Petersen Research and Consulting, LLC

Development and Implementation of New Alpha Building Downwash Options in AERMOD

By

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Outline

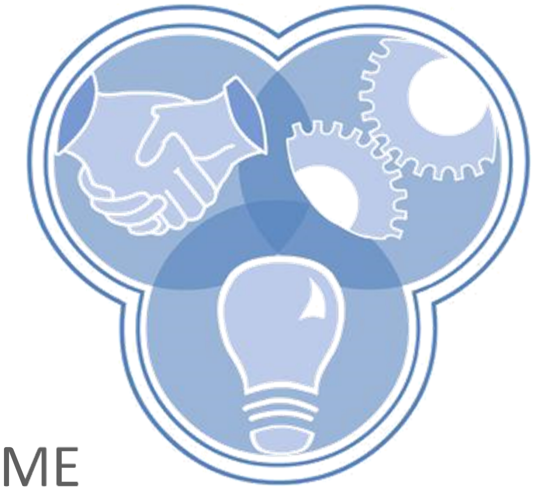
- New Building Downwash Enhancements
- Genesis of PRIME2 and ORD Enhancements
- PRIME2 Alpha Version Development
- Alpha Version Model Evaluation
- Plume Rise Enhancements and Model Evaluation
- What's Next?

New Building Downwash Enhancements

- PRIME2
  - New wake theory based on Industry Funded research with AWMA review and oversight
  - Alpha Option in AERMOD_19191
- ORD
  - New cavity and wind speed theory based on research carried out by EPA ORD
  - Alpha Option in AERMOD_19191
- PRIME PLUME RISE
  - API Funded Research with AWMA review and oversight
  - Will likely be included in next AERMOD release

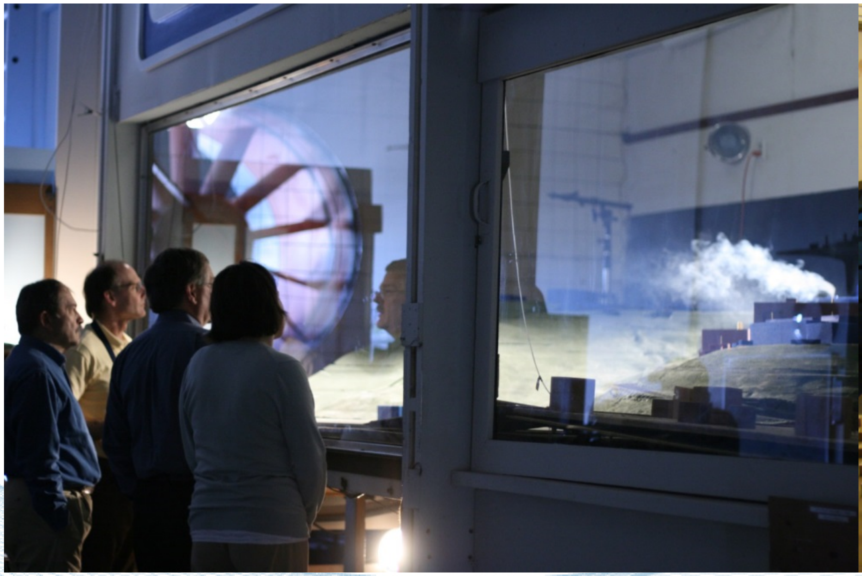
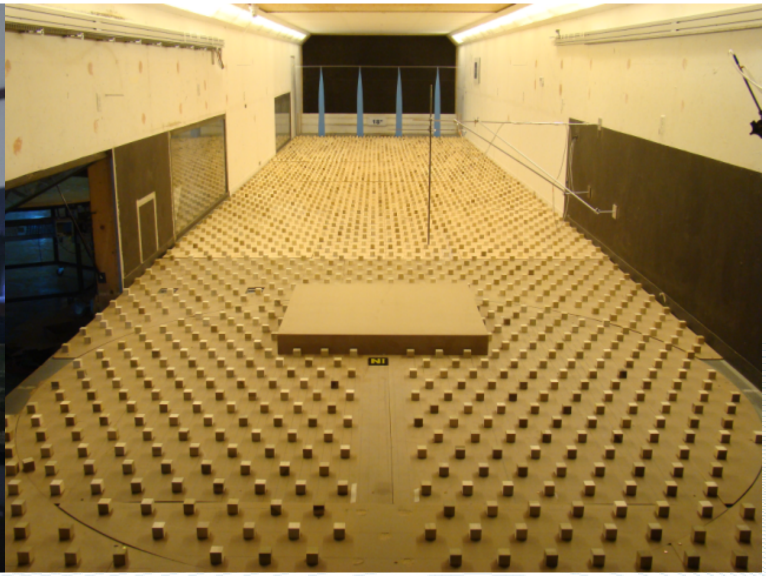
Genesis of PRIME2

- Technical problems with PRIME presented at 2016 11th EPA Modeling Conference and 2016 AWMA Path Forward Conference
- PRIME2 Subcommittee of AWMA's APM Formed to:
  - Establish a mechanism to review, approve and implement new science into the model for this and future improvements
  - Provide a technical review forum to improve the PRIME building downwash algorithms

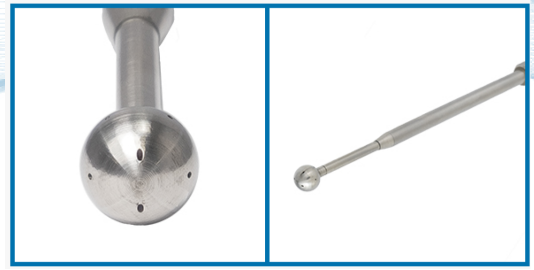


Genesis of PRIME2

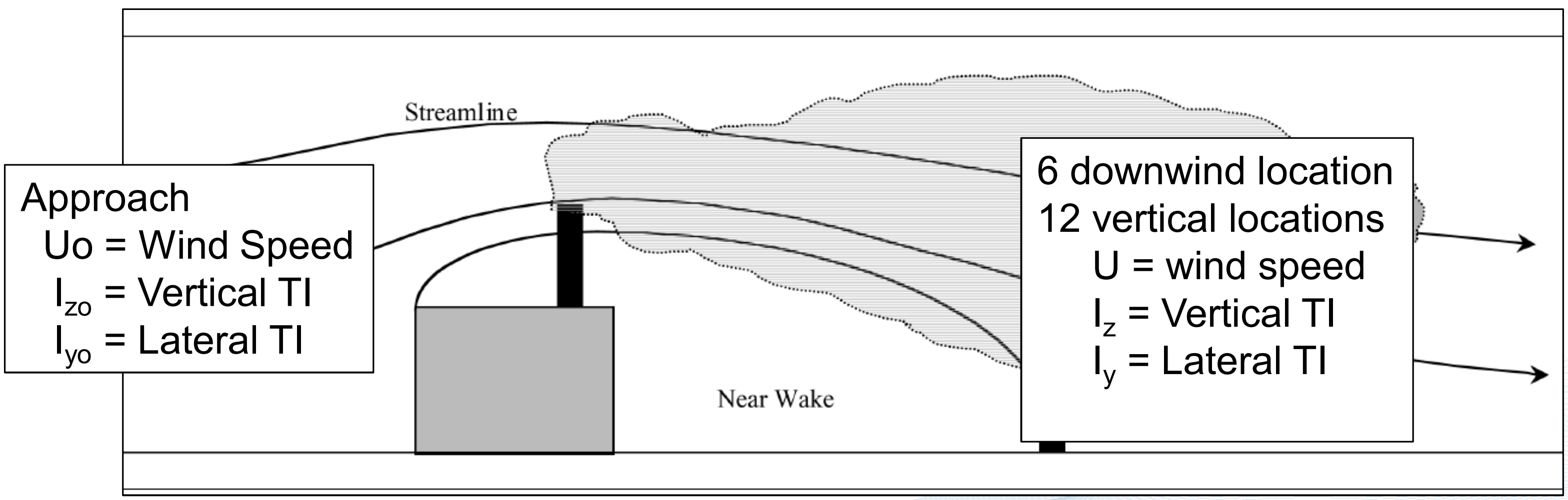
- CPP obtained industry funding in late 2016 and early 2017
  - Electric Power Research Institute
  - American Petroleum Institute
  - American Forest & Paper Association
  - Corn Refiners Association

Velocity Measurements



Omniprobe used which can measure three components of velocity



Genesis of PRIME2

- Initial results presented at EPA's 2016 Regional, State, and Local Modelers' Workshop
  http://www.cleanairinfo.com/regionalstatelocalmodelingworkshop/archive/2016/Presentations/1-14_CPP_AERMOD-PRIME-Next-Generation_Downwash_Model.pdf
- Journal article published in JAWMA documenting the main issues with the current downwash theory, August 2017
  https://www.tandfonline.com/doi/full/10.1080/10962247.2017.1279088
- 2017 EPA Releases White Papers
  - EPA ORD had been doing building downwash research and has made some improvements to PRIME
  - JAWMA article referenced

New Equation Documented

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PRIME2: Development and evaluation of improved building downwash algorithms for rectangular and streamlined structures

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ABSTRACT

Theoretical flaws in PRIME (the building downwash formulation in AERMOD) have recently been documented. To improve PRIME, an industry funded research study was initiated with the following overall objectives: 1) correct the known problems in the theory; 2) incorporate and advance the current state of science; 3) expand the types of structures that can be accurately handled (e.g., streamlined, long, wide); 4) properly document and verify the model formulation and code for the updated PRIME (PRIME2); and 5) collaborate with EPA to work toward implementing the improved model. This paper presents the results from the wind tunnel study used to develop a database of wind speed and turbulence intensity measurements downwind of various rectangular and streamlined structures for three different approach turbulence conditions. Based on those measurements, new equations were developed to estimate the velocity deficit and turbulence intensity increase in the building wake as a function of downwind distance, height, building shape, and approach turbulence intensity. Comparisons of the new equations versus wind tunnel observations showed good agreement; whereas, the equations in PRIME do not agree well above the height of the building and show mixed agreement below the top of the building.

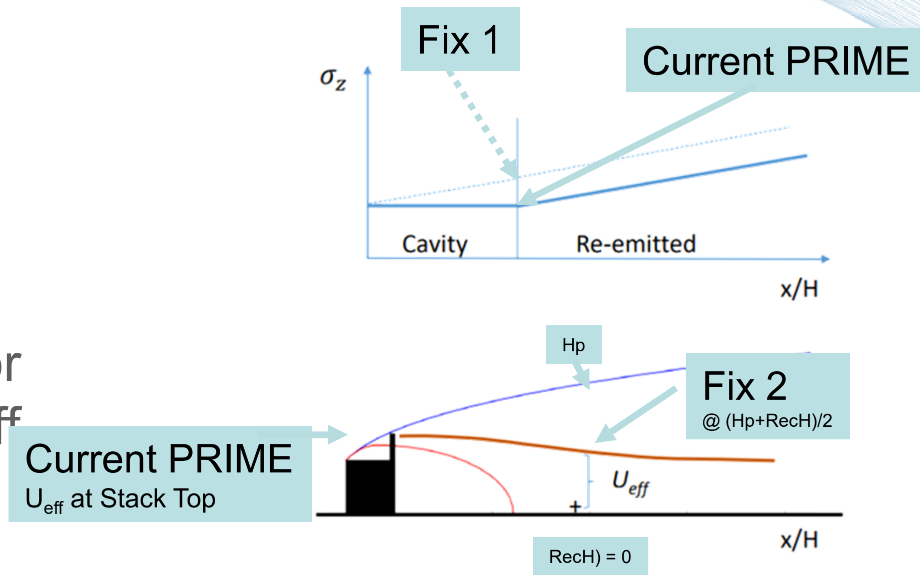
https://doi.org/10.1016/j.jweia.2017.11.027

PRIME2 Enhancements

- Building wake effects decay rapidly back to ambient levels above the top of the building.
- Lateral turbulence enhancement in the wake is less than vertical turbulence enhancement (currently PRIME has them identical).
- The approach turbulence and wind speed are calculated at a more appropriate height.
- Wake effects for streamlined structures are reduced.
- Wake effects decrease as approach roughness increases.

EPA Office of Research and Development (ORD)

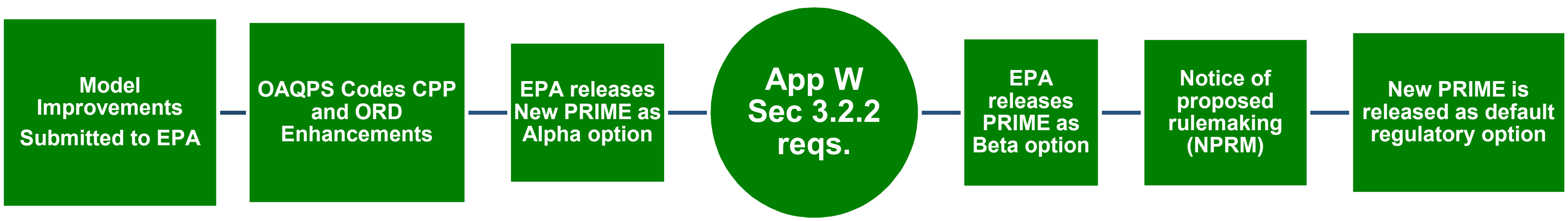
1. Fix mismatch in plume vertical spread at transition between cavity and far wake.
2. Use effective wind speed, Ueff, for primary plume versus stack height for concentration calculations where Ueff is the wind speed at the average between plume height and receptor height.
3. Adjust the vertical turbulence intensity, wiz0 from 0.6 to 0.7.



PRIME2 Alpha Version

- 2/28/2018: Downwash Summit
  - Building downwash workshop at RTP to go over new PRIME2 model and ORD enhancements. Very beneficial!
  - EPA OAQPS confirmed that the PRIME2 updates could be included as an Alpha option in a future model release.
  - Review of PRIME2 from OAQPS could take between 3-4 months but will depend on workload.
  - EPA OAQPS preferred that each of the PRIME2 and ORD updates be implemented separately as "switches" that can be turned "on" and "off" for evaluation purposes.
  - Requirements from App W Section 3.2.2 would be needed before an Alpha version becomes Beta. Many of these requirements have already been met!

Next Steps: Implementation



Alpha option needs to meet the alternative refined model requirements in App W, Section 3.2.2 before it can become a Beta option. These requirements include:

1-Model has received a scientific peer review;

2-Model can be demonstrated to be applicable to the problem on a theoretical basis;

3-The data bases to perform analysis are available and adequate;

4-Appropriate performance evaluations show model is not biased toward underestimation;

5-A protocol on methods and procedures to be followed has been established

Timeline

- 5/3/2018: Meeting between Petersen Research and EPA to discuss making PRIME2 into Alpha version. Followed plan recommended by EPA
  - PRIME2 and ORD formulations should be included as separate options
  - Switches should be used to apply (turn on/turn off) different options
  - AERMOD must be able to run in the regulatory model as well as with the new options
- 10/3/2018: PRIME2 code with switches to turn on/off downwash options was submitted to EPA

Timeline

- 3/26/2019: PRIME2 committee and EPA met to discuss path forward to Alpha version of PRIME2
  - A bug was identified in previous PRIME2 submittal and EPA agreed to fix it before next release.
  - Future potential industry research discussed (PRIME plume rise, streamline, platform structures).
  - Future EPA ORD research discussed. Elongated buildings and updated BPIP.
- 8/21/2019: AERMOD 19191 released with PRIME2 and ORD Alpha options.

PRIME2 Switches

- ***Keyword: AWMADWNW***
- ***Parameters***
  - **AWMAUeff (PRIMEUeff)** defines the height used to compute effective parameters Ueff, Sweff, Sveff and Tgeff at plume height and at 30 m.
  - ***AWMAUTURB (PRIME2UTurb)*** enables enhanced calculations of turbulence and wind speed
  - ***AWMA Streamline*** defines the set of constants for modeling all structures as streamlined. If omitted, rectangular building constants are used.

ORD Switches

- ***Keyword: ORDDWNW***
- ***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 from 0.6 to 0.7.
  - ***ORDCav:*** modifies the cavity calculations: Used for PRIME2.
- If no switch applied, current AERMOD methodology used.

Summary

- From the start of research to getting PRIME2 code to EPA, it took about 13 months
- Getting to an implemented PRIME2 Alpha version took about 10 months once the code was provided to EPA
- Interaction with EPA along the was very good and useful, especially since this was the first time.

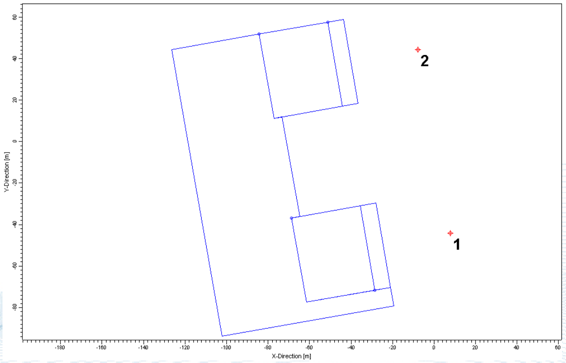
Alpha Version Evaluation: AERMOD/PRIME; PRIME2 and ORD Versus Field Observations

Databases

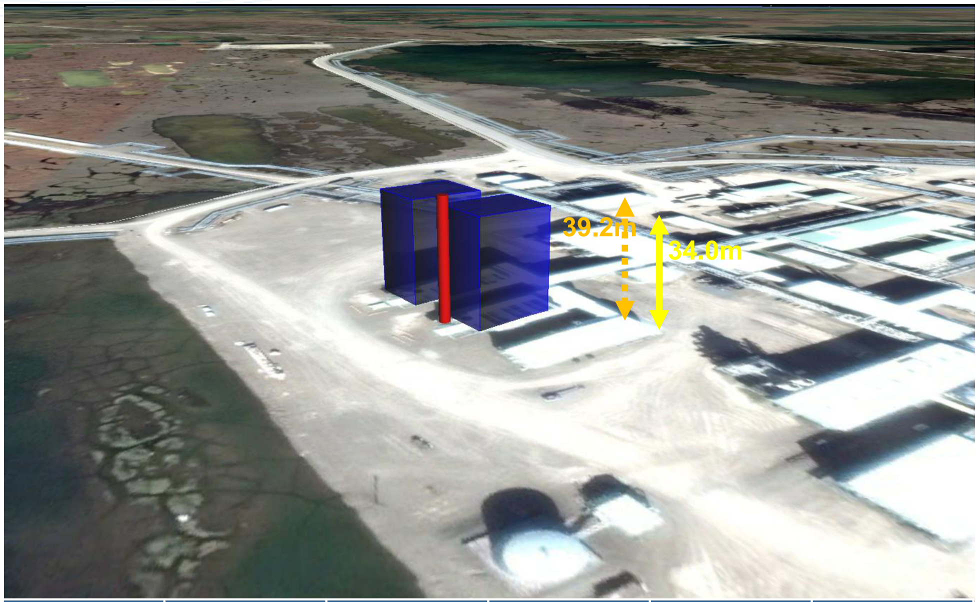
Bowline Point

	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

- 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)

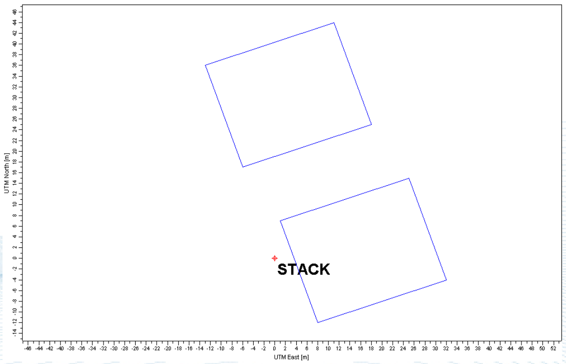


Alaska North Slope Field Study



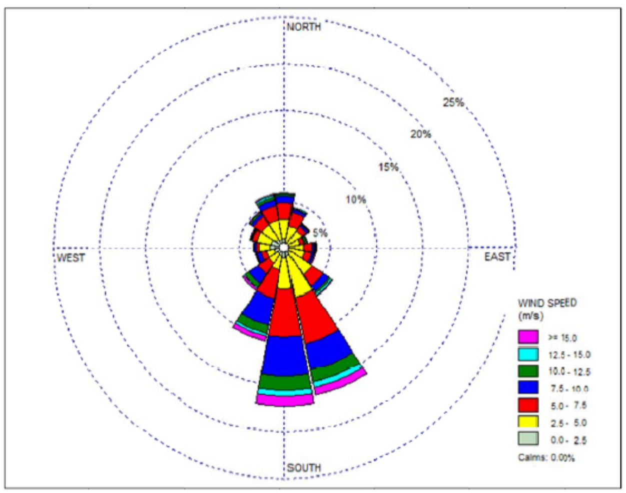
	Q (g/s)	Hs (m)	Ts (K)	Vs (m/s)	Ds (m)
STACK	1	39.2	554-584	17-21	3.66

- 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

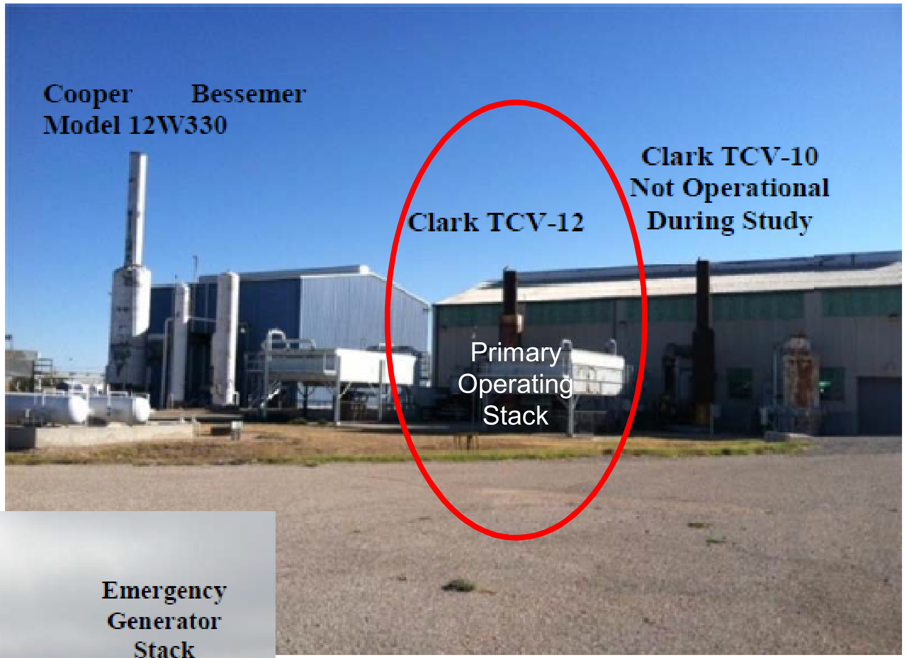


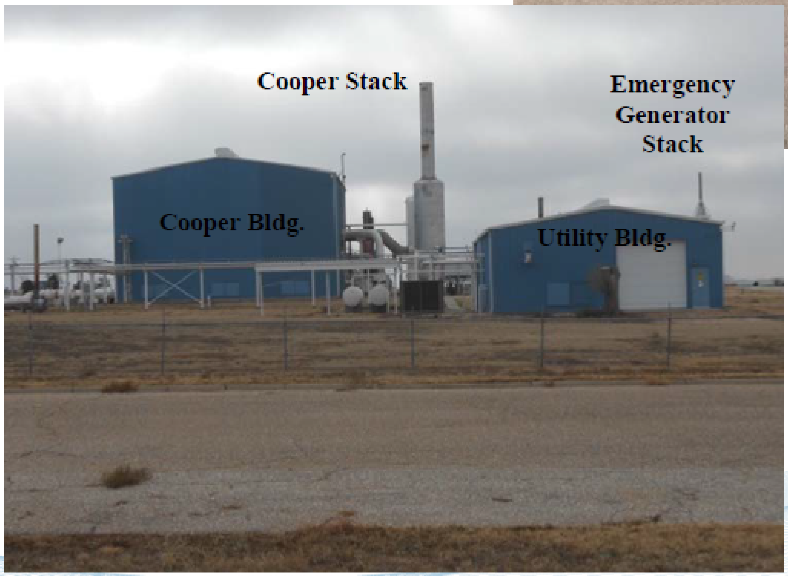
PRCI Balko OK
Monitor Locations

Annual 10 m onsite wind rose for 13-month monitoring period.



PRCI Balko OK Stack Locations





Source Parameters

Source Name	Q (g/s)	H_s (m)	T_s (K)	V_e (m/s)	D (m)
C9: Clark TCV 12	~ 15 g/s	10.50	588.7	23.3	1.04
		Primary Source			
C10: Cooper-Bessemer	Intermittent	20.73	549.82	19.8	1.22
EGEN	Intermittent	8.44	810.93	13.1	0.21
Boiler	Intermittent	6.7	699.82	0.001	0.3048

Definition of Key Terms

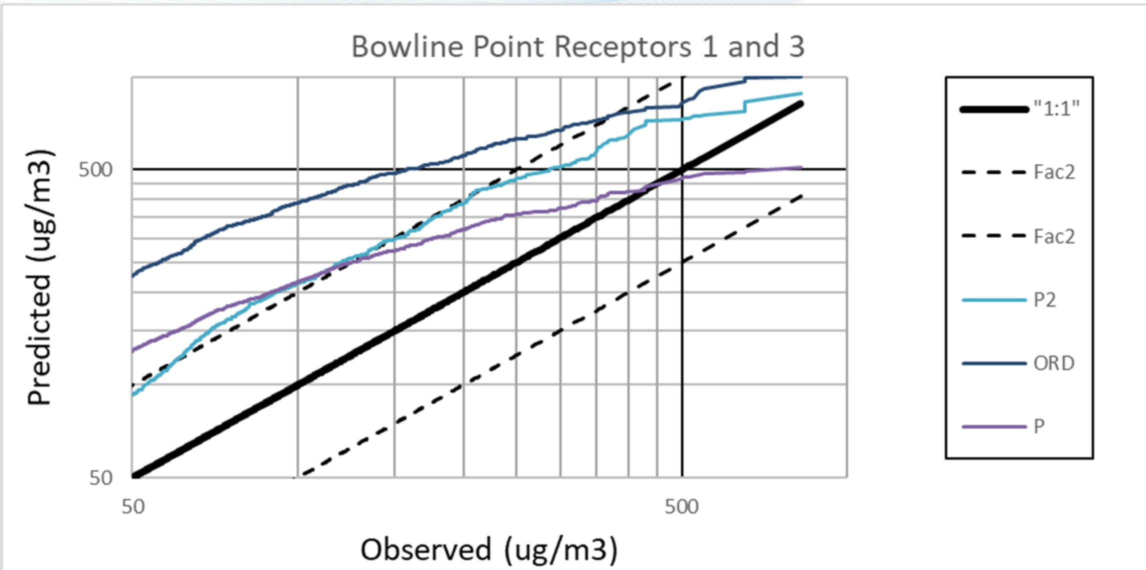
- RHC: the Robust Hight Concentration. Represents a smoothed estimate of the highest concentration based on an exponential fit to the top 25 concentrations.
- Q-Q plot:

  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.

Model Runs

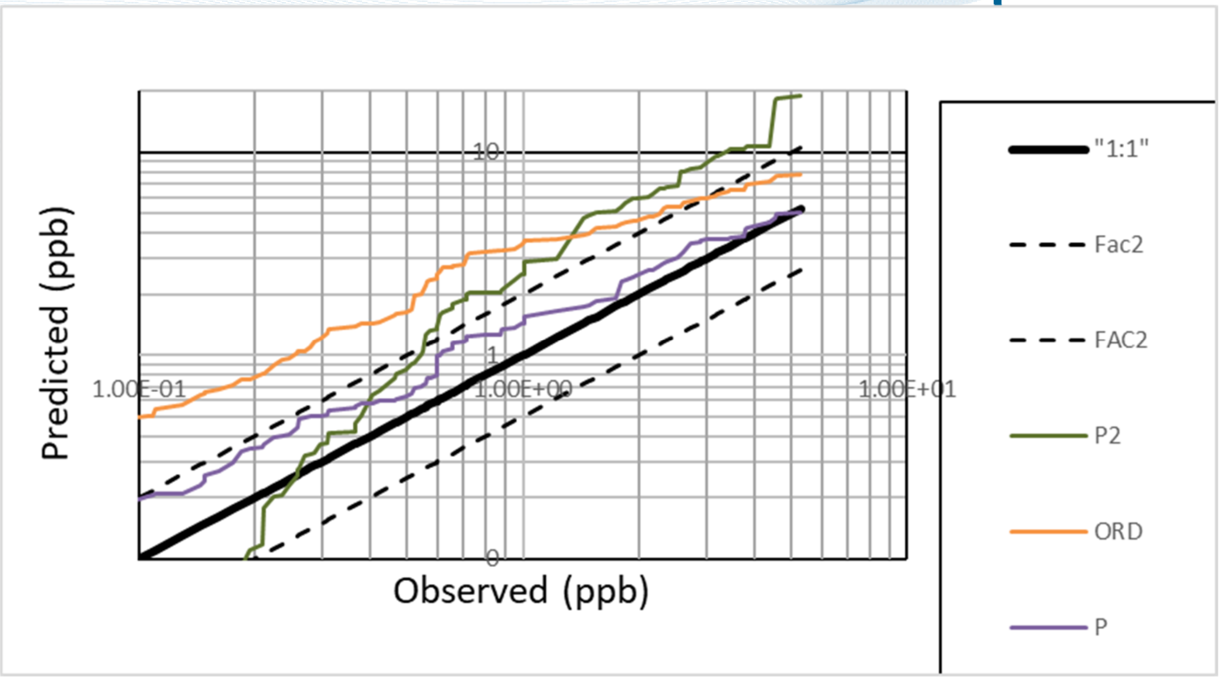
1. ***P2***: 19191 PRIME2; Uses plume height wind speed for concentration calculations (includes ORD cavity fix) – Official PRIME2 Option
2. ***ORD***: 19191 ORD
3. ***P***: 19191 AERMOD/PRIME

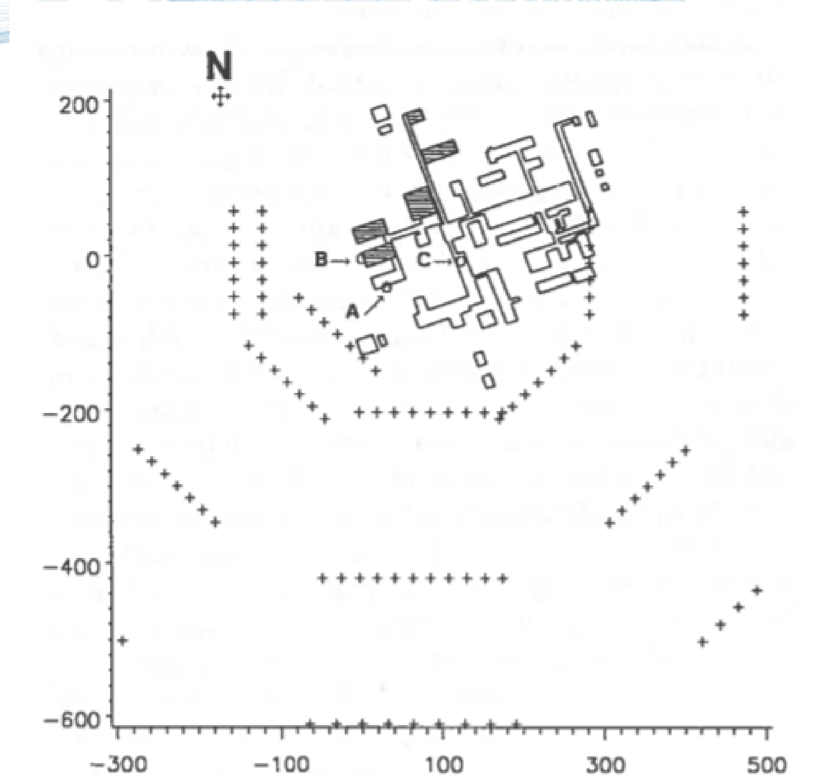
Bowline Point Receptor 1&3



Model Scenario		RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/ RHC_{obs}
P2		975.55	763.40	1.28
ORD		1106.07	763.40	1.45
P		630.98	763.40	0.83

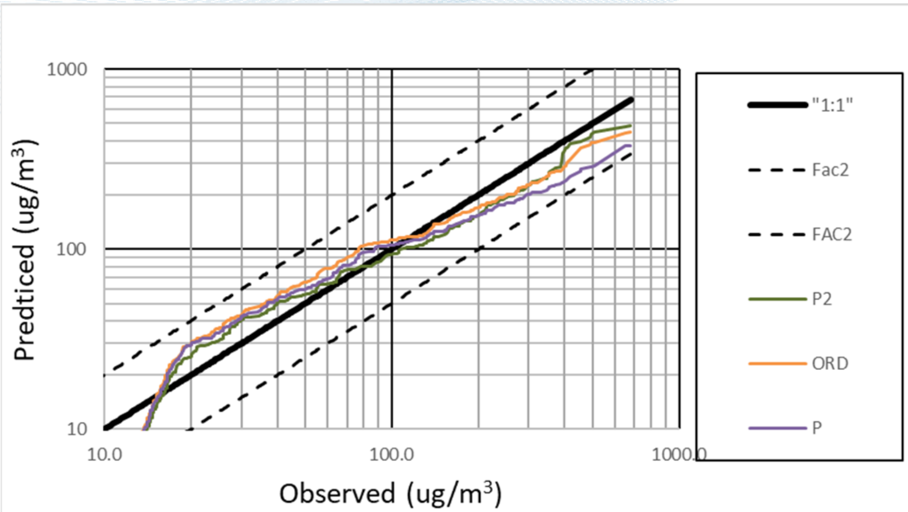
Alaska North Slope





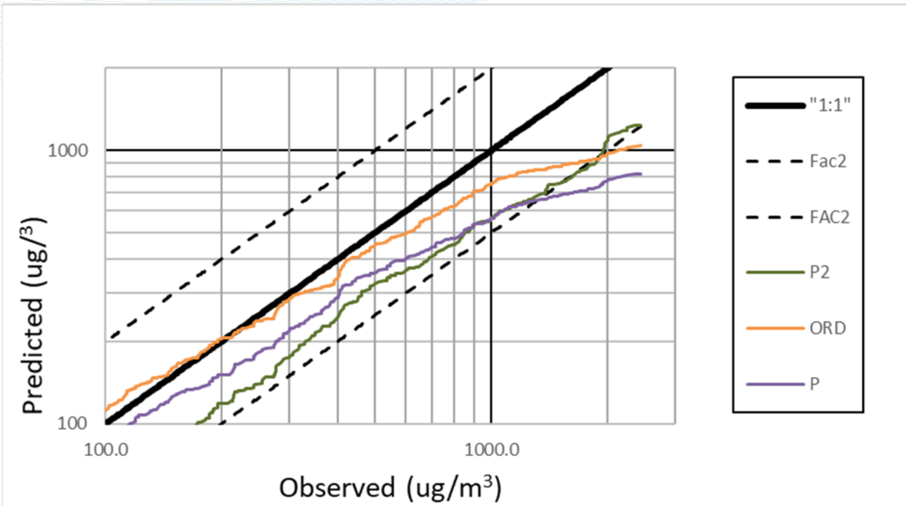
Model Scenario		RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/ RHC_{obs}
P2		19.28	6.35	3.04
ORD		9.85	6.35	1.55
P		6.70	6.35	1.06

PRCI Monitor 1 – Far North (425 m)



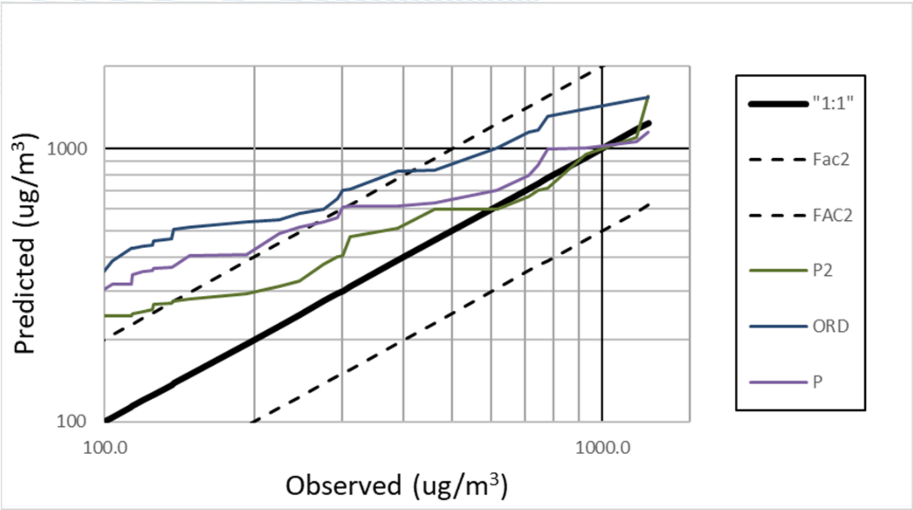
Model Scenario	RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/ RHC_{obs}
P2	599.37	697.5	0.86
ORD	498.90	697.5	0.72
P	361.72	697.5	0.52

PRCI: Monitor 2 – North Close-In (140 m)



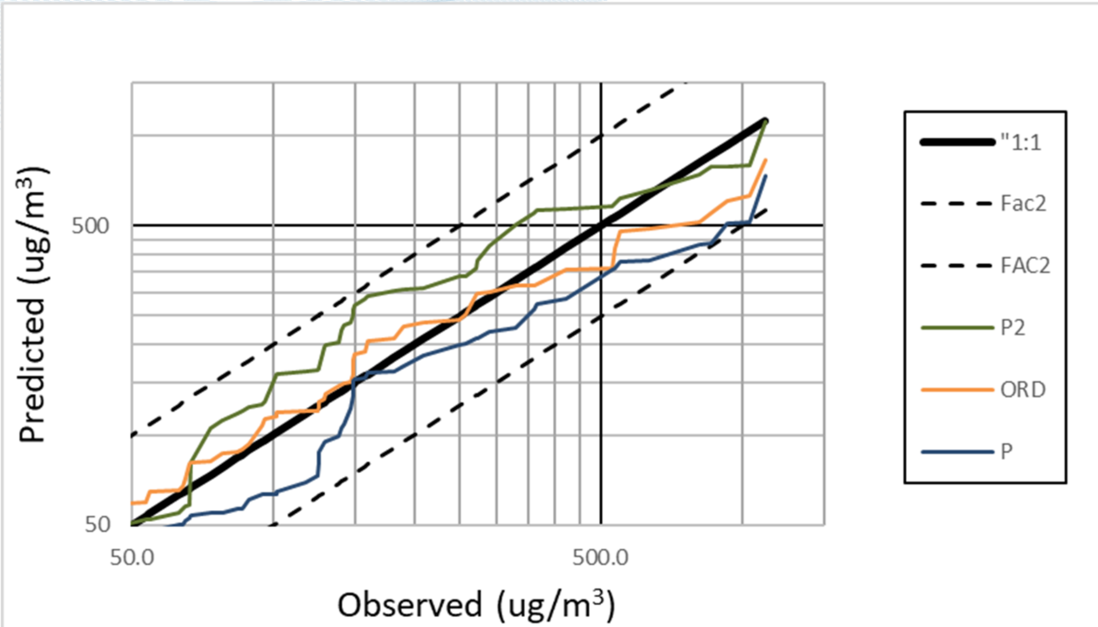
Model Scenario		RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/RHC_{obs}
P2		1549.63	2617.59	0.59
ORD		1111.15	2617.59	0.42
P		1030.82	2617.59	0.39

PRCI: Monitor 3 – East Close-In ~ 100 m)



Model Scenario		RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/ RHC_{obs}
P2		1156.11	1197.48	0.97
ORD		1855.12	1197.48	1.55
P		1600.12	1197.48	1.34

PRCI Monitor 4 Southwest ~ 250 m)



Model Scenario		RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/ RHC_{obs}
P2		1179.73	1216.35	0.97
ORD		879.47	1216.35	0.72
P		678.40	1216.35	0.56

Summary of Model Performance Table of RHC_p/RHC_o Values

Model Scenario	Data Base					
	Alaska	PRCI #1	PRCI #2	PRCI #3	PRCI #4	Bowline
P2	3.04	0.86	0.59	0.97	0.97	1.28
ORD	1.55	0.72	0.42	1.55	0.72	1.45
P	1.06	0.52	0.39	1.34	0.56	0.83

Best Performance

API/AWMA PRIME PLUME RISE EVALUATION

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.
- Plume rise model accounts for:
  - Temperature stratification;
  - Wind shear and initial plume size,
  - Streamline ascent/descent,
  - Enhanced dilution due to building induced turbulence.
  - Velocity deficit in the building wake
- Similar to the model developed by other researchers who tested their model against wind tunnel and field observations.

Reasons For Plume Rise Assessment

- PRIME2 has shown a tendency to overpredict observations for the Bowline Point and Alaska North Slope field databases.
- If PRIME is underestimating plume rise, this could explain the PRIME2 overprediction tendency.
- The PRIME plume rise algorithm has never been tested against field and/or wind tunnel observations for building wake situations.
- PRIME entrainment constants ***(Alpha and Beta)*** differ from those used by other researchers who developed a similar model and tested their integral models against observations.
- ***Alpha and Beta were evaluated in this study***

Plume Rise Databases EPA (Huber/Snyder)

- EPA data base:
  - Concentration profiles versus height were measured at several downwind distances for stack height to building height ratios.
  - All information is documented in a peer reviewed paper.
- CPP Wind Tunnel Data Base
  - Plume visualizations from the Mirant Power Plant EBD wind tunnel study were evaluated to estimate plume rise
  - Four cases were selected where the building dimensions changed: heights varied from 30 to 42 m. The buildings were directly upwind of the 48.2 m stack.

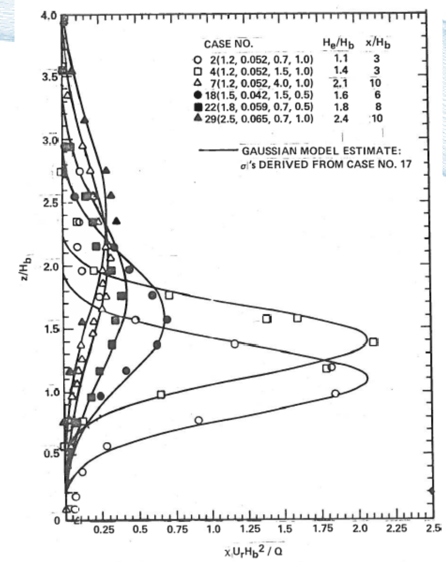


Figure 10. Vertical concentration profiles for isolated stack. In this and following legends, H_e/H_b identifies the presumed effective stack height as determined from analysis of vertical concentration profiles at position, x/H_b (see table 3).

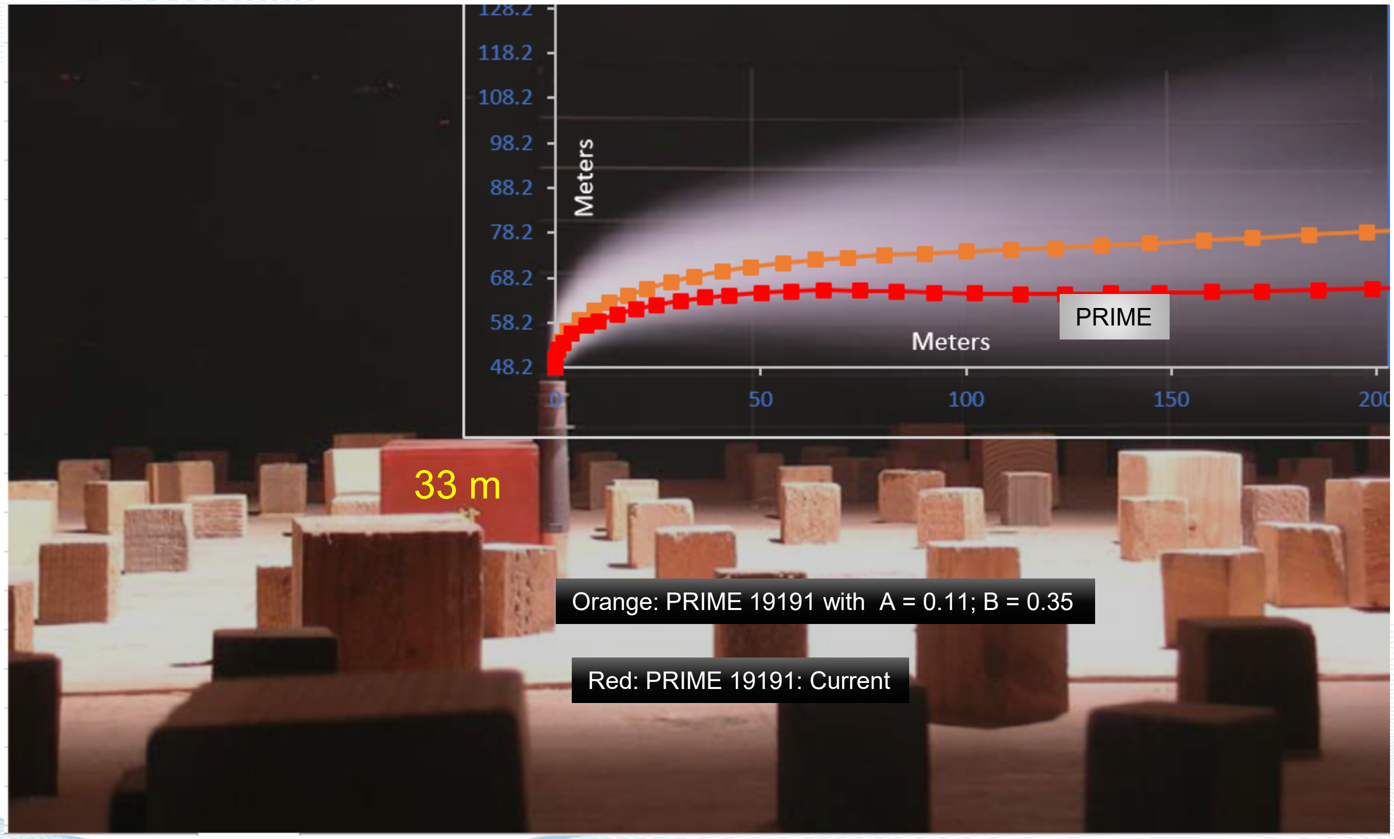
Methodology

- The 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.
- Based on the comparison, the PRIME entrainment constants, Alpha (A) and Beta (B), in AERMOD_v19191 were varied as follows to obtain better agreement with observations.
  - Case 1: Current AERMOD: Alpha = A= 0.11; Beta0 = 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 Results

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

Current PRIME Underestimates Plume Rise; Modified PRIME Better



Basic Finding From Plume Rise Assessment

- The recommended entrainment constants, Alpha = 0.11 and Beta = 0.35, provide overall better agreement with plume rise observations
- Recommended entrainment constants should be used to evaluate AERMOD and PRIME2 against field observations (i.e., Bowline Point, Alaska and PRCI).

Task 2:

Modify AERMOD to Include Updated PRIME Entrainment Constants and Evaluate Against Field Observations

Scope of This Phase

- Assemble all monitoring data and meteorological data for the Bowline Point, Alaska and PRCI field databases.
- Assemble all AERMOD input files
- Run AERMOD/PRIME, PRIME2 and ORD
- Prepare Q-Q plots of model versus observed concentrations for all cases
- Compute the robust highest (RHC) for all model predictions and observations and compare.

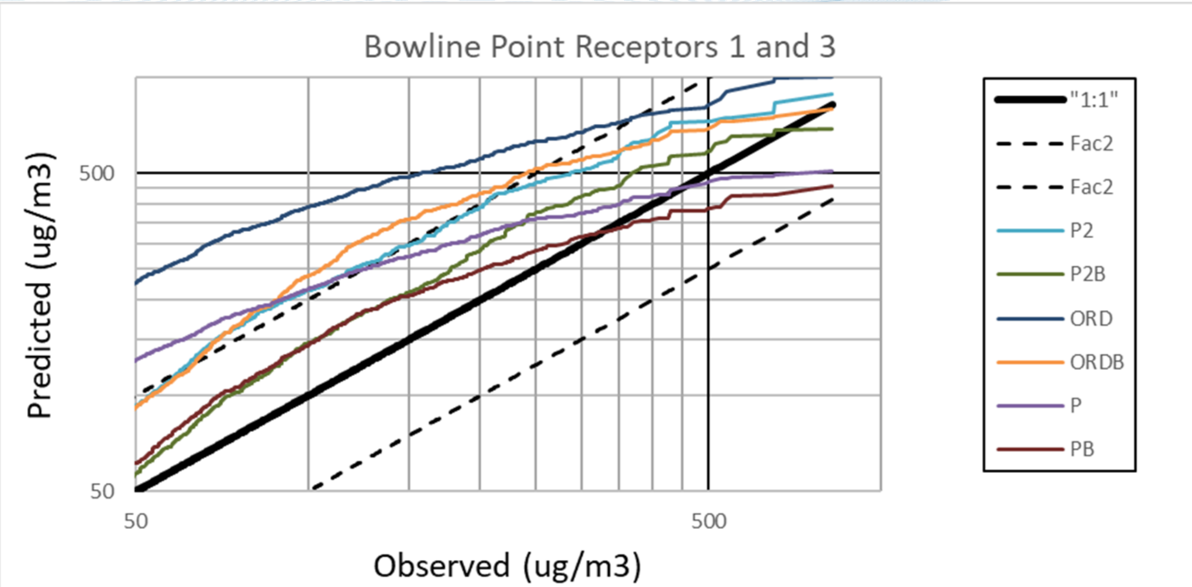
Model Runs

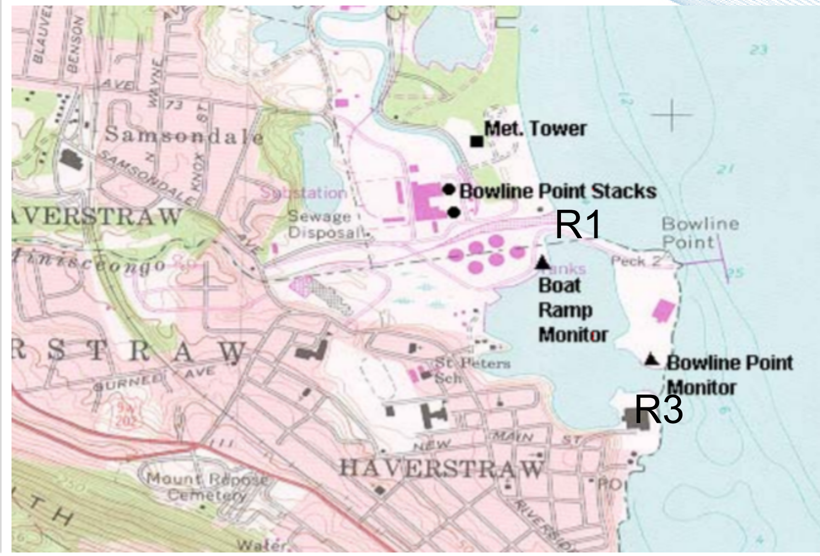
1. ***P2***: 19191 PRIME2 : Uses plume height wind speed for concentration calculations (includes ORD cavity fix) – Official PRIME2 Option
2. ***P2B***: 19191 PRIME2 with Beta = 0.35
3. ***ORD***: 19191 ORD
4. ***ORDB***: 19191 ORD with Beta = 0.35
5. **P**: 19191 AERMOD/PRIME
6. ***PB***: 19191 AEMOD/PRIME with Beta = 0.35

Model Evaluation

- Data Bases
  - Bowline Point
  - Alaska North Slope Field Study
  - PRCI
- Statistics
  - Q-Q Plots
  - Robust Highest Concentration Ratio RHC_p/RHC_o - top 25

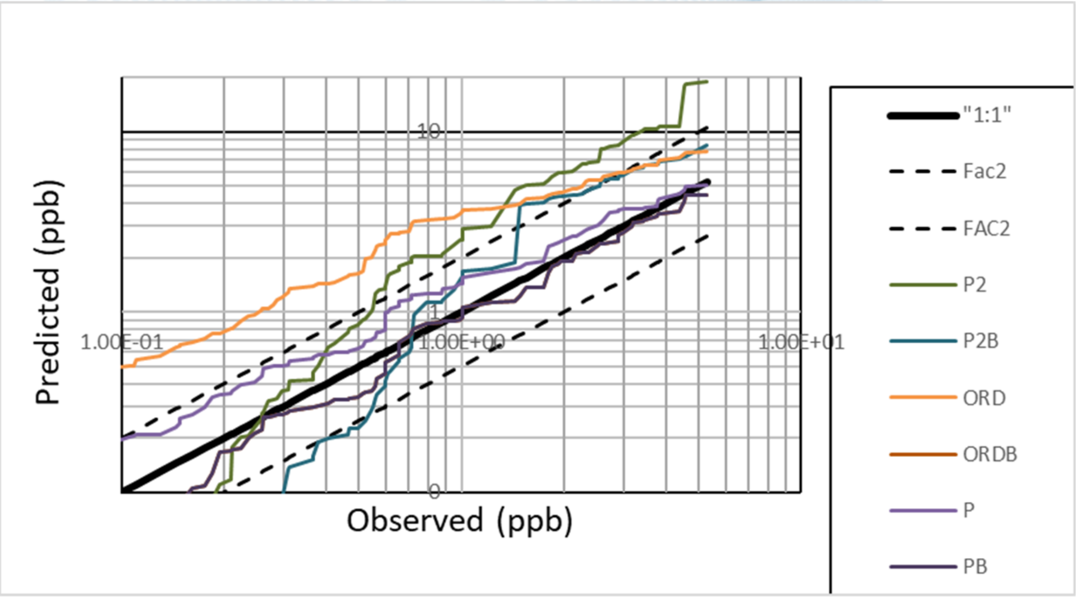
Bowline Point Receptor 1&3

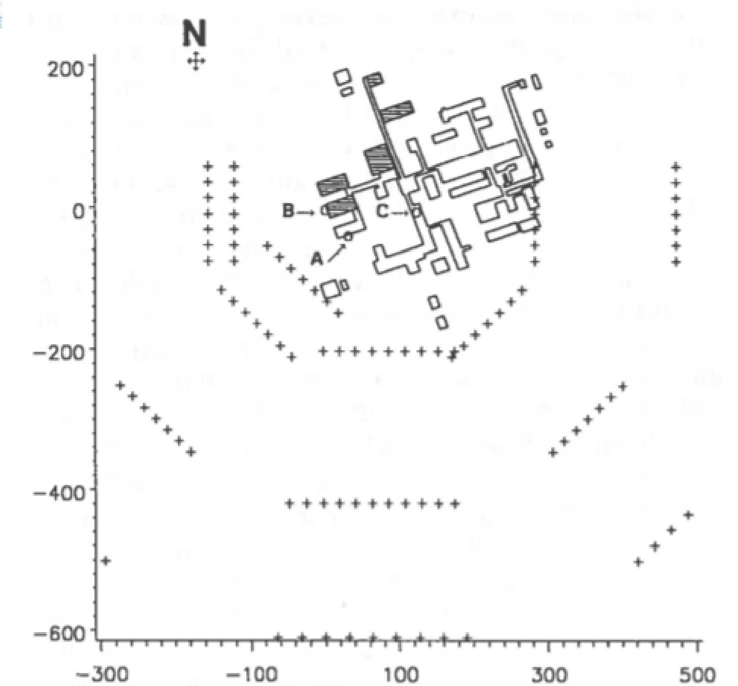




Model Scenario	RHC_{pre} (ug/m3)	RHC_{obs} (ug/m3)	RHC_{pre}/RHC_{obs}
P2	975.6	763.4	1.28
P2B	821.0	763.4	1.08
ORD	1106.1	763.4	1.45
ORDB	864.8	763.4	1.13
P	631.0	763.4	0.83
PB	480.5	763.4	0.63

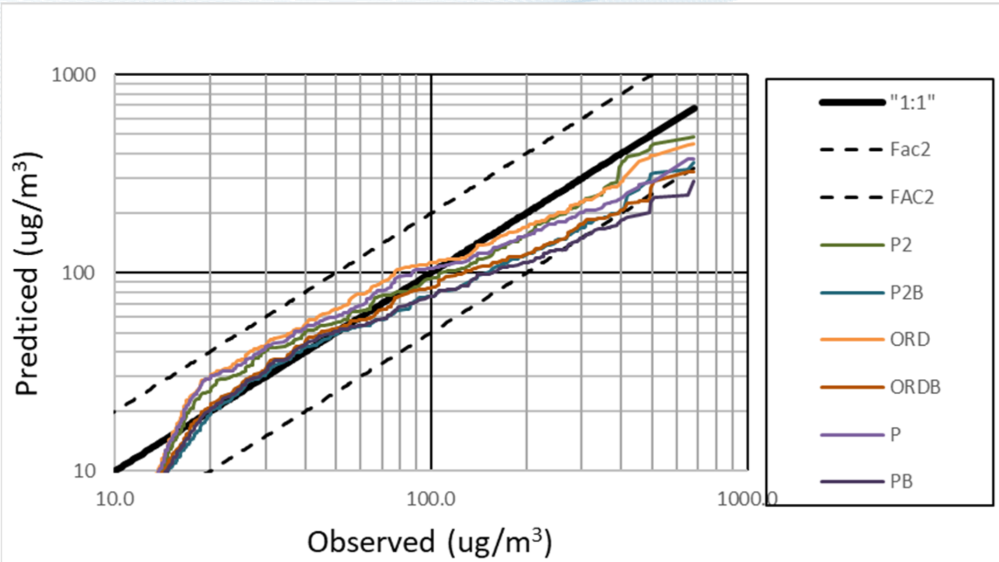
Alaska North Slope

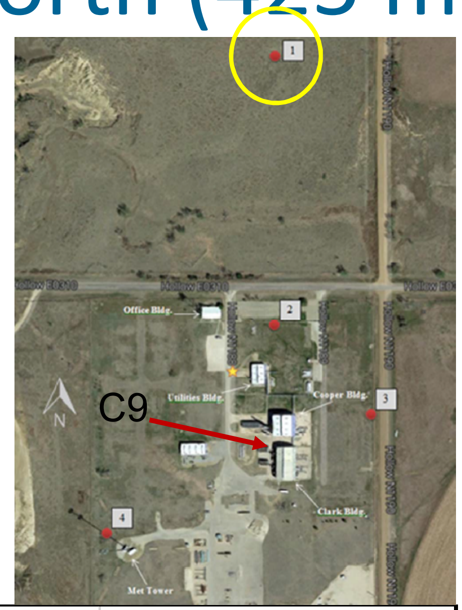




Model Scenario	RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/RHC_{obs}
P2	19.3	6.3	3.04
P2B	9.7	6.3	1.52
ORD	9.9	6.3	1.55
ORDB	5.6	6.3	0.88
P	6.7	6.3	1.06
PB	5.6	6.3	0.88

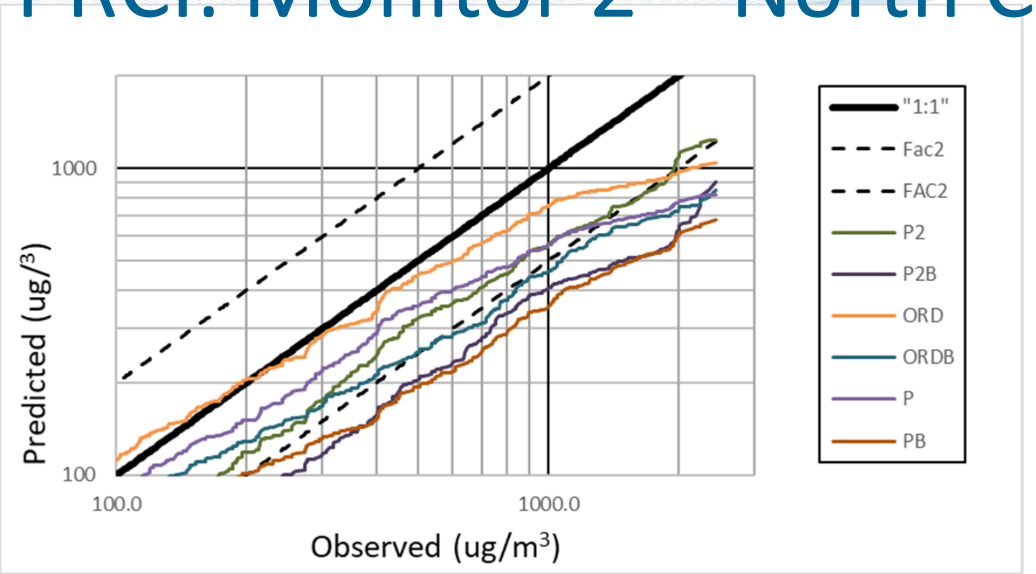
PRCI Monitor 1 – Far North (425 m)





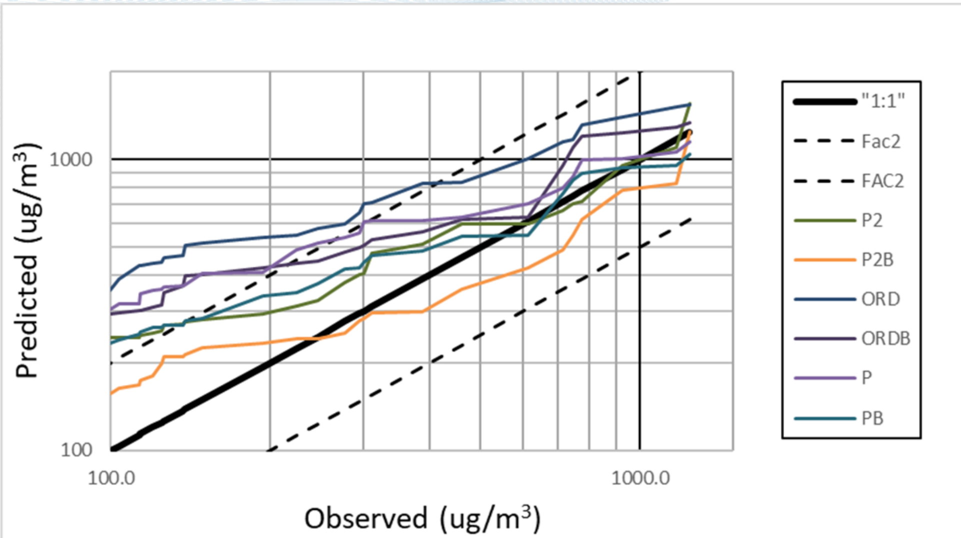
Model Scenario		RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/RHC_{obs}
P2		599.4	697.5	0.86
P2B		366.1	697.5	0.52
ORD		498.9	697.5	0.72
ORDB		306.4	697.5	0.44
P		361.7	697.5	0.52
PB		274.9	697.5	0.39

PRCI: Monitor 2 – North Close-In (148 m)



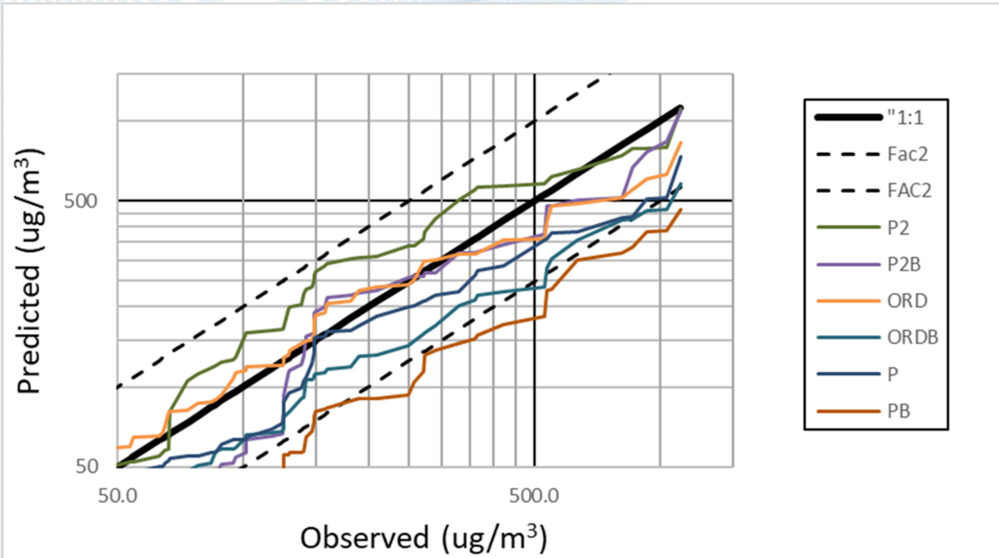
Model Scenario	RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/RHC_{obs}
P2	1549.6	2617.6	0.59
P2B	917.2	2617.6	0.35
ORD	1111.2	2617.6	0.42
ORDB	850.6	2617.6	0.32
P	1030.8	2617.6	0.39
PB	779.2	2617.6	0.30

PRCI: Monitor 3 – East Close-In (~ 100 m)



Model Scenario	RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/RHC_{obs}
P2	1156.1	1197.5	0.97
P2B	923.1	1197.5	0.77
ORD	1855.1	1197.5	1.55
ORDB	1591.7	1197.5	1.33
P	1600.1	1197.5	1.34
PB	1166.4	1197.5	0.97

PRCI Monitor 4 Southwest (~250 m



Model Scenario		RHC_{pre} (ppb)	RHC_{obs} (ppb)	RHC_{pre}/RHC_{obs}
P2		1179.7	1216.4	0.97
P2B		946.5	1216.4	0.78
ORD		879.5	1216.4	0.72
ORDB		686.2	1216.4	0.56
P		678.4	1216.4	0.56
PB		473.6	1216.4	0.39

Summary of Model Performance
Table of RHC_p/RHC_o Values

19191 Current PRIME Plume Rise

Model Scenario	Data Base					
	Alaska	PRCI #1	PRCI #2	PRCI #3	PRCI #4	Bowline
P2	3.04	0.86	0.59	0.97	0.97	1.28
ORD	1.55	0.72	0.42	1.55	0.72	1.45
P	1.06	0.52	0.39	1.34	0.56	0.83
Best Performance						

19191 with Beta = 0.35: Improved Plume Rise

Model Scenario	Data Base					
	Alaska	PRCI #1	PRCI #2	PRCI #3	PRCI #4	Bowline
P2B	1.52	0.52	0.35	0.77	0.78	1.08
ORDB	0.88	0.44	0.32	1.33	0.56	1.13
PB	0.88	0.39	0.30	0.97	0.39	0.63
Best Performance						

Summary of Model Performance Table of RHC_p/RHC_o Values

19191 Current PRIME Plume Rise Versus PRIME with Beta = 0.35

Model Scenario	Data Base					
	Alaska	PRCI #1	PRCI #2	PRCI #3	PRCI #4	Bowline
P2B	1.52	0.52	0.35	0.77	0.78	1.08
P2	3.04	0.86	0.59	0.97	0.97	1.28
P	1.06	0.52	0.39	1.34	0.56	0.83
Best Performance						
2nd Best						

Conclusions

- The current PRIME plume rise model tends to underpredict plume rise. Better agreement with observations is seen when Beta is changed from 0.6 to 0.35.
- With improved plume rise (Beta = 0.35), the large overpredictions previously seen with PRIME2 for the Alaska field data base were decreased by a factor of two but PRIME2 still overpredicts.

Conclusions

- With the current plume rise, PRIME2 (P2) provides the best overall agreement with field observations.
- With improved plume rise (Beta = 0.35), PRIME2 provides the overall best agreement with field observations.
- P2 and P2B agree better with all field observations than the current AERMOD 19191 (P). P2 show the overall best agreement.

What's Next

- Evaluate why all models tend to underpredict for the PRCI database – in process and maybe a surface roughness issue.
- A more accurate model should be available to users sometime in the near future (may be in the form of Alpha Options)
- API is funding additional research to improve PRIME2 and submit a peer reviewed paper to Journal
- The updated entrainment constant will be included as an Alpha Option in the next AERMOD release: early 2021.
- Hopefully, the Alpha Options that perform best become Beta Options and then standard Features of AERMOD

Questions?

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