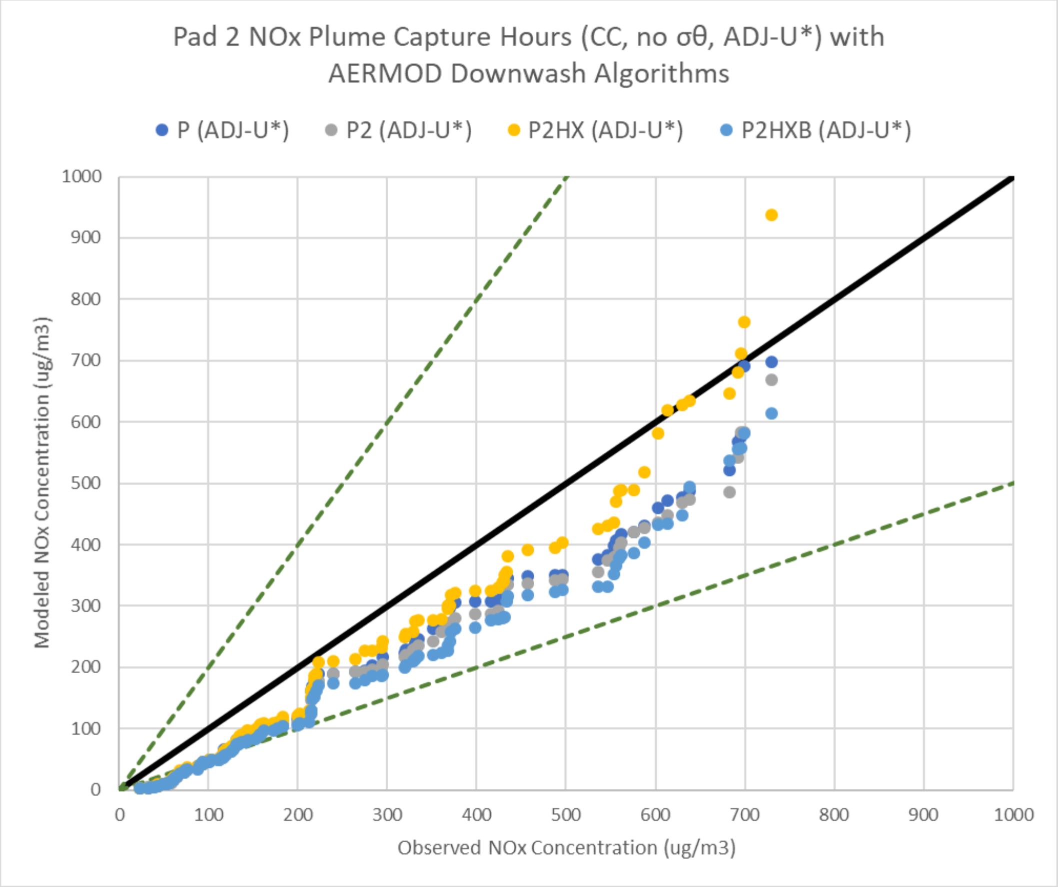
Provided by Christopher Warren and Bob Paine, AECOM

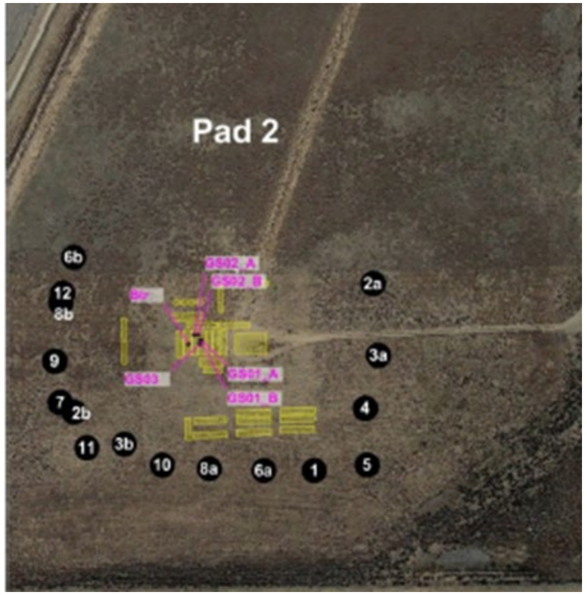


Model Scenario	RHC_{pre} (µg/m³)	RHC_{obs} (µg/m³)	RHC_{pre}/RHC_{obs}
P	944.98	855.29	1.10
P2	**805.88**	**855.29**	**0.94**
P2HX	1034.12	855.29	1.21
P2HXB	986.48	855.29	1.15
Best Agreement			

Colorado Pad 2

Provided by Christopher Warren and Bob Paine, AECOM





Model Scenario	RHC_{pre} (µg/m³)	RHC_{obs} (µg/m³)	RHC_{pre}/RHC_{obs}
P	775.01	928.24	0.83
P2	760.21	928.24	0.82
P2HX	**1012.47**	**928.24**	**1.09**
P2HXB	724.30	928.24	0.78
Best Agreement			

Summary of Overall Model Performance
RHC_p/RHC_o Values

Field Database	Model Scenario			
	P2	P2HX	P2HXB	P
Alaska	3.04	3.05	1.59	1.06
Bowline R1	1.35	1.46	1.13	0.65
Bowline R3	1.08	1.11	0.94	0.92
PRCI R1	0.86	0.87	0.56	0.52
PRCI R2	0.59	0.61	0.39	0.35
PRCI R3	0.97	1.28	0.98	1.34
PRCI R4	0.97	0.99	0.85	0.56
Colorado Pad 1	0.94	1.21	1.15	1.10
Colorado Pad 2	0.82	1.09	0.78	0.83
GeoMetric Mean	1.06	1.18	0.87	0.75

Best Performance

Note: When two or more models RCH ratios are similar, all are shaded.

Summary of Model Performance by Database

RHC_p/RHC_o Values

Field Database	Model Scenario			
	P2	P2HX	P2HXB	P
Alaska	3.04	3.05	1.59	1.06
Bowline R1	1.35	1.46	1.13	0.65
Bowline R3	1.08	1.11	0.94	0.92
Geometric Mean	1.21	1.27	1.03	0.77
PRCI R1	0.86	0.87	0.56	0.52
PRCI R2	0.59	0.61	0.39	0.35
PRCI R3	0.97	1.28	0.98	1.34
PRCI R4	0.97	0.99	0.85	0.56
Geometric Mean	0.83	0.91	0.65	0.61
Colorado Pad 1	0.94	1.21	1.15	1.10
Colorado Pad 2	0.82	1.09	0.78	0.83
Geometric Mean	0.88	1.15	0.95	0.96
[redacted]				

Best Performance

Note: When two or more models RCH ratios are similar, all are shaded.

Conclusions

- PRIME2 (P2) showed the overall best agreement and had the most frequent best agreement with the field databases **(slide 29)**.
- PRIME2 with enhanced plume rise (P2HXB) showed the 2nd overall best agreement. **(slide 29). Best option theoretically.**
- AERMOD/PRIME (P) showed the overall worst agreement and had the least frequent best performance rating **(slide 29).**
- P2HXB had the overall best agreement for the Bowline Point and Colorado databases **(slide 30). Best option theoretically.**
- PRIME (P) had the overall best agreement for the Alaska and Colorado databases **(slide 30).**
- P2HX had the overall best agreement for the PRCI database **(slide 30).**

Questions?

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