NO_2 Conversion Model Development

EPA RSL Workshop

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

Monday, June 21, 2021

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NO_2 Conversion - Development

- **Purpose/Goal:** Improve NO_2 predictions for a wide variety of sources
- **External Collaboration:** API, PRCI, AECOM, ERM, CERC, WRAP/WESTAR, R2 & R6, BLM, EPRI
- **AERMOD v.21112:** Two new **alpha** options; developed by CERC and AECOM/ERM/EPA
  - Travel Time Reaction Method (TTRM), conversion of NO to NO2 based on reaction time limitations calculated from the travel time from source to receptor.
  - General Reaction Set Method (GRSM), conversion based on equilibrium chemistry between NO, NO2, and ozone.
- **Two near-field NO_2 field datasets finalized in 2019-2020**
  - Balko, OK: 4 monitors, ~12 months of data
  - Denver-Julesburg Basin, CO: 12 monitors, ~2 months of data
- **Additional datasets for evaluations**
  - Existing NO2 datasets, Palaau, Empire Abo, Wainwright, & Prudhoe Bay
  - Identify any supplemental datasets from NO_2 network

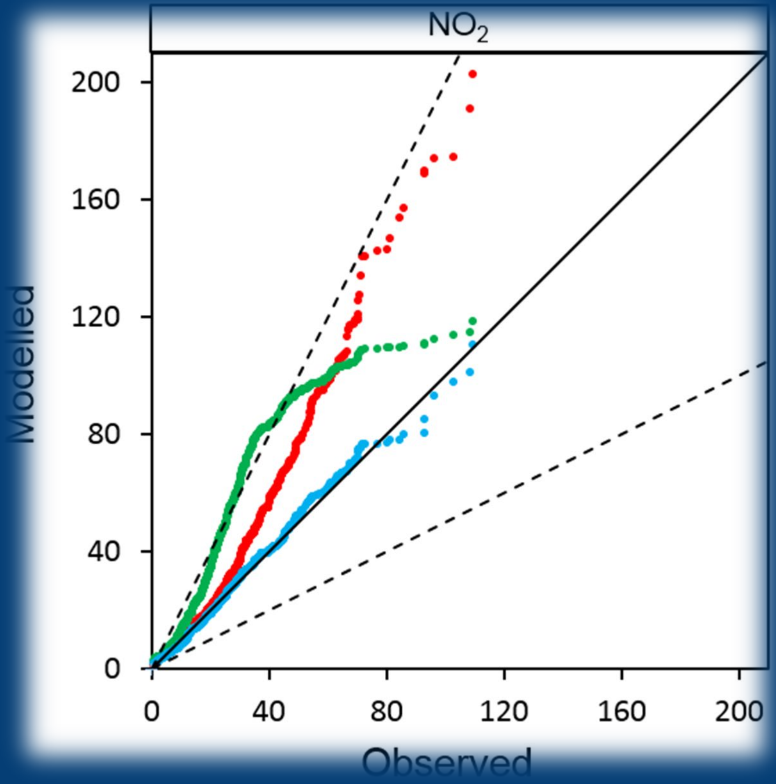
NO_2 Conversion - Work Needed

- **Testing for TTRM and GRSM**
  - Both were added to the AERMOD code relatively late in the development process, need to be tested to verify functionality
- **Determine the appropriate application of TTRM**
  - Unclear if TTRM is a stand-alone method (unlikely) or needs to be paired with ARM2, OLM, or PVMRM for near-field
- **Evaluation with new and old datasets**
  - Comprehensive model evaluations of all methods with all datasets
  - Determine if there is a best performing model & that there is no bias to underpredict
  - Add best performing model to newer source types (e.g., RLINE)

NO_2 Conversion – NO2/NOx ISRs

- NO2/NOx in-stack ratio database updated Oct 2020
  - Database combined with old "alpha" database
  - Added new survey data from EPRI and PRCI
  - Four different tabs of data in the spreadsheet
- Varying levels of detail provided in each dataset
  - "Alpha" dataset not associated with alpha/beta options in AERMOD, data was just the first round collected prior to the formal data collection (2074 entries)
  - "NO2_ratio_dataset" has extensive meta-data, intended to provide traceability and some QA (2379 entries)
  - "PRCI" (3199 entries) and "EPRI" (123 entries) result of surveys conducted by each trade group
- No hierarchy to the data, all data is provided as-is
  - Up to the regulating agency to determine the applicability of any data in the database

Theory, application and evaluation of the Generic Reaction Set Method (GRSM) for NO_2 chemistry



Dr. Jenny Stocker

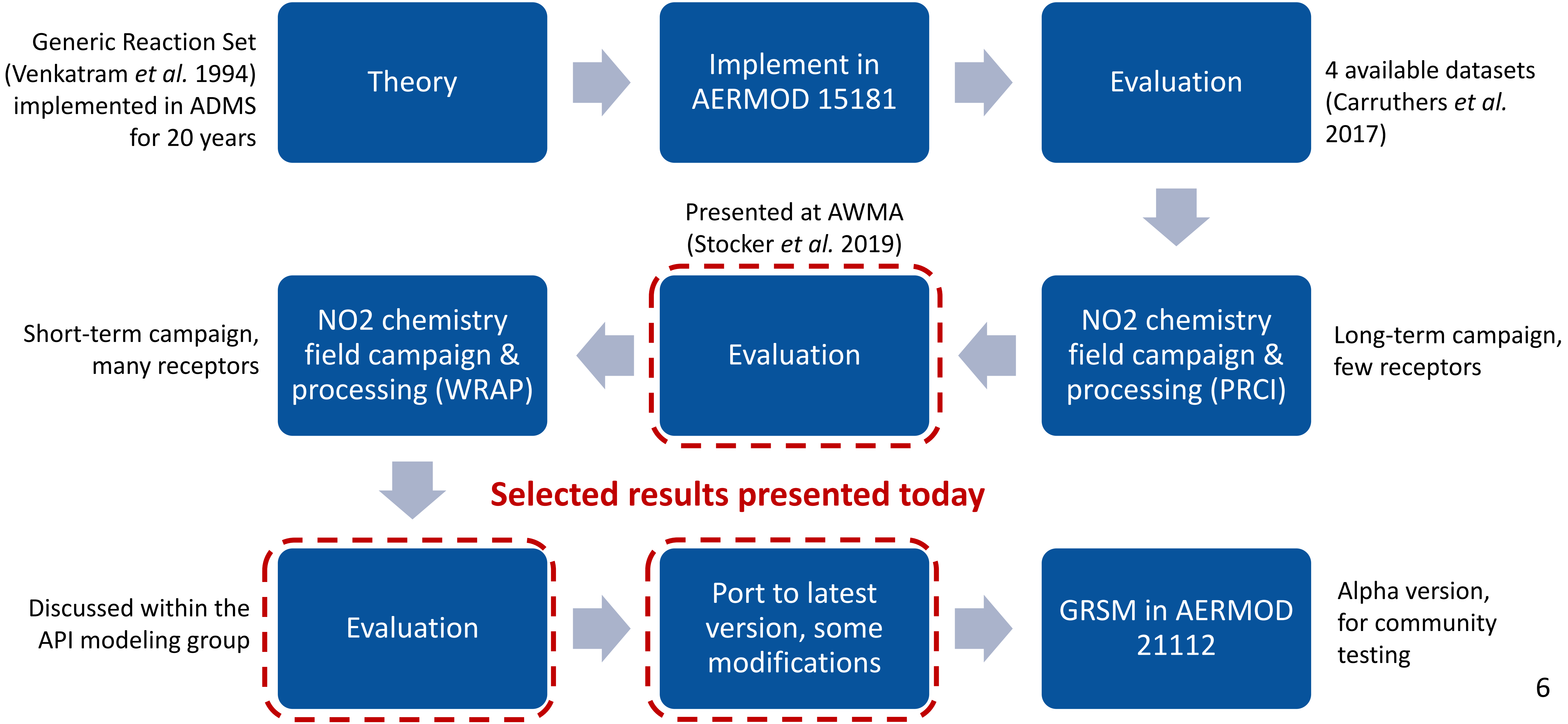
2021 EPA Regional/State/Local Dispersion Modelers' Workshop

21 June 2021

Online

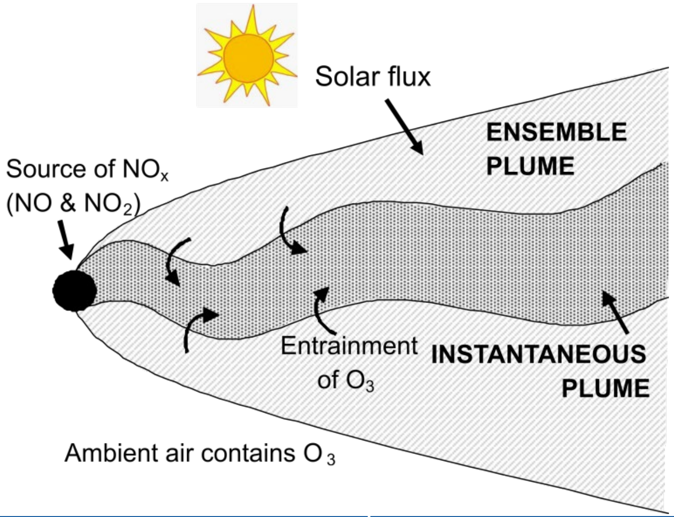
GRSM development

Development of GRSM (2015-2021, funded by API)



AERMOD chemistry schemes

*Comparison of **regulatory** NO_2 conversion options that require O_3 background compared to GRSM **alpha** option*



NO_x chemistry

'Ozone titration'

$NO + O_3 \rightarrow NO_2 + O_2$

'Photolysis'

$NO_2 + \text{sunlight} \rightarrow NO + O_3$

Fast reactions (seconds - minutes)

Item	OLM (Ozone-Limiting Method) *regulatory*	PVMRM (Plume Volume Molar Ratio Method) *regulatory*	GRSM (GRS Method) *alpha*
Hourly background	O_3	O_3	O_3, NO_x, NO_2
Method for 'O_3 titration'	100% conversion	100% conversion	Explicit calculation
Method for 'photolysis'	Neglects	Neglects	Explicit calculation
Method for entrainment of O_3 into the plume	Fully entrained into *ensemble* plume	Limited entrainment (volume-based approach) into *instantaneous* plume	Limited entrainment (cross-sectional area-based approach) into *instantaneous* plume
Main sources of inaccuracy of predicted NO_2	Full entrainment into ensemble plume so upper bound for NO_2	Neglects reaction rates; assumptions relating to entrainment method	Reaction rates; assumptions relating to entrainment method

Evaluation methodology

- Configure AERMOD to model NO_x concentrations (*initial model set up by API contractor, AECOM*)
- Evaluate NO_x model performance
- Modify configuration to ensure best NO_x performance - e.g., evaluate different met options
- Configure AERMOD to model NO_2 concentrations using OLM, PVMRM and GRSM
- Evaluate NO_2 model performance in terms of:
  - Performance relative to NOx - e.g., if is NO_x is under-predicting, so should NO_2 and vice versa
  - Chemistry performance - e.g., compare measured and observed NO_2/NO_x
  - Near-field and far field performance

Ensure data paired in space and time

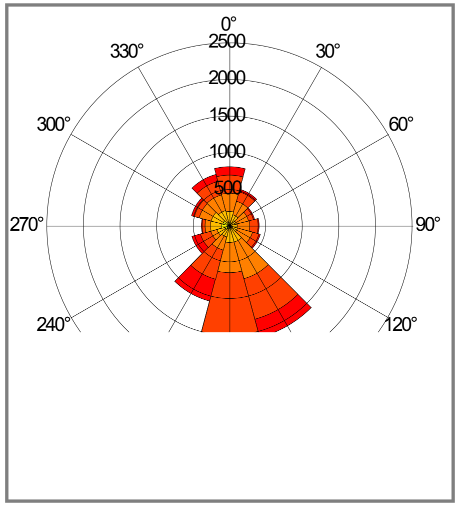
PRCI NO_2 chemistry field campaign (1 of 3)

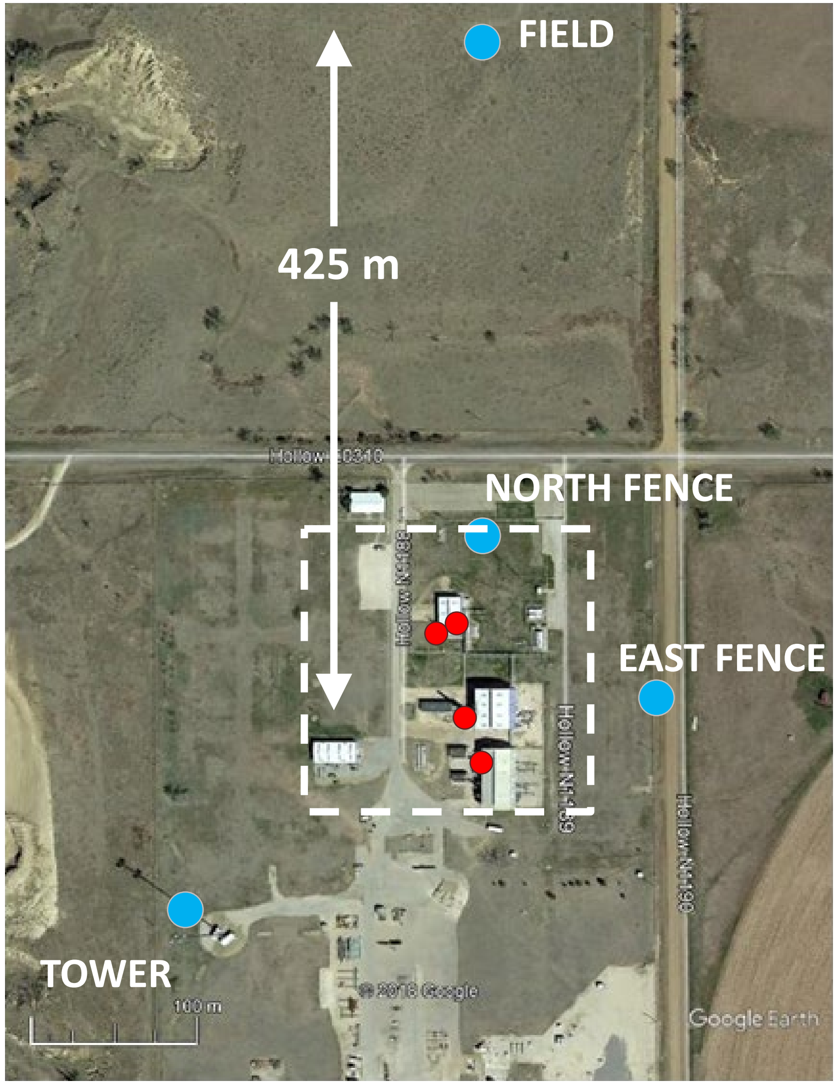
13 month campaign at Balko, Oklahoma

4 main NO_2 sources:

- 2 compressor engine stacks
- 1 boiler
- 1 emergency generator

Meteorological instruments on 30 m tower





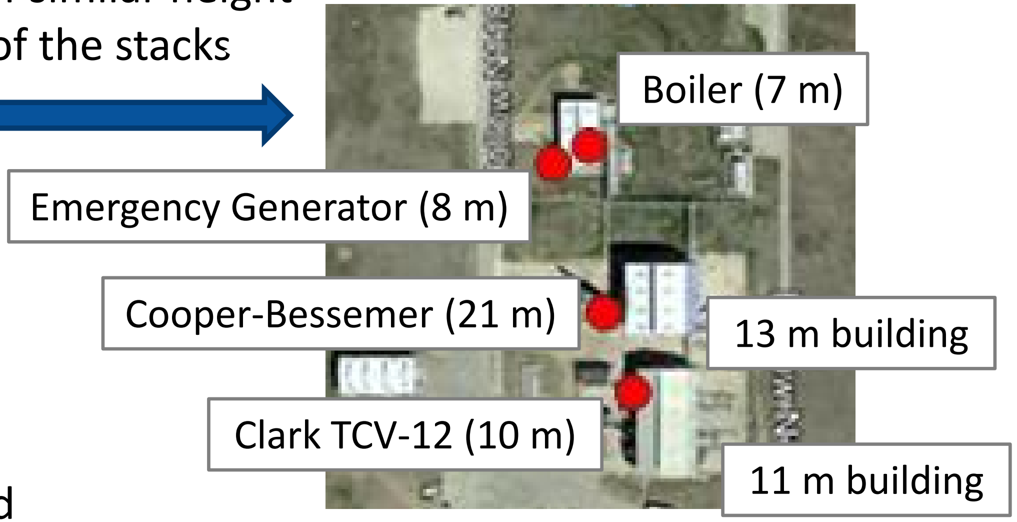
Parametric Emissions Monitoring Systems (PEMS) recorded hourly engine parameters (compressor engines only)

4 monitors:

- 'North Fence' and 'Field' in alignment with the stacks and the prevailing wind
- 'East Fence'
- 'Tower'

'Downwind sector' datasets analysed

Buildings adjacent to compressor engine stacks of similar height to one of the stacks

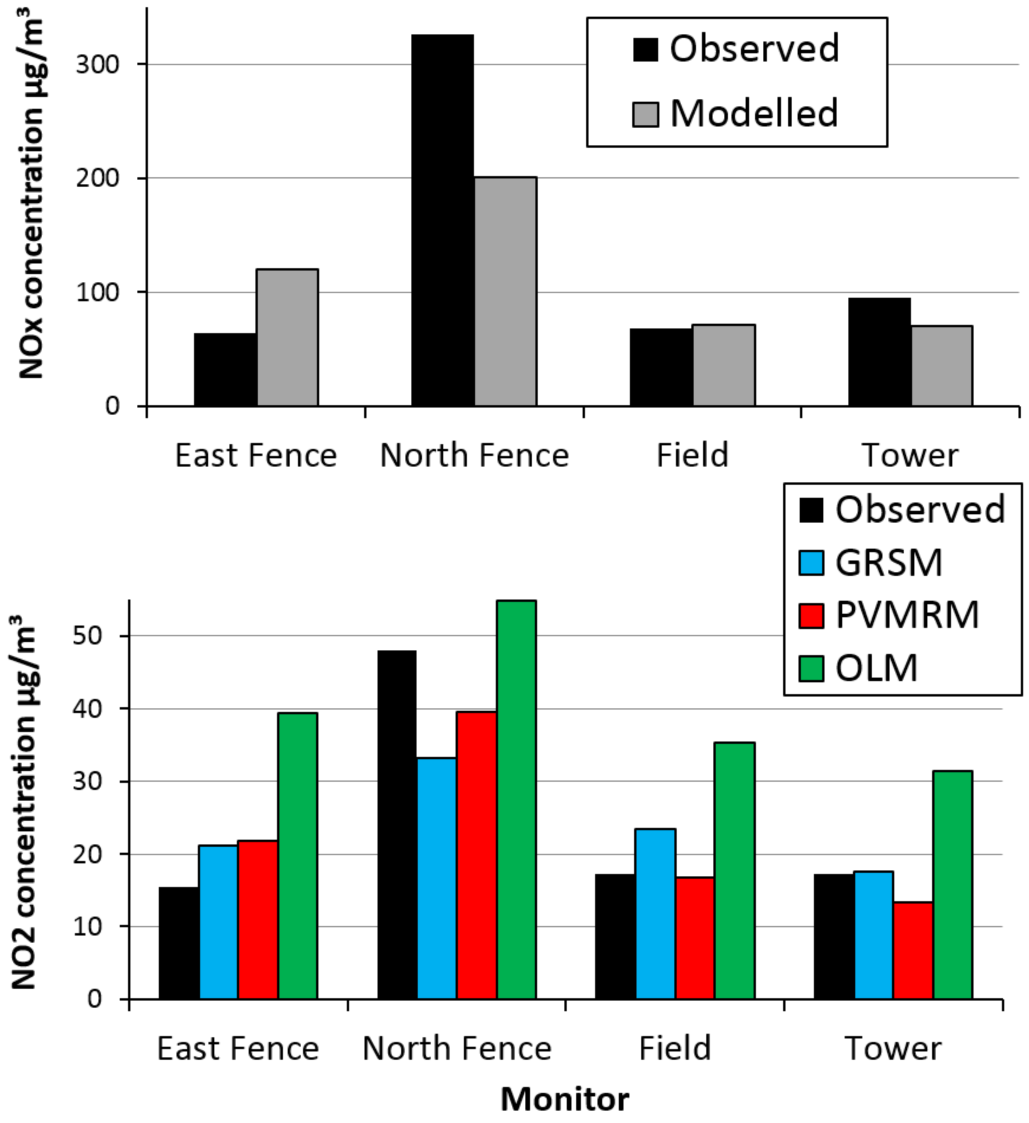


Flat, scrubby grassland

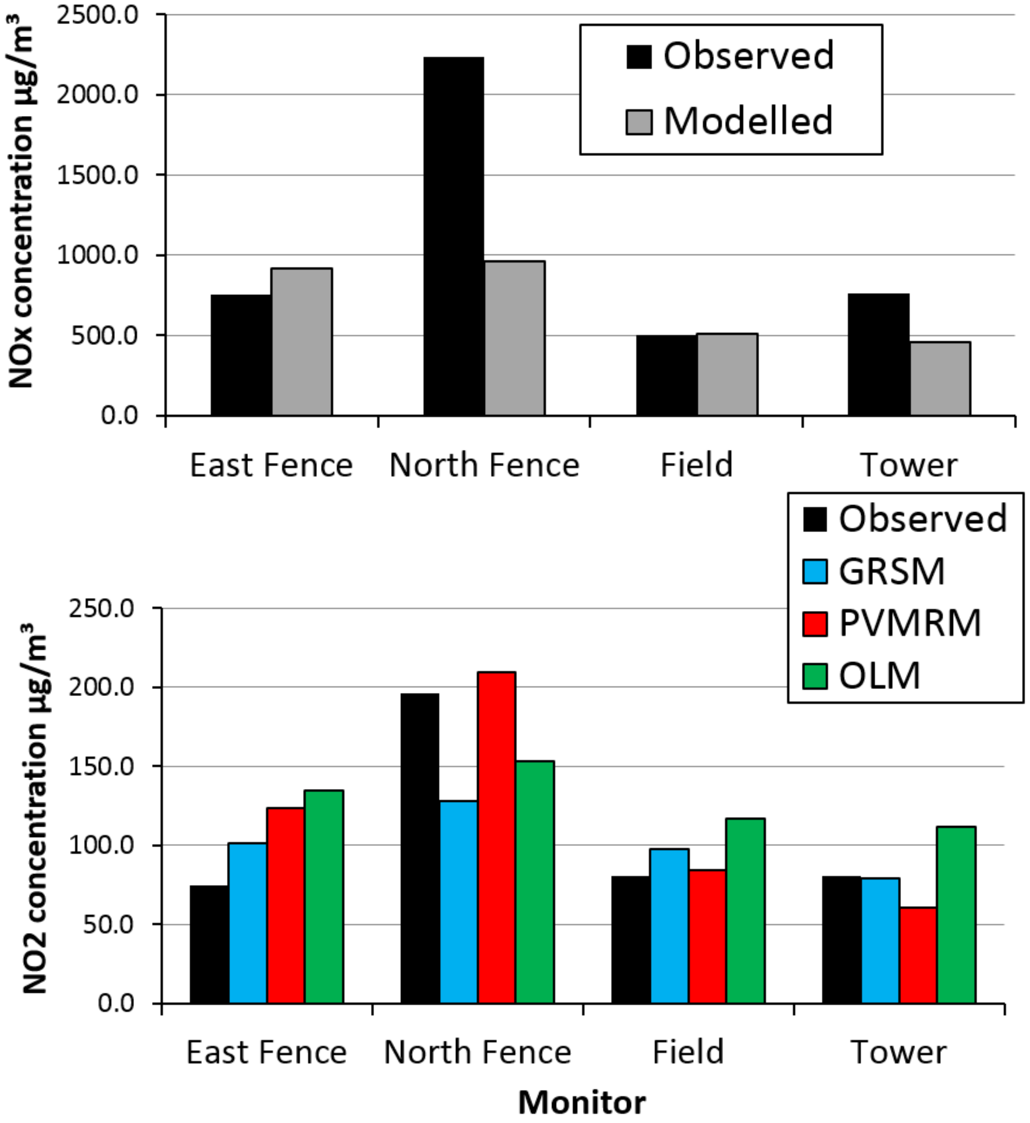
Clark TCV-12 compressor engine emissions dominate

PRCI NO_2 chemistry field campaign (2 of 3)

Period average: all monitors



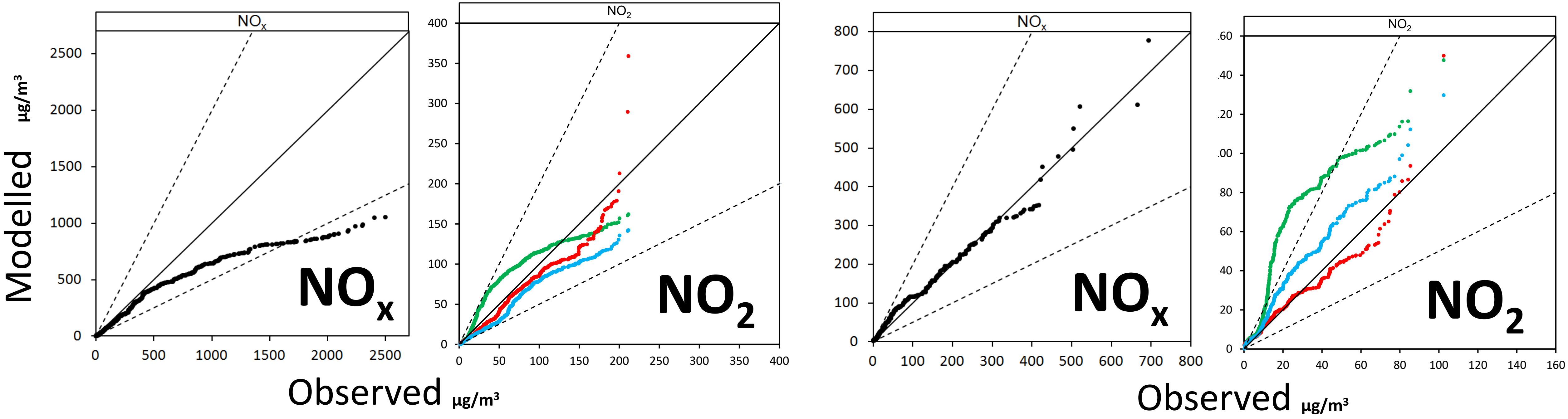
Highest 10 values: all monitors



PRCI NO_2 chemistry field campaign (3 of 3)

QQ plots:

North Fence (140 m) **Field (425 m)**



- For high concentrations, GRSM NO_2 slightly over-predicted relative to NO_x at 140 m & 425 m downwind - may be related to uncertainty in ISR
- GRSM demonstrates consistency between NO_x & NO_2 with downwind distance
- PVMRM NO_2 over-predicts at 140 m & slightly under-predicts at 425 m

- NOx
- NO2 (OLM)
- NO2 (PVMRM)
- NO2 (GRSM)

WRAP NO_2 chemistry field campaign (1 of 4)

2 sequential campaigns at adjacent Colorado drill rig sites ~ 5 weeks in total (October-November)

12 monitors (~ 100 m from main stacks) record NO_x and NO_2, 2 monitors also record O_3

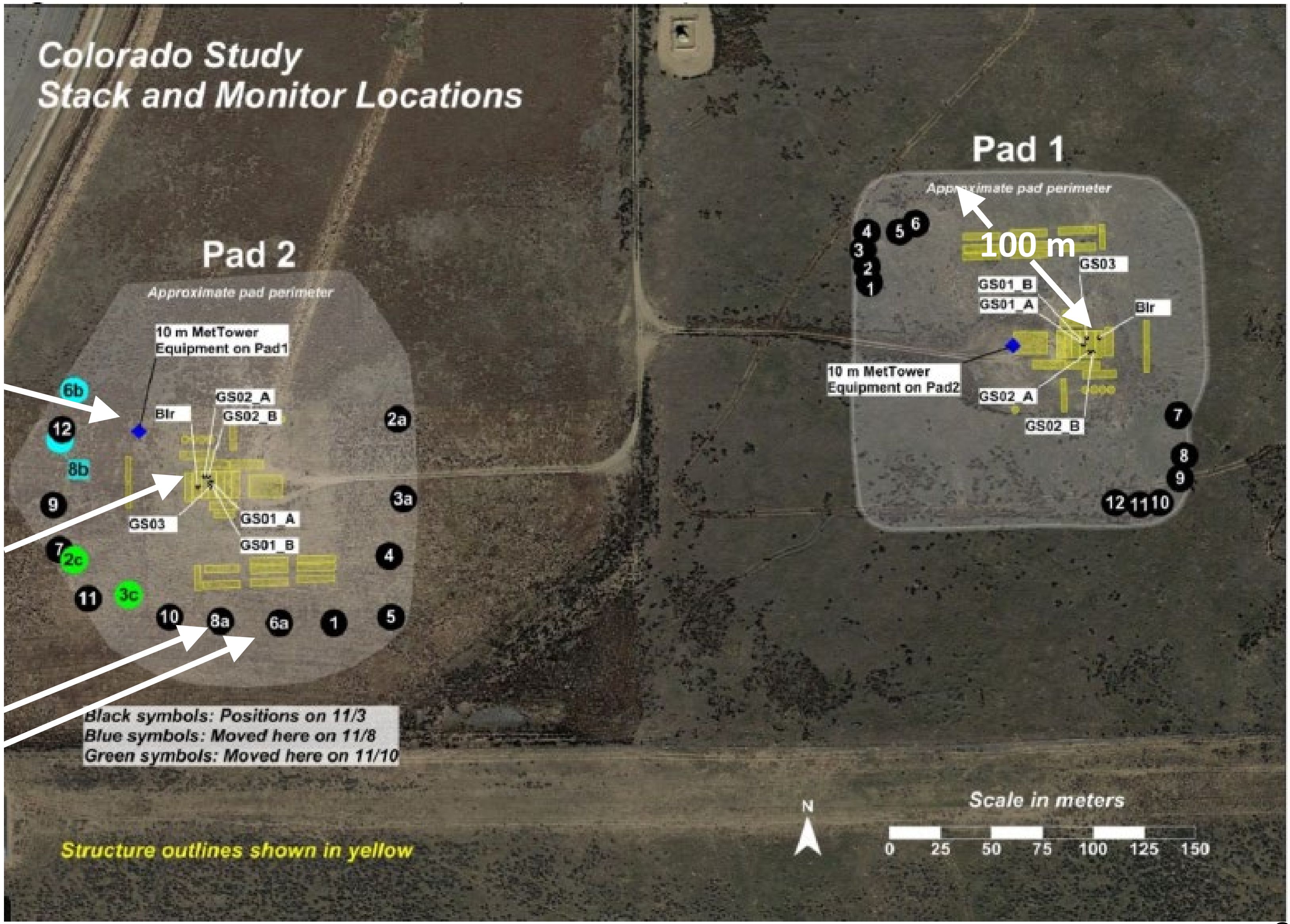
Meteorological instruments on 10 m onsite tower

Two diesel fired Caterpillar 3512B generators, one diesel fired Caterpillar C27 generator (all 5.5 m, EPA Tier 2 engines) + cold weather boiler

Sudden change in wind direction at Pad 2: some monitors moved

Flat terrain

'Downwind sector' datasets analysed



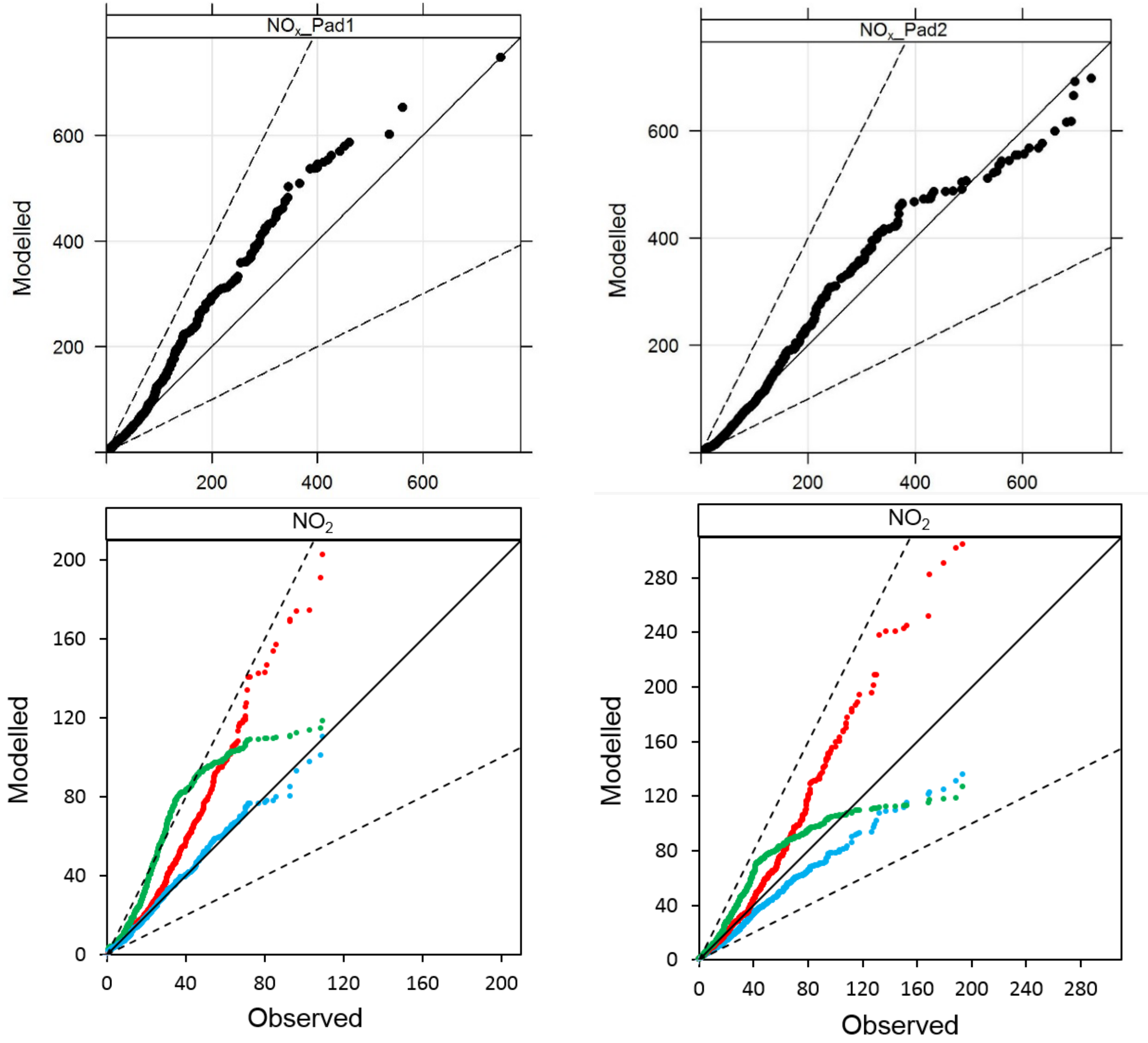
From: Colorado Field Study Workgroup Technical Support Document, 2020

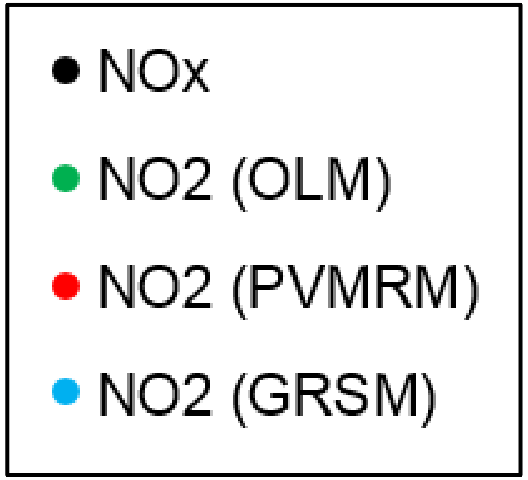
WRAP NO_2 chemistry field campaign (2 of 4)

QQ plots: **Pad 1** **Pad 2**

NO_x

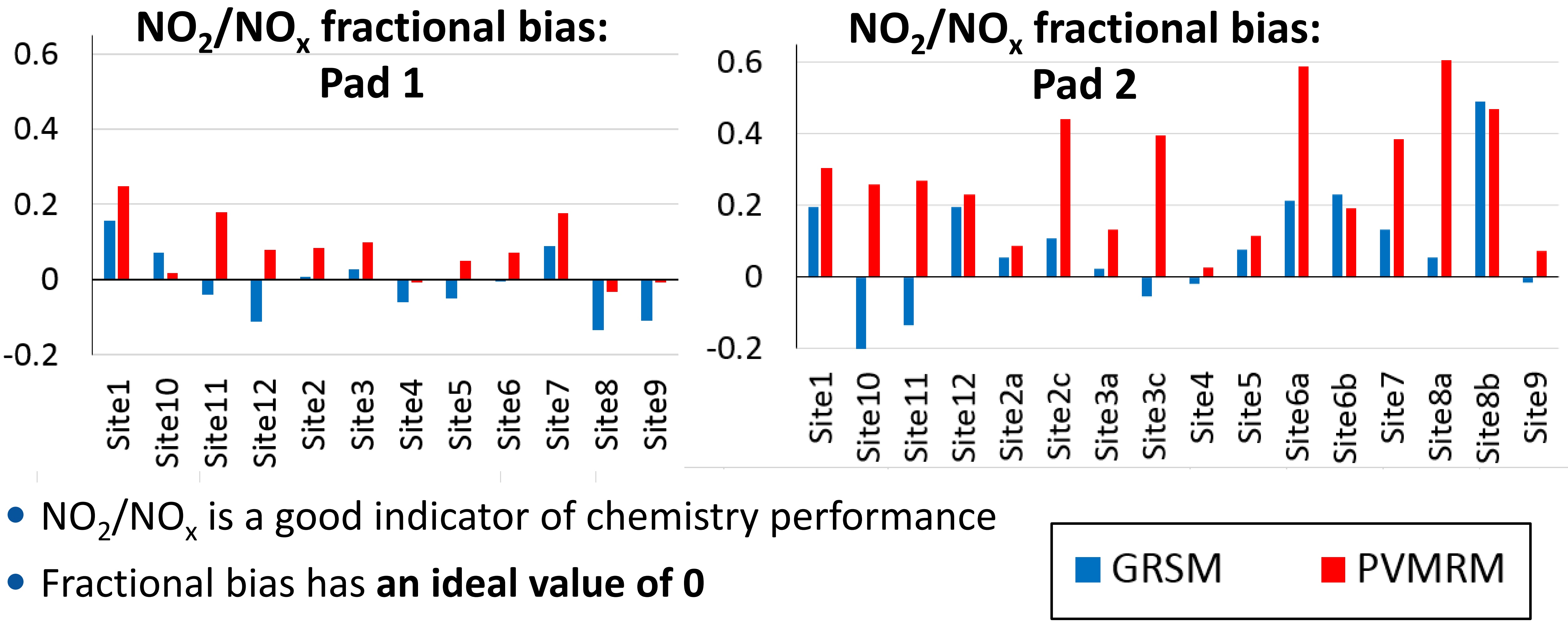
NO_2





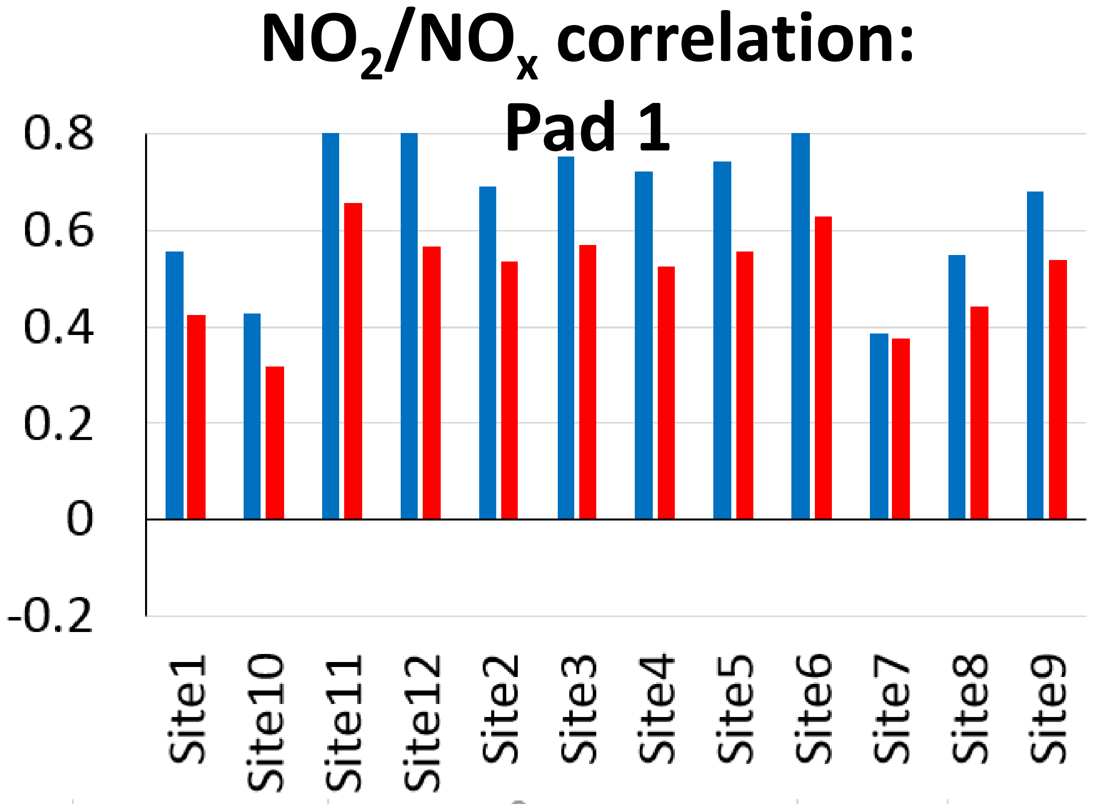
- For high concentrations, GRSM NO_2 slightly under-predicted relative to NO_x at Pads 1 & 2 - may be related to uncertainty in ISR
- All models demonstrate consistency between NO_x and NO_2 for the two Pads
- PVMRM over-predicts NO_2 at high concentrations

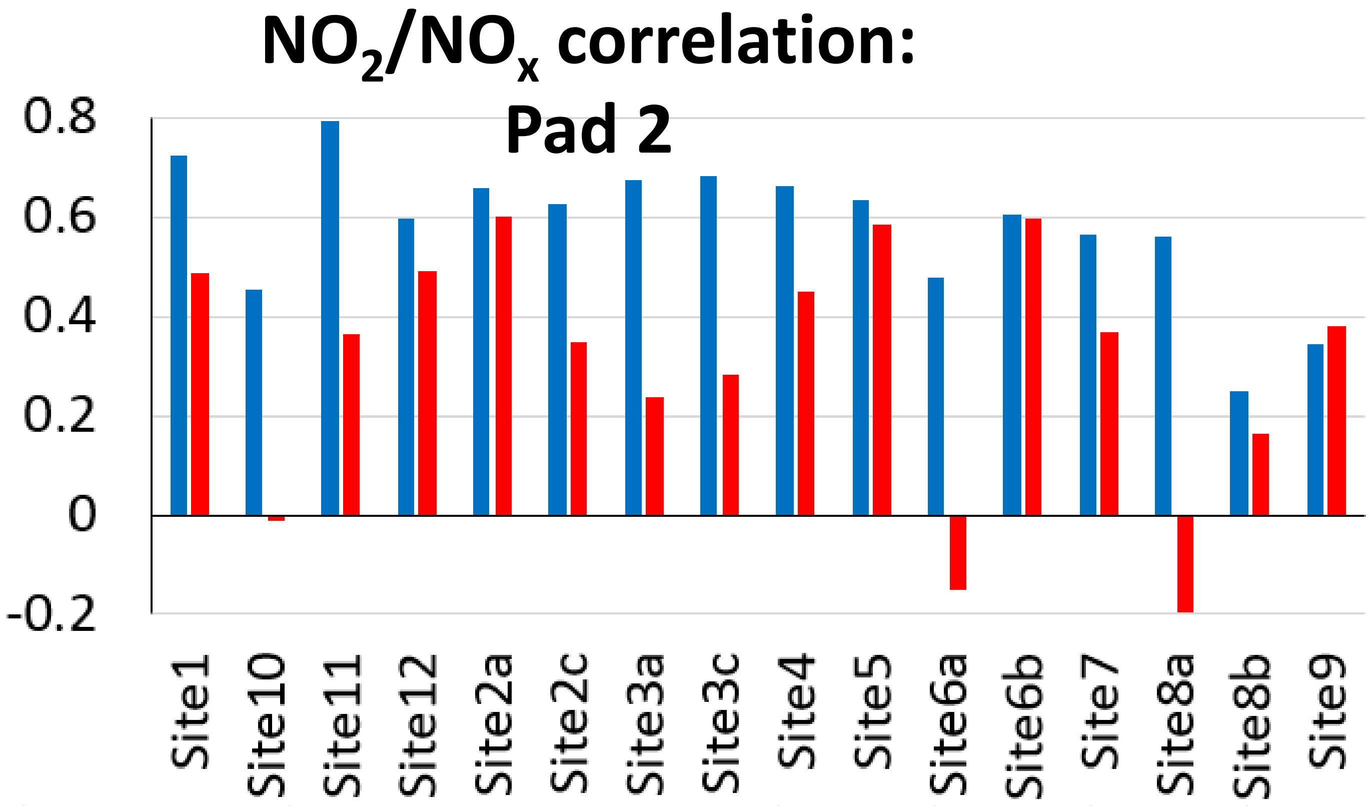
WRAP NO_2 chemistry field campaign (3 of 4)

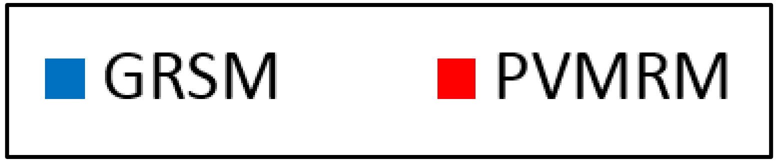


- NO_2/NO_x is a good indicator of chemistry performance
- Fractional bias has **an ideal value of 0**
- Looking in detail (monitor-by-monitor), for GRSM some sites over-predict and some under-predict (PVMRM almost always over-predicts NO_2 concentrations relative to NO_x concentrations)

WRAP NO_2 chemistry field campaign (4 of 4)







- NO_2/NO_x is a good indicator of chemistry performance
- Correlation has **an ideal value of 1**
- Looking in detail (monitor-by-monitor), for GRSM, correlations almost always higher (PVMRM has some negative correlations, likely related to few data points)

Generic Reaction Set Method (GRSM): Summary

- GRSM has been extensively evaluated using a range of datasets
- Model performance is generally good:
  - Consistency between modelled NO_x and NO_2 concentrations across both studies presented
  - Better NO_2 chemistry scheme performance than PVMRM
- The scheme developers are looking forward to feedback from the community regarding this AERMOD alpha option

References

Venkatram A., P. Karamchandani, P. Pai, and R. Goldstein.1994 The development and application of a simplified ozone modelling system (SOMS). Atmos. Environ. 28(22): 3365–78

Carruthers, D.J.; Stocker, J.R.; Ellis, A.; Seaton, M.D.; Smith, S.E., Evaluation of an explicit NOx chemistry method in AERMOD; Journal of the Air and Waste Management Association. 2017, 67:6, 702-712

Stocker J, Carruthers D, Kalisz C, Paine R, Seaton M, Smith S and Warren C, 2019: Evaluation of explicit NOx chemistry methods in AERMOD using a new compressor station dataset. Guideline on Air Quality Models: Planning Ahead, Durham, North Carolina, USA, March 2019

Innovative Environmental Solutions, 2017. Balko OK Compressor Station 102: Data Summary and Initial AERMOD Performance Assessment, Report no. PR-312-15201-R01

Colorado Field Study Workgroup, 2020: 2014 Colorado Oil and Gas Drill Rig Field Study Model Evaluation Database - Technical Support Document

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ERM
Mark Garrison

Questions?

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Travel Time Reaction Method (TTRM) Procedure and Evaluation for AERMOD NO_2 Modeling

Presentation at EPA's 2021 Modeling Workshop June 21, 2021

AECOM

Overview of Travel Time Reaction Method

- High level review Travel Time Reaction Method formulation
- Initial implementation
- Evaluation with Colorado drill rig and Balko, OK studies
- Conclusions
- Appendix with details of the Balko evaluation

- Acknowledgements: funding for the documentation, coding, and evaluation of TTRM was provided in large part by the American Petroleum Institute. Coding and evaluation of the TTRM option were conducted by Carlos Szembek and Chris Warren.

AECOM

TTRM Formulation

- A refined approach to supplement the Tier 2 (ARM2) and Tier 3 (OLM and PVMRM) methods for converting NO to NO_2 is available for very short travel times in the near-field (e.g., fence line impacts)
- The full reaction of ozone with NO can be represented as such:
  - $NO + O_3 \rightarrow NO_2 + O_2$
- Simplified to the forward reaction yields a scaling factor for NO:
  - $NO_{2\text{-}frac} = 1 - e^{\{-k[O3]\ t\}}$

  where *t* is the *travel time* to a receptor from the source and *k* is the *reaction rate* represented as (from Hanrahan, 1999):
  - $k = (15.33/T_a)\ e^{(-1450/Ta)}$ in $ppb^{-1}\ sec^{-1}$ where T_a is the *hourly ambient temperature*
- The conversion factor is capped at 0.9 and would scale any available NO remaining that is released from the stack
- This fractional NO_2 would then be added to the in-stack converted NO_2 to calculate the final NO_2 concentration.

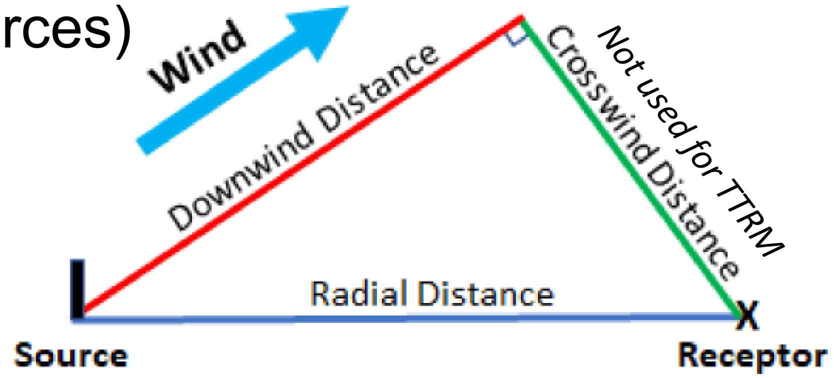
TTRM Example Spreadsheet Calculation Table

Conversion Fraction of NO to NO_2 as a function of Ozone Concentration and Transport Time (at Standard Temperature)

Travel time (sec)	Ozone = 35 ppb	Ozone = 55 ppb	Ozone = 75 ppb
10	0.130	0.196	0.257
20	0.242	0.353	0.448
30	0.340	0.480	0.590
40	0.426	0.582	0.696
50	0.500	0.664	0.774
60	0.565	0.730	0.832

Travel Time Reaction Rate (TTRM) Procedure: Step 1

- TTRM is designed to supplement the results of an existing NO_2 modeling option
- **Step 1a**: Run AERMOD using a Tier 2 or Tier 3 option
- **Step 1b**: Also run AERMOD using the TTRM option for the same sources/receptors
- TTRM calculates travel time by selecting the "type" of distance and effective wind speed based on the dominant plume type.
- Distances vary between coherent or random plumes
  - Downwind (coherent plume for point and volume)
  - Radial (random plume for point/volume and all area sources)
- Effective wind speed (based on plume treatment):
  - Ueff: stable hours and indirect plumes
  - Ueffd: direct plumes
  - Ueff3: penetrated plumes



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Travel Time Reaction Method (TTRM) Procedure: Step 2

- **Optional Step 2**: Import both sets of modeling results (TTRM and a Tier 2 or 3 method) into a spreadsheet for each hour and receptor (or use your own post-processing software)
- In the very near-field, TTRM results are likely to be lower
- After the "crossover" where travel time is larger, the TTRM NO_2/NOx ratio approaches 0.9, and the Tier 2 or 3 approaches are then applicable
- Recommendation: take the lower of the two results for each hour and receptor as the appropriate concentration
- At some point in the future, Steps 1 and 2 could be done within one AERMOD run, but for this implementation, two model runs must be done and post-processed manually (or by using post-processing software)

Model Evaluations of TTRM

- –Denver-Julesburg, CO
- –Balko, OK

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Evaluation Using 2014 Colorado Drill Rig Study Plume Capture Hours

- Located north-northeast of Denver, CO.
- October 10 – November 16, 2014
- Adjacent well pads
  - (Pad 1, Pad 2)
- 12 ambient AQ monitors generally within 100 m.
- CEMS were used to measure exhaust level at six stack sources (5 generators, 1 boiler) on the drill rig.
- ISR values ranged from 0.04 to 0.09 for most sources.

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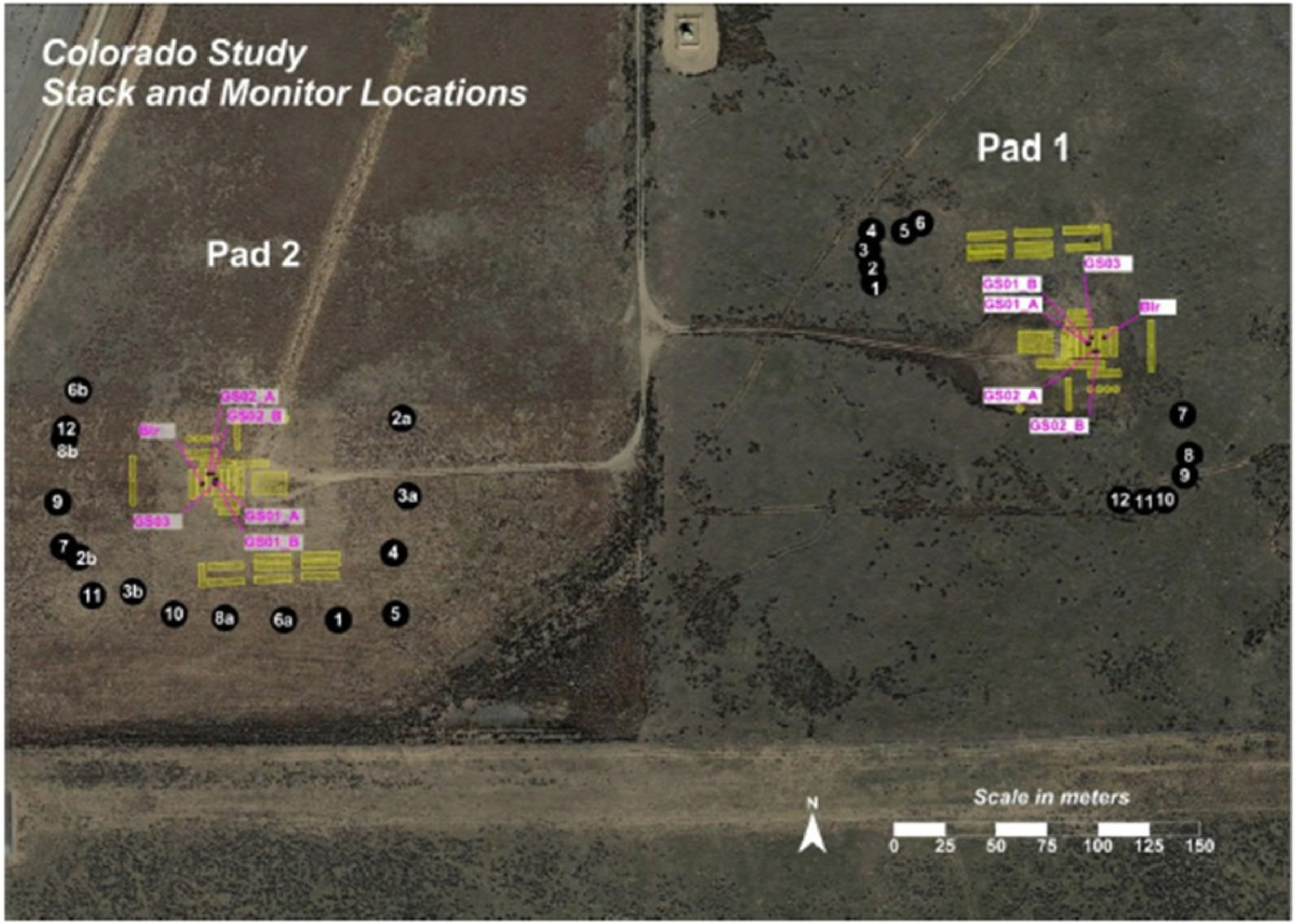
Colorado Drill Rig Study – Pad Layouts at Two Locations



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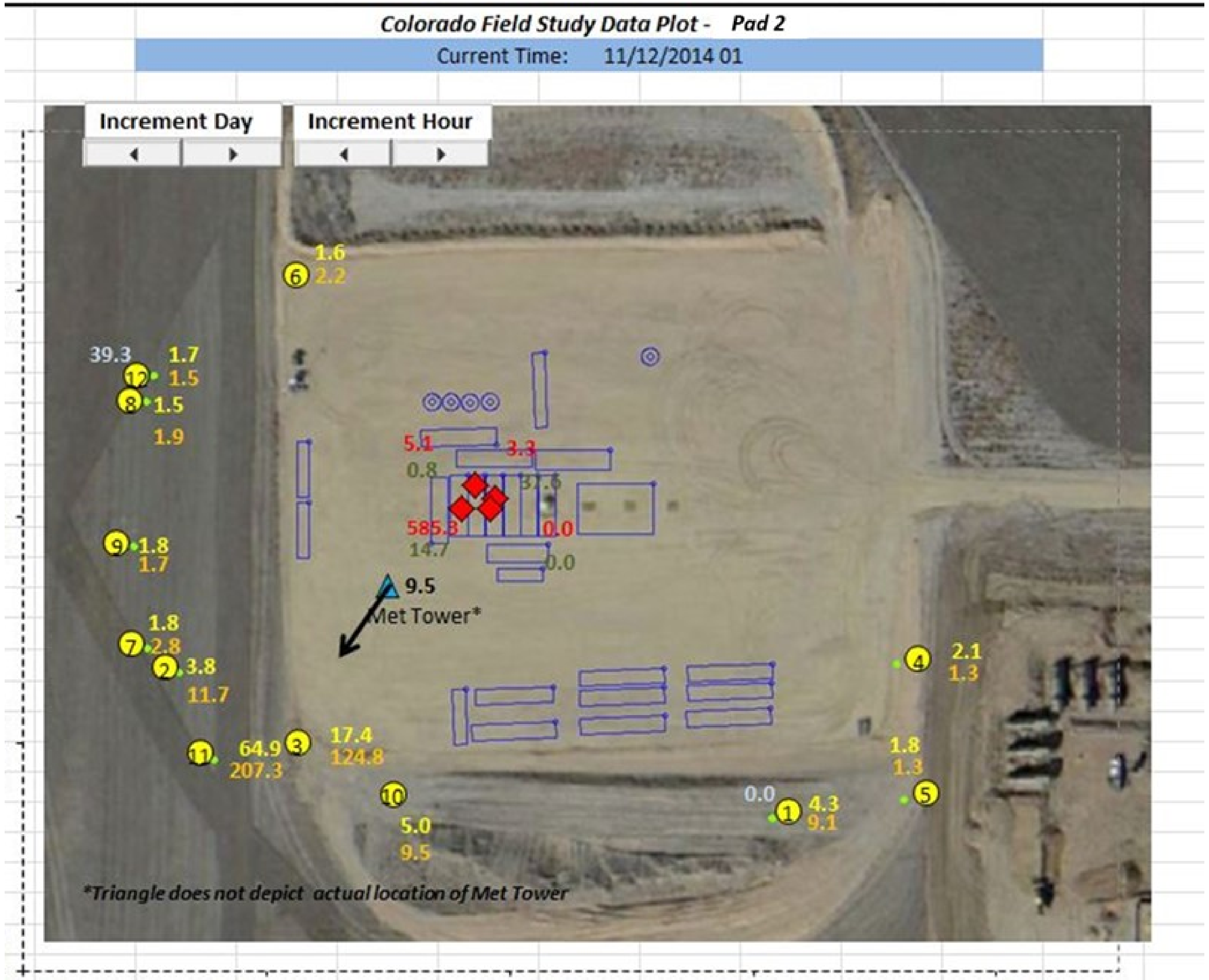
Colorado Drill Rig Study – Sample Ambient Monitor Plot



“Plume Capture” Modeling Hours:

These 160 hours feature a monitor with a peak concentration with lower monitored values available on either side of the peak measurement.

Pad Layout	Plume Capture Hours
Pad 1	48
Pad 2-A	29
Pad 2-B*	83

* monitors relocated to provide more plume capture hours.

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Model Evaluation Analysis

- Use one observation and prediction for each plume capture hour (paired for the peak plume capture monitor location)
- Model with the following AERMOD options:
  - NOx (Tier 1 approach; tests AERMOD without NO_2 chemistry)
  - ARM2 (Tier 2)
  - OLM (Tier 3), using OLMGROUP ALL
  - PVMRM (Tier 3)
  - TTRM, then post-processed with ARM2, OLM, and PVMRM
- After TTRM is run, the hourly concentrations at each receptor were compared to those from another option, and the lower of the two values was used
- TTRM results are only applicable for near-field locations, where the fraction of NO_2/NOx is low due to incomplete ozone reaction

Focus is on NO_2/NOx Ratio for Evaluation

- Key difference for these modeling approaches is the conversion of NO to NO_2
- That fraction (NO_2/NOx) should be the focus of the evaluation, not simply the magnitude of the NO_2 concentrations, because…
- If NOx is underpredicted, then NO_2 will be underpredicted by an unbiased chemistry model
- Evaluation results are given for each pad separately due to different model performances for NOx predictions
- Each modeled hour produced just a single observation – prediction pair
- For quantile-quantile plots, the hourly values were ascribed to a single “downwind” receptor (peak impact site)
- Meteorological / model option: cloud cover, no turbulence, ADJ_U*, actual wind directions

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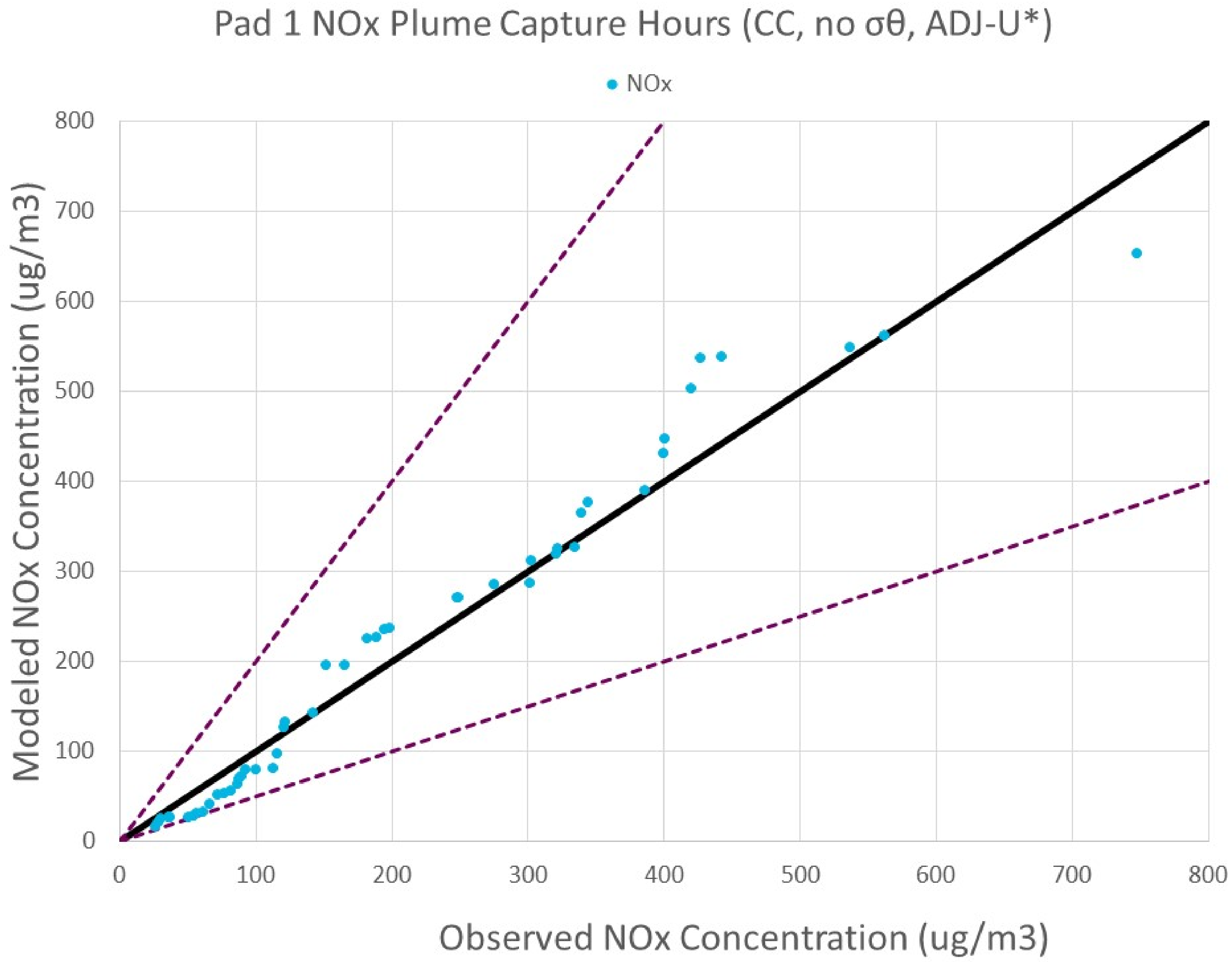
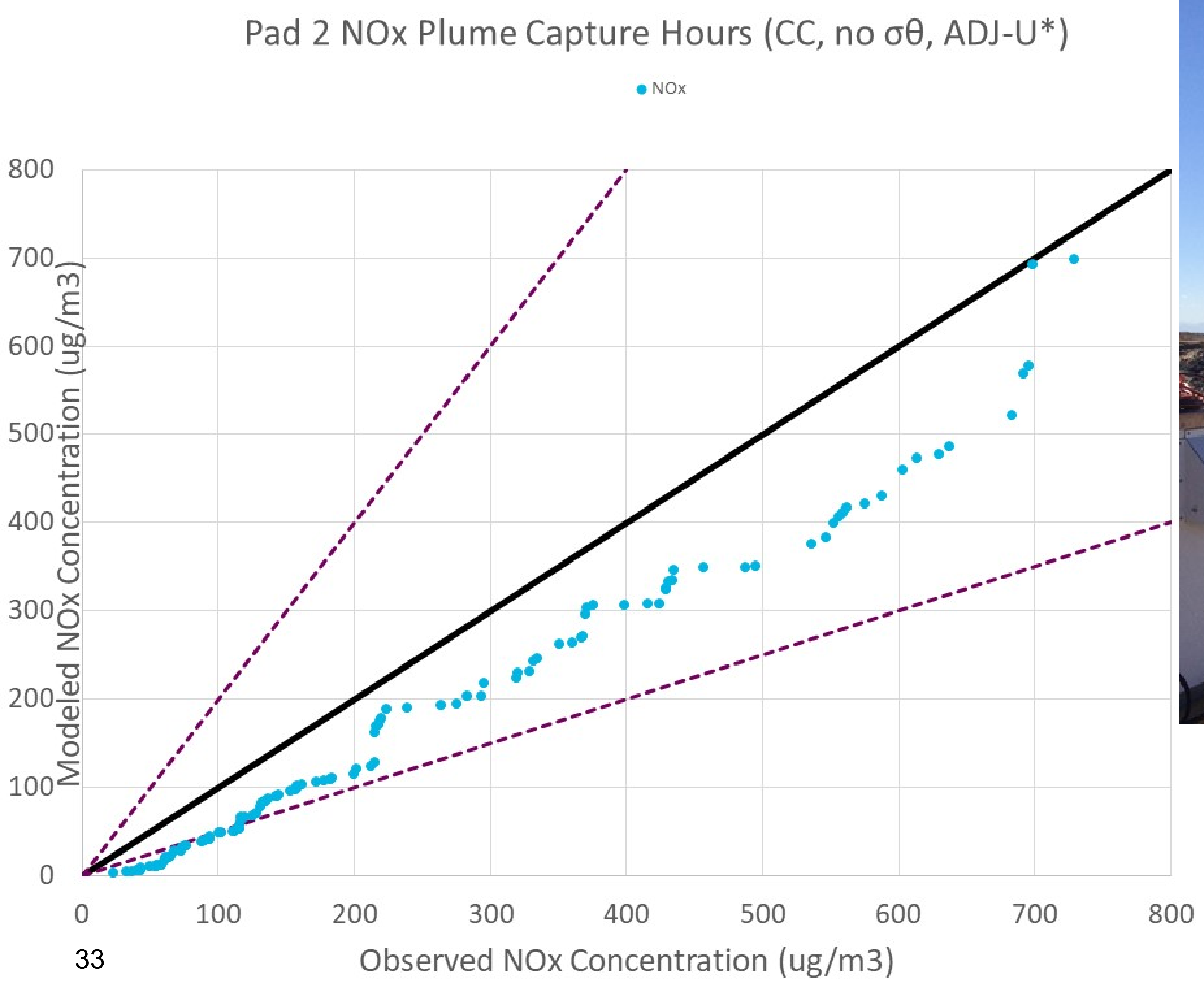
NOx Q-Q Plot for Pad 1 – Nearly Unbiased



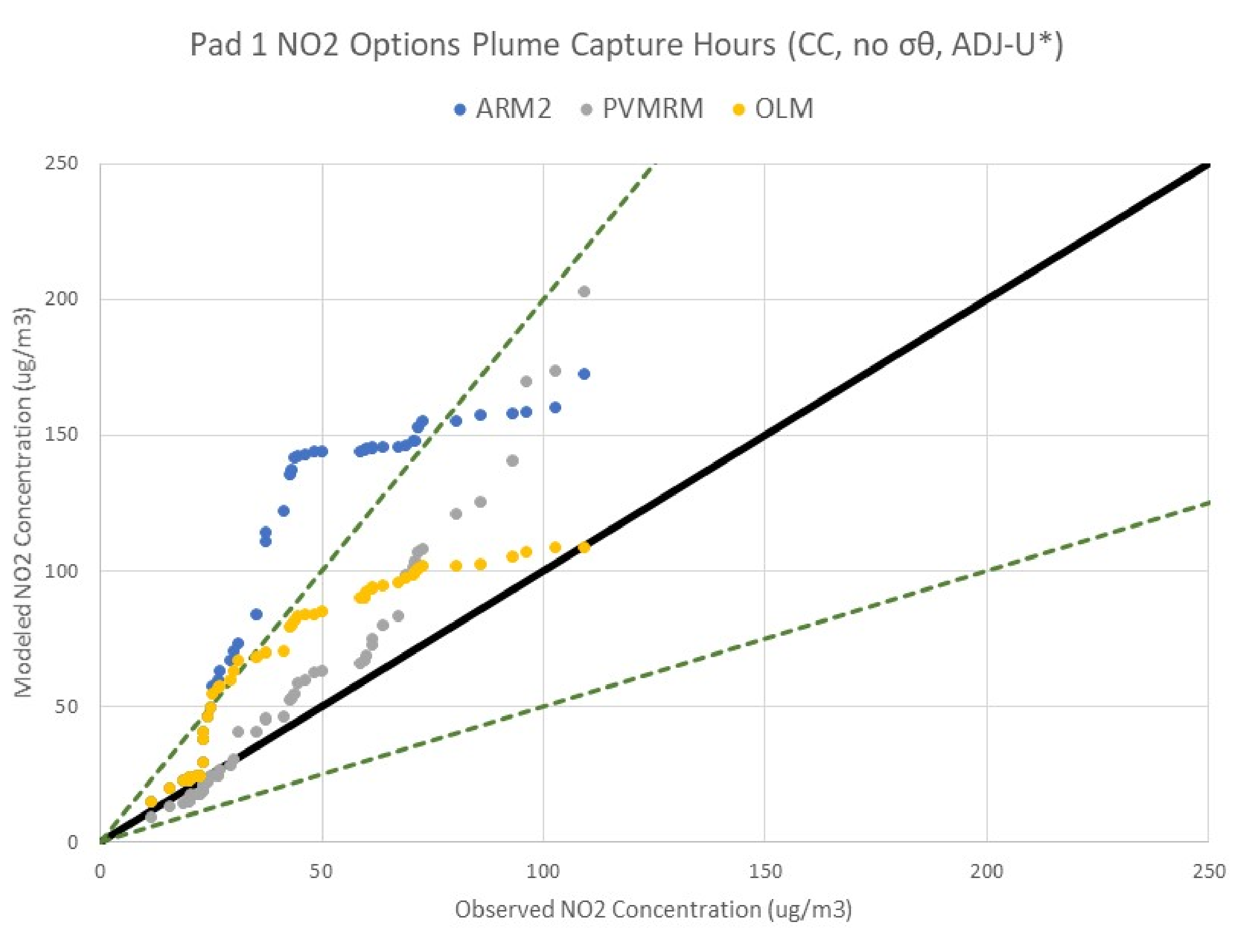
NOx Q-Q Plot for Pad 2 – Underprediction – perhaps due to receptor elevation heights being misrepresented



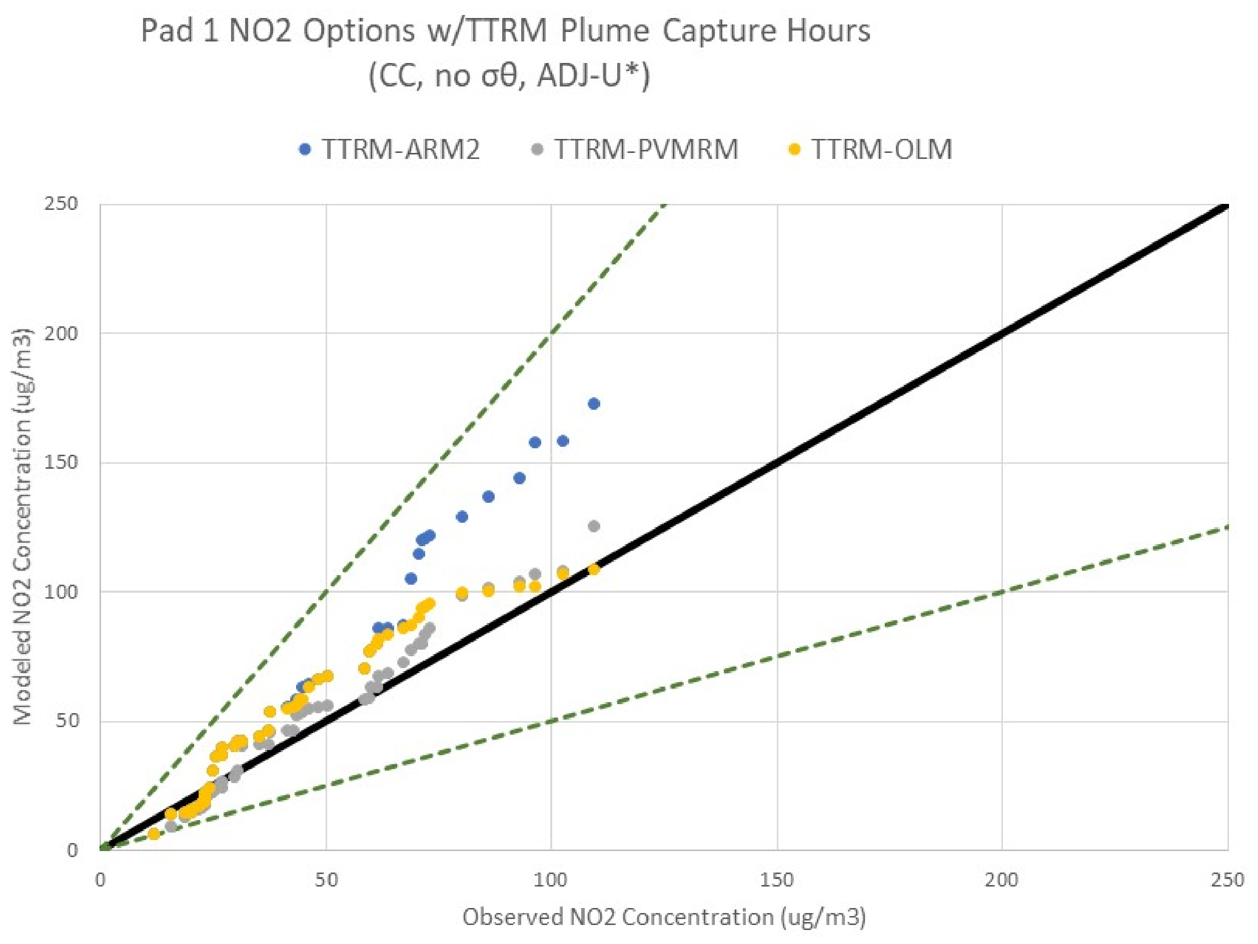
Monitors on southern berm should be modeled with increased elevation; this might mitigate the underprediction.

Q-Q Plot for Pad 1: NO_2 with TTRM Added on the Right

Without TTRM



Includes TTRM Enhancement



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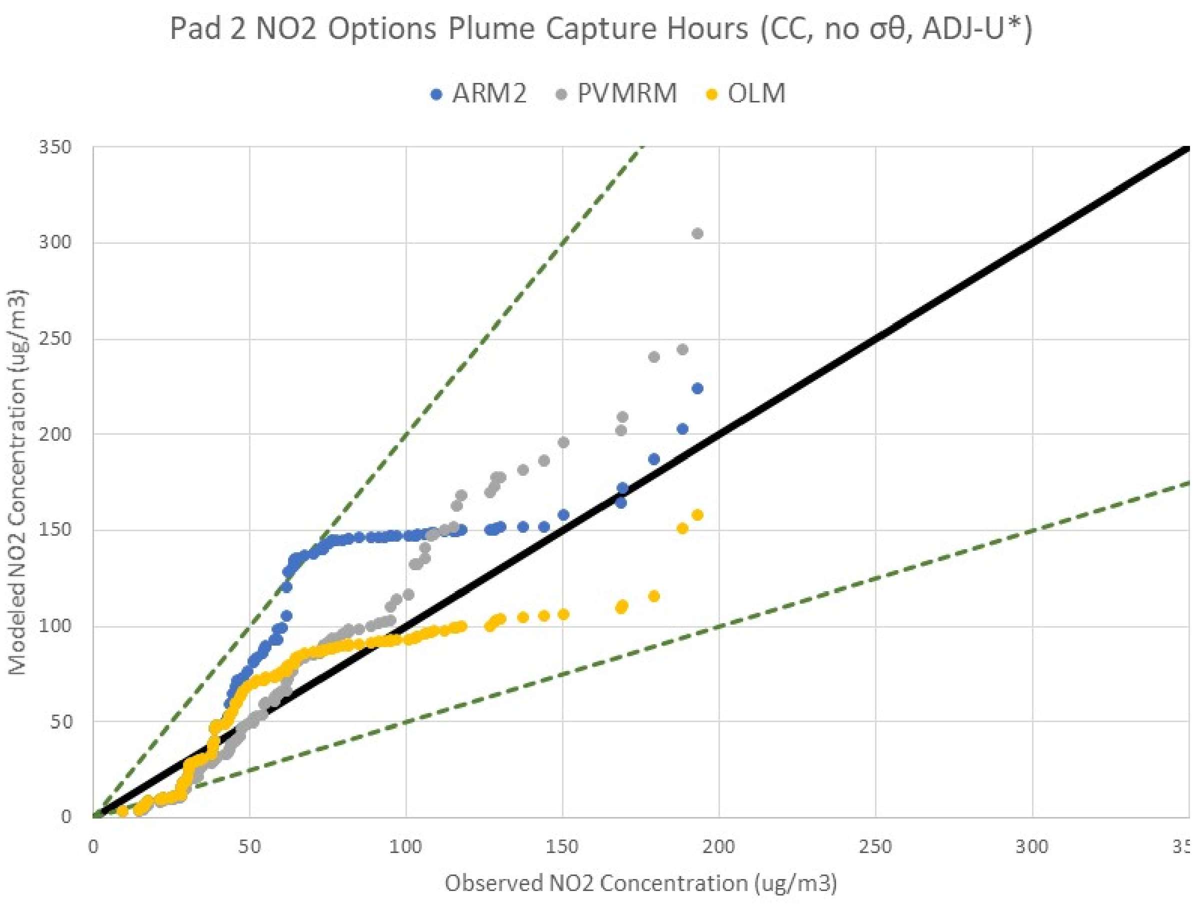
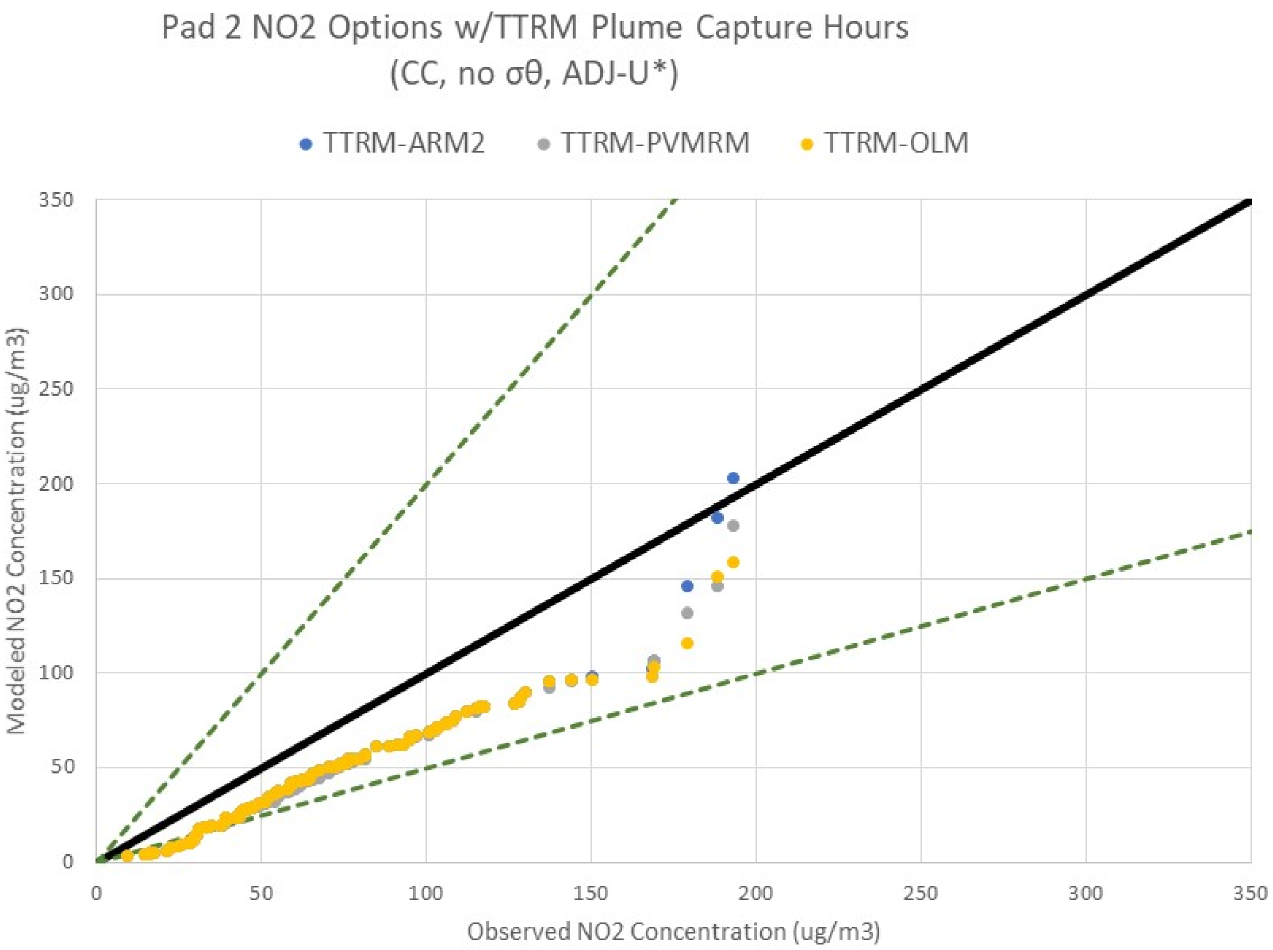
Q-Q Plot for Pad 2: NO_2 with TTRM Added on the Right

Without TTRM



Includes TTRM Enhancement



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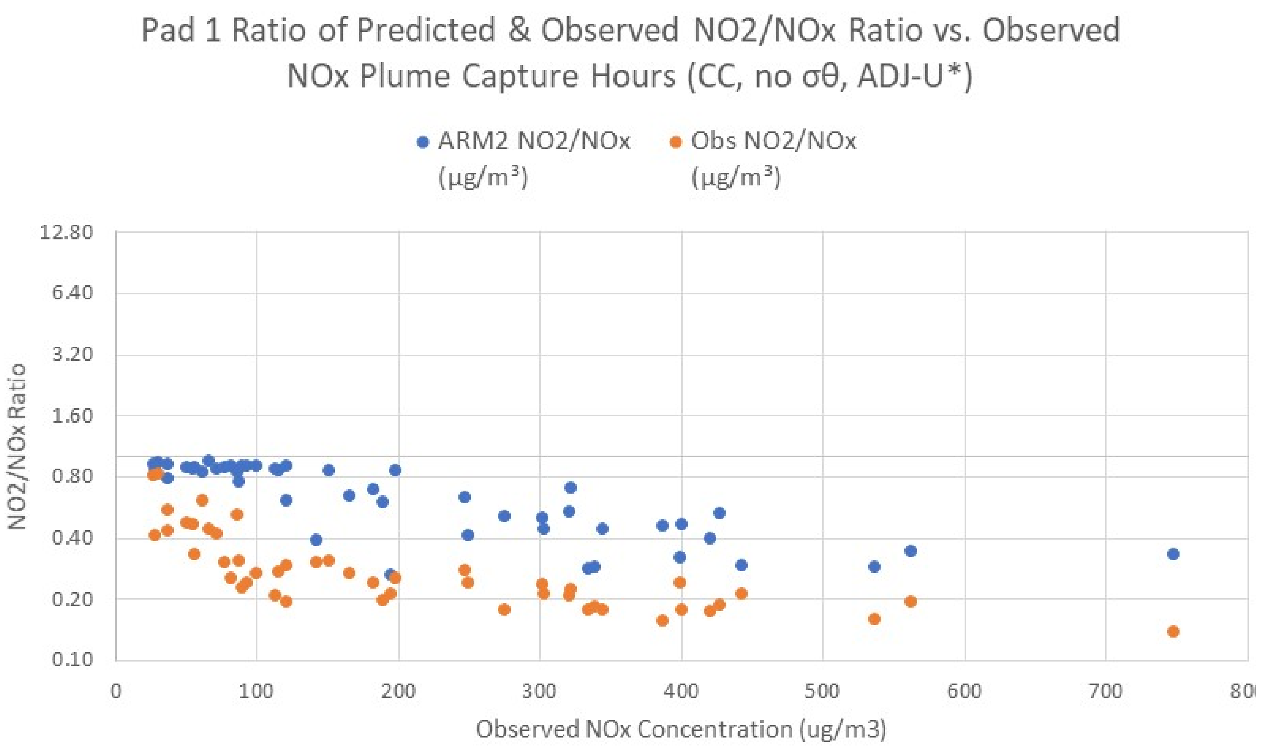
Further Analysis to Remove Effect of NOx Bias

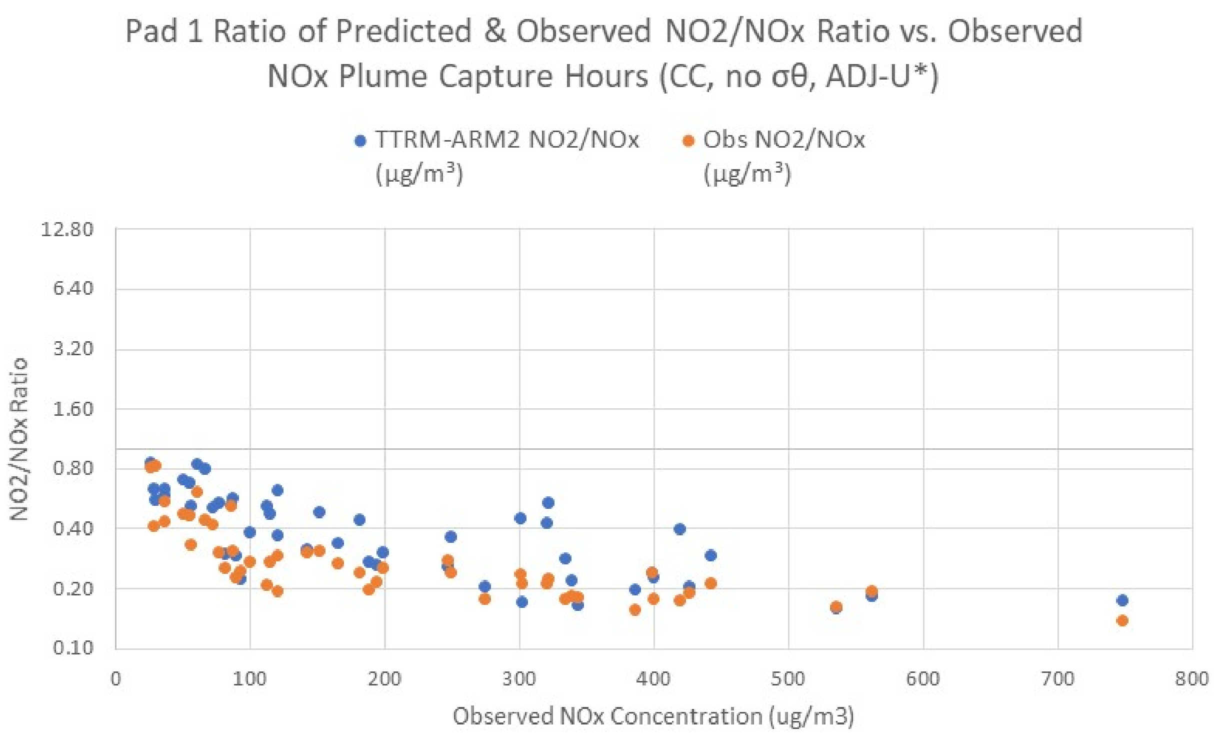
- The real model performance issue is the ratio of NO_2/NOx
- We next show plots of observed as well as predicted NO_2/NOx ratio for each model
- The NO_2/NOx ratio is expected to decrease as observed NOx increases
- The plots show the NO_2/NOx ratio on the y axis and observed NOx on the x axis

Pad 1: NO_2/NOx Ratio vs. NOx for ARM2 and ARM2 + TTRM

ARM2

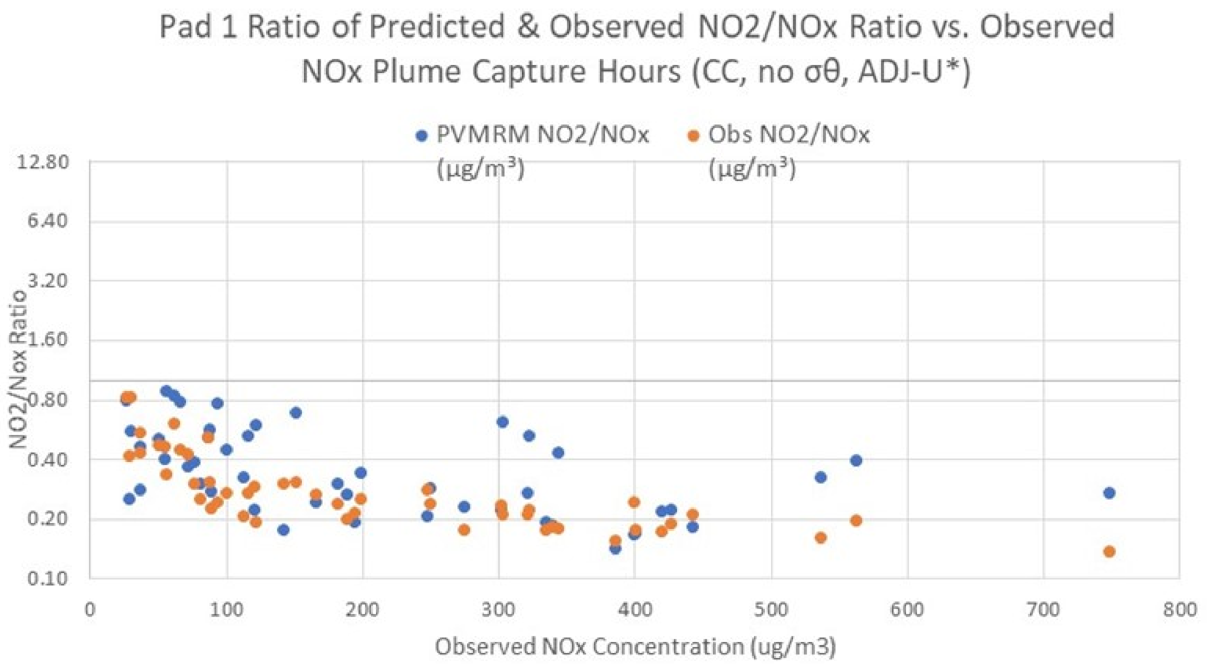


ARM2 + TTRM

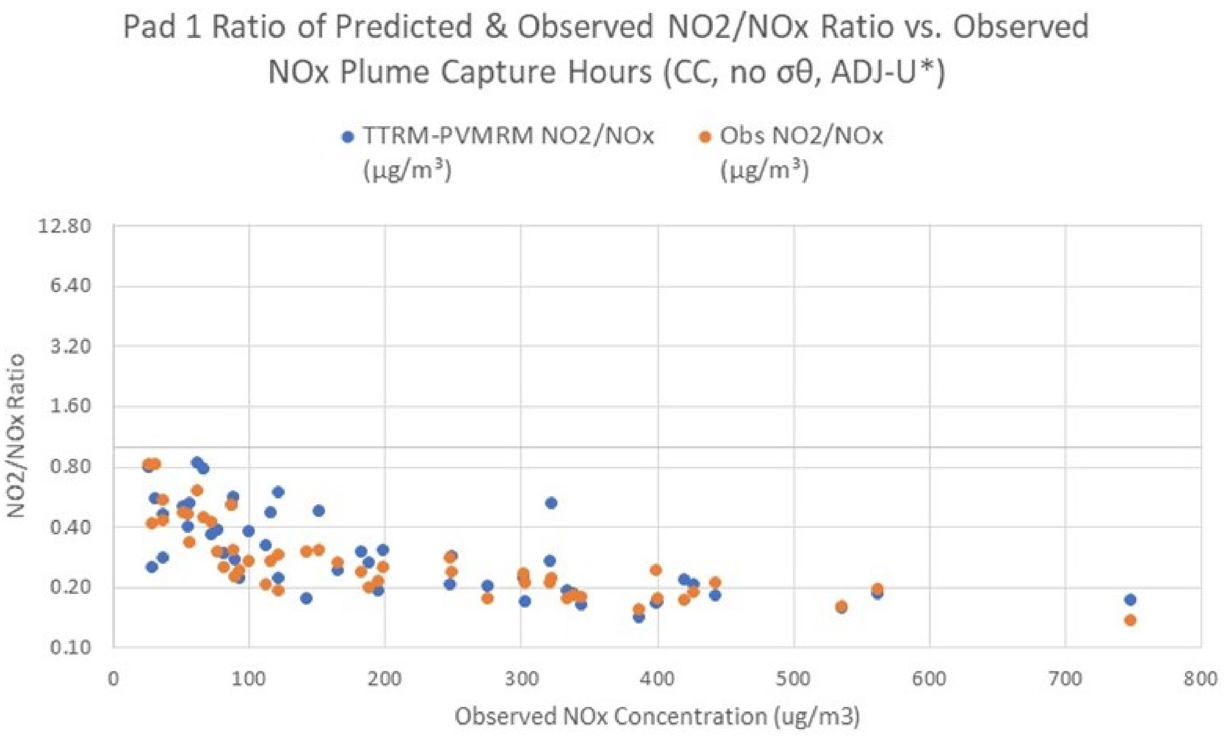


Pad 1: NO_2/NOx Ratio vs. NOx for PVMRM and PVMRM + TTRM

PVMRM



PVMRM + TTRM



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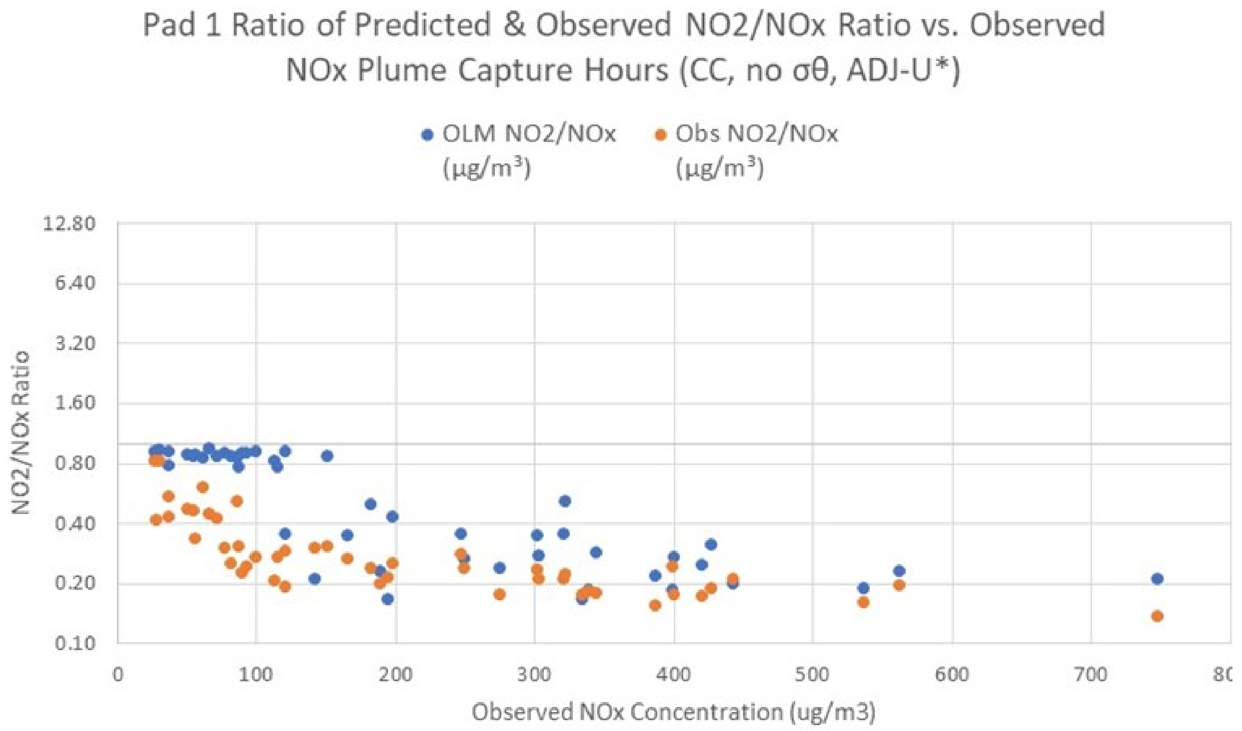
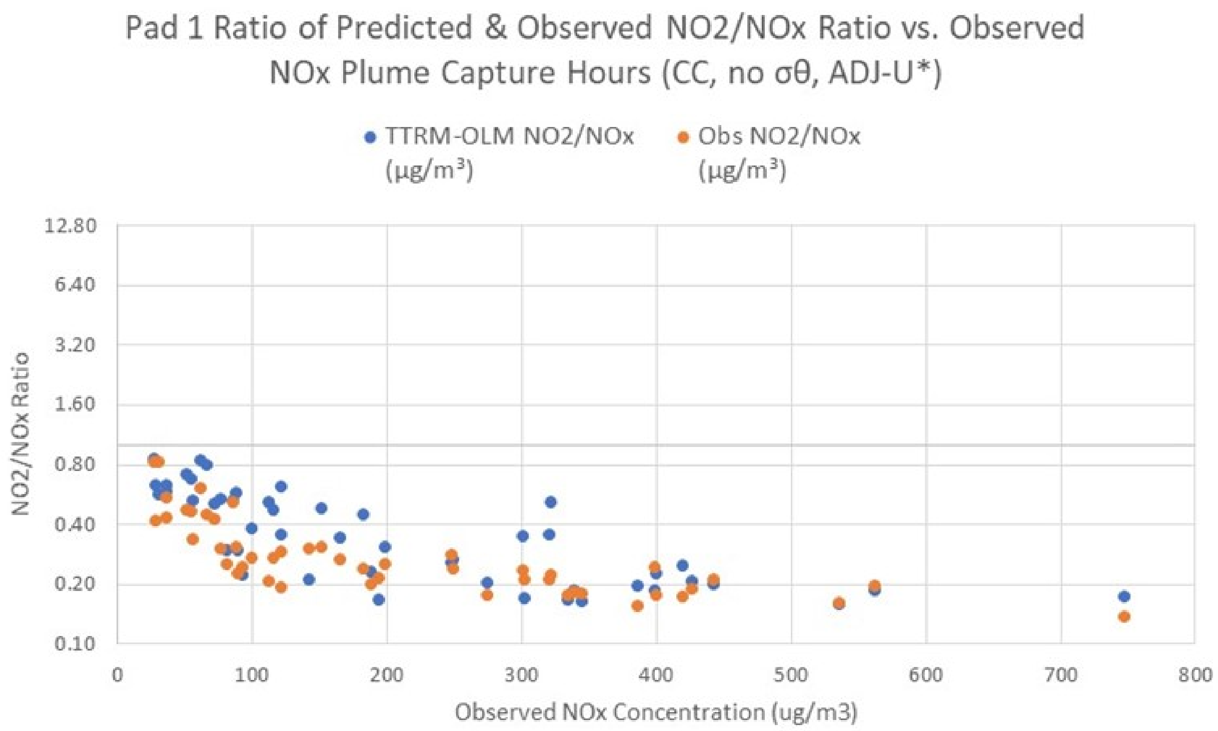
Pad 1: NO_2/NOx Ratio vs. NOx for OLM and OLM + TTRM

OLM



OLM + TTRM



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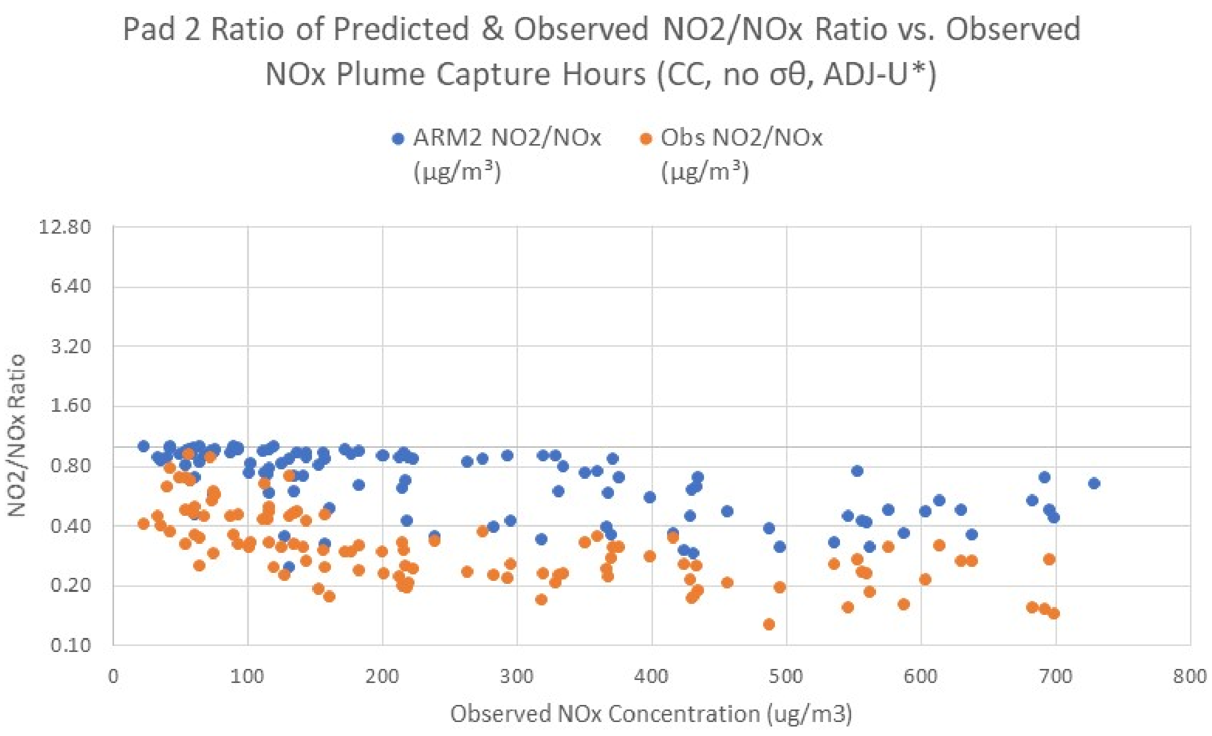
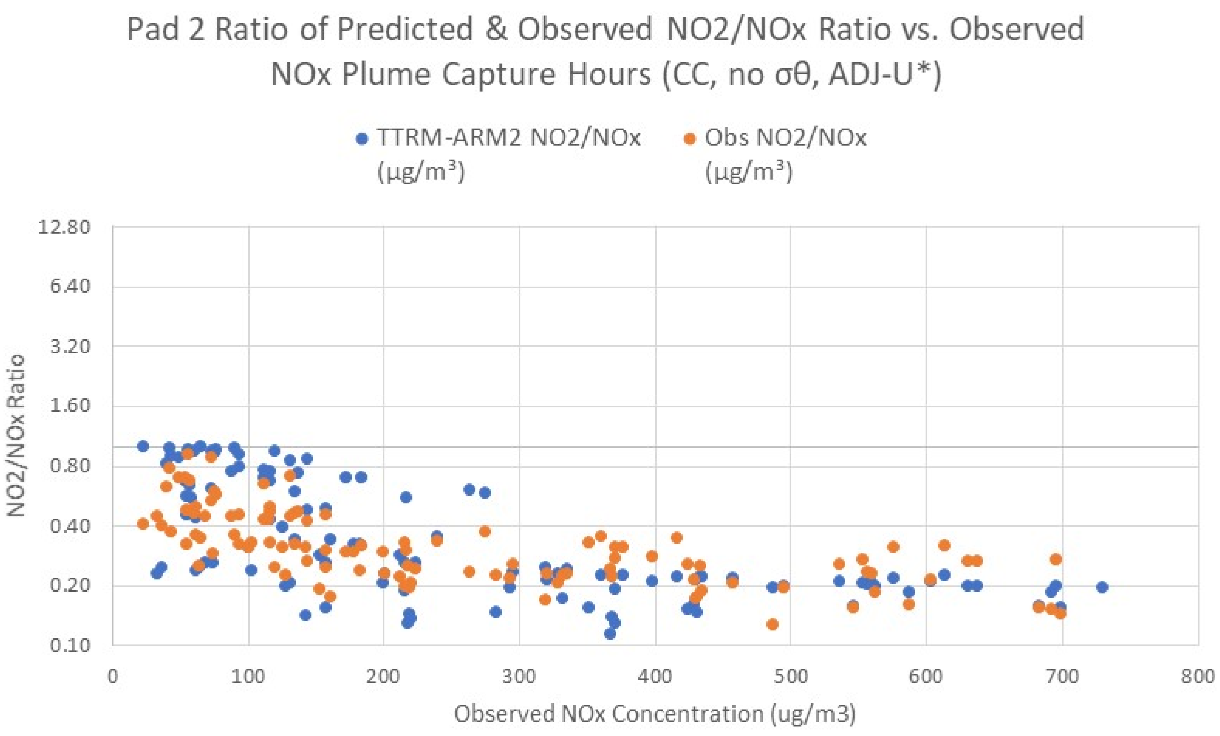
Pad 2: NO_2/NOx Ratio vs. NOx for ARM2 and ARM2 + TTRM

ARM2

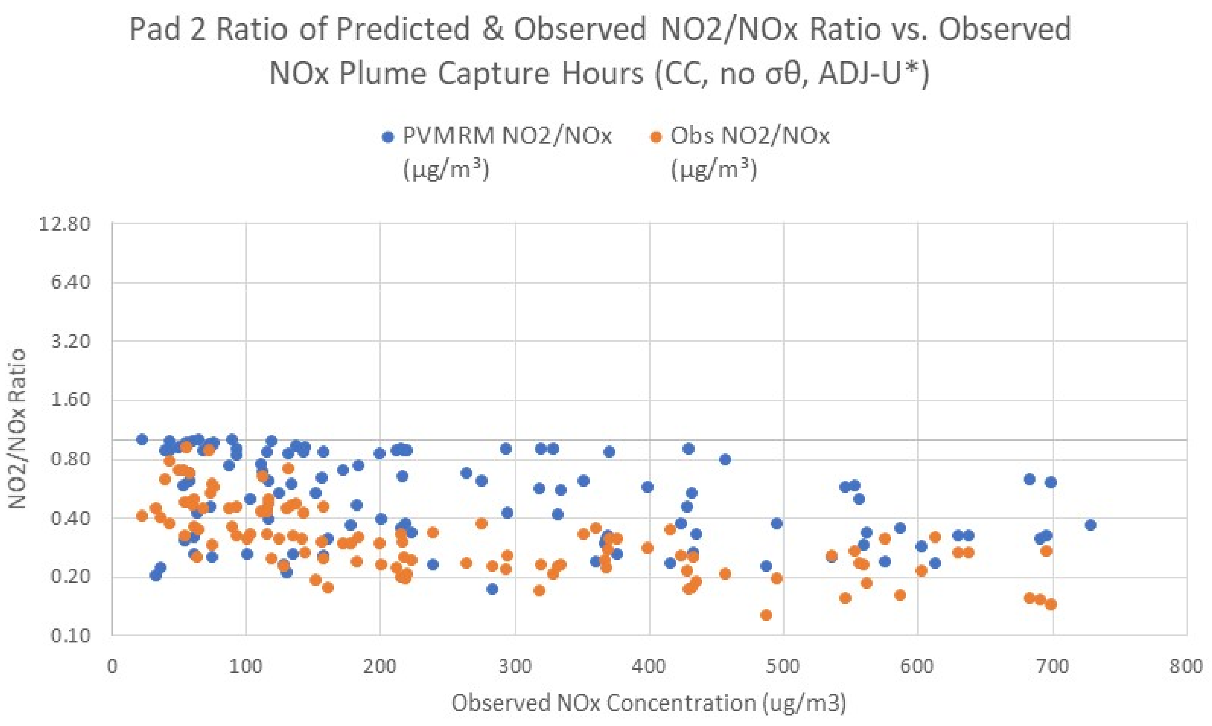


ARM2 + TTRM

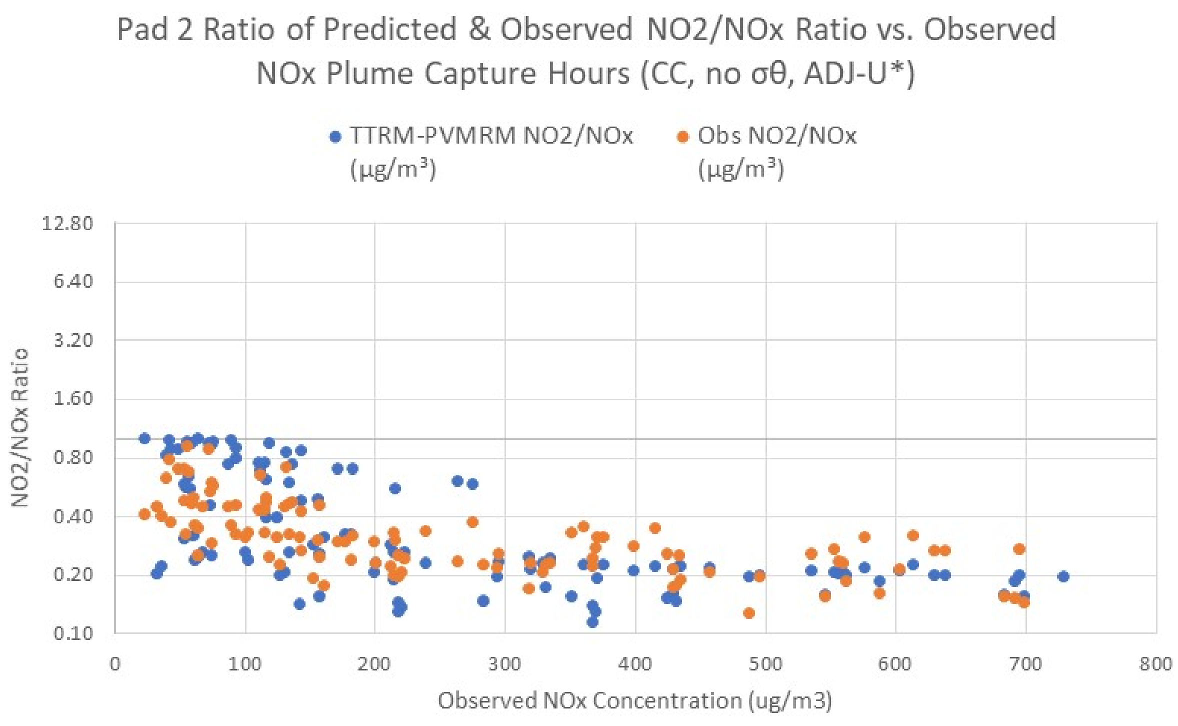


Pad 2: NO_2/NOx Ratio vs. NOx for PVMRM and PVMRM + TTRM

PVMRM



PVMRM + TTRM



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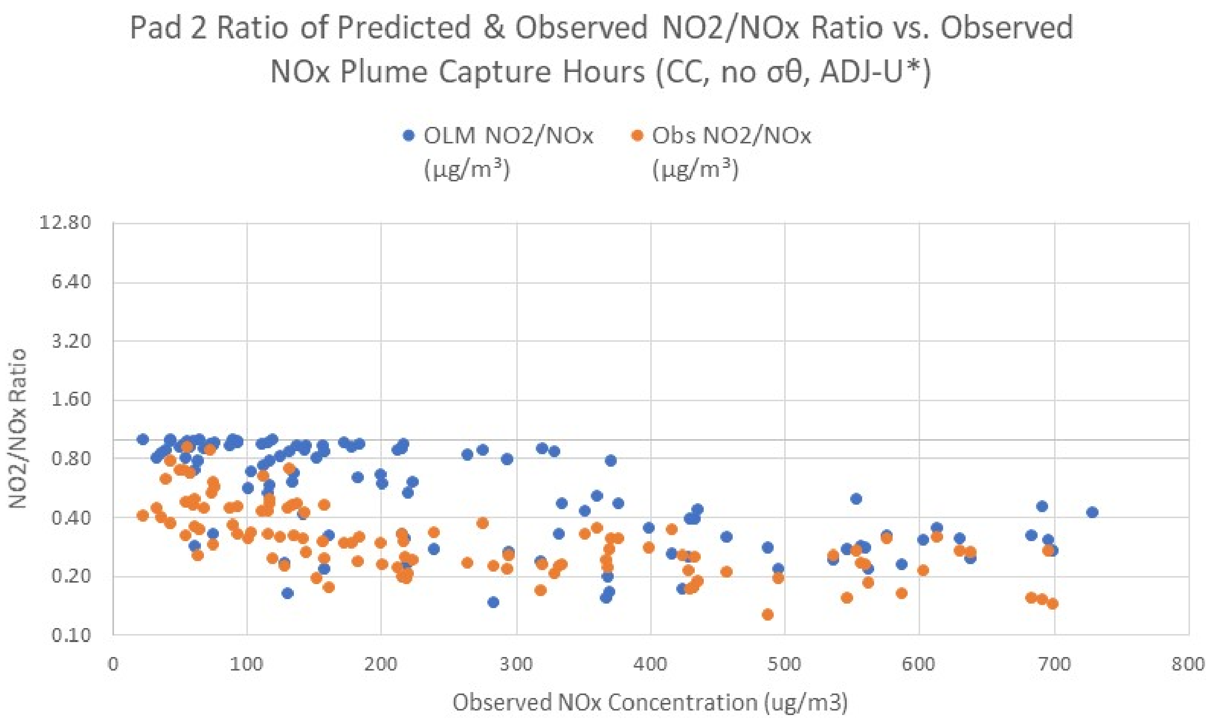
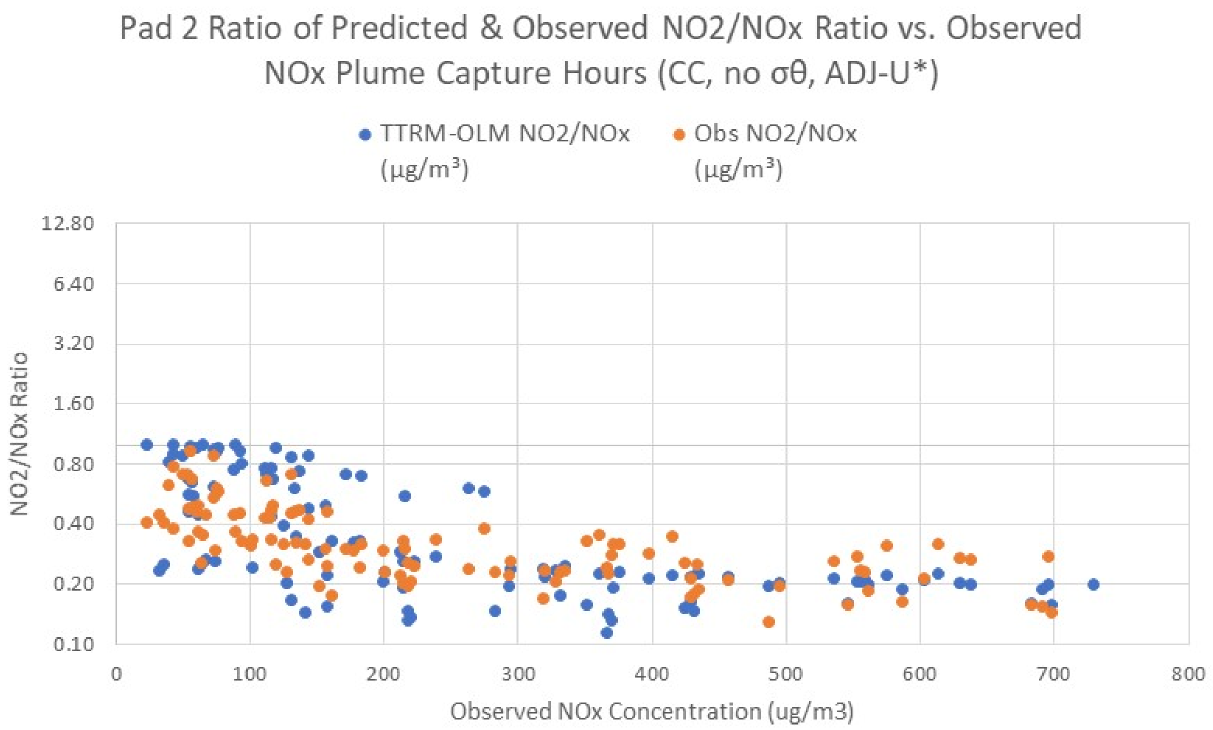
Pad 2: NO_2/NOx Ratio vs. NOx for OLM and OLM + TTRM

OLM



OLM + TTRM



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Summary of Colorado Evaluation with TTRM

- AERMOD NOx predictions are relatively unbiased for Pad 1, underpredicting for Pad 2
- Reason for underpredicting at Pad 2 still unclear; might be due in part to corner vortex downwash issues or elevated berm for monitor placement that needs to be modeled more accurately
- Key performance issue is predicting the ratio of NO_2/NOx
- Before applying TTRM, we find that ARM2 overpredicts more than OLM and PVMRM for that ratio
- OLM (with OLMGROUP) performs the best (PVMRM a close second), but they still overpredict the NO_2/NOx ratio
- With TTRM added, all of these options perform better for both pads
- PVMRM and OLM with TTRM are close to unbiased, especially for high NOx

Balko, OK Database – Compressor Station

Figure 5-1. Four Ambient Monitoring Sites at Balko Compressor Station

Monitor 1: North Field (~425 m from Clark TCV-12)

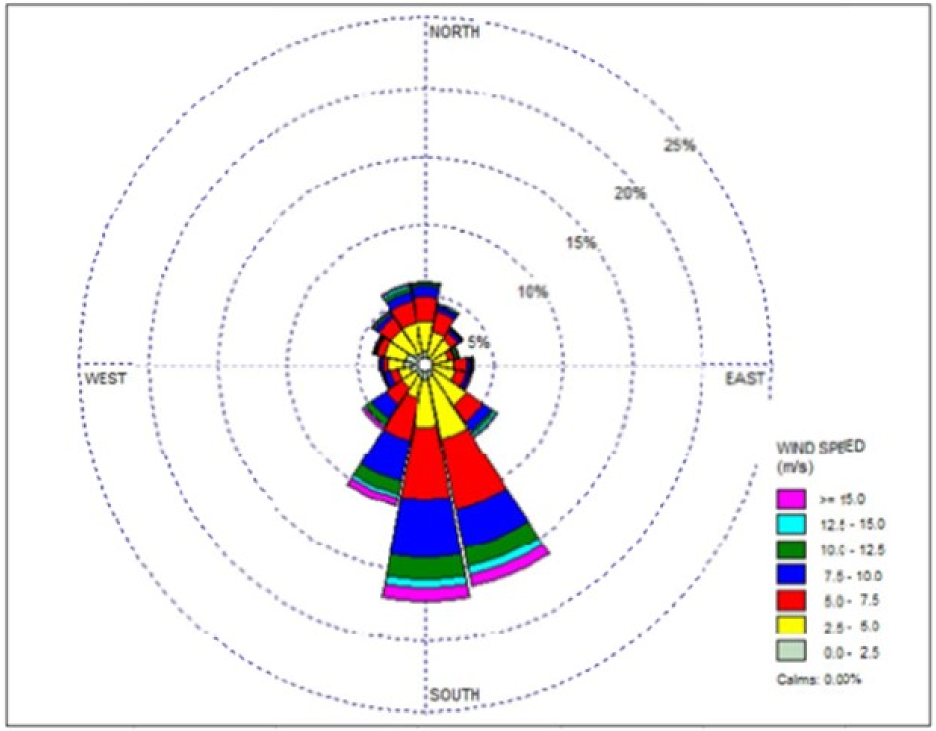
Monitor 2: North Fence (~140 m from Clark TCV-12)

Monitor 3: East Fence (~100 m from Clark TCV-12)

Monitor 4: Tower (~190 m from Clark TCV-12)

These monitors are more distant than those from CO database

Annual 10-meter On-site Wind Rose December 2015 – December 2016



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Model Evaluation for Sources of NO_2

- Primary sources of NO_2 associated with Clark-12 (C9) and to a lesser extent Cooper Bessemer (C10).
- An emergency generator and small boiler were also included in the modeling.
- Used observed NOx and NO_2 data files provided by CERC for model evaluation.
- Most sources had an ISR=0.1.

Figure 2-6. Station 102 Compressor Buildings and Stacks

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Model Evaluation Analysis

- Each monitor site was evaluated independently
- Model with the following AERMOD options:
  - NOx (Tier 1 approach; tests AERMOD without NO_2 chemistry)
  - ARM2 (Tier 2)
  - OLM (Tier 3), using OLMGROUP ALL
  - PVMRM (Tier 3)
  - TTRM supplemented with runs using ARM2, OLM, and PVMRM
- When TTRM was run, the hourly concentrations at each receptor were compared to those from another option, and the lower of the two was used
- TTRM only affects concentrations for near-field locations, where the fraction of NO_2/NOx is low due to incomplete ozone reaction
- See Appendix for details on the model evaluation results for TTRM

Summary of Balko, OK Evaluation with TTRM

- AERMOD NOx predictions are relatively unbiased for North Field, underpredicted for North Field and Tower, and overpredicted for the East Fence monitor.
- Before applying TTRM, for the closer monitors (North and East Fences) PVMRM overpredicted the most, while ARM2 overpredicted the most at the far-field monitors.
- With TTRM added, biggest model improvements seen at North Fence monitor.
- In general, due to the larger distance to these monitors vs. the Colorado database, the effect of TTRM was less.
- PVMRM+TTRM has the best performance with some overprediction tendency.
- Use of TTRM does not result in an underprediction tendency for the NO_2/NOx ratio, and it either reduces overprediction or results in little change for the peak predictions at the more distant monitors.

Overall Results and Conclusions

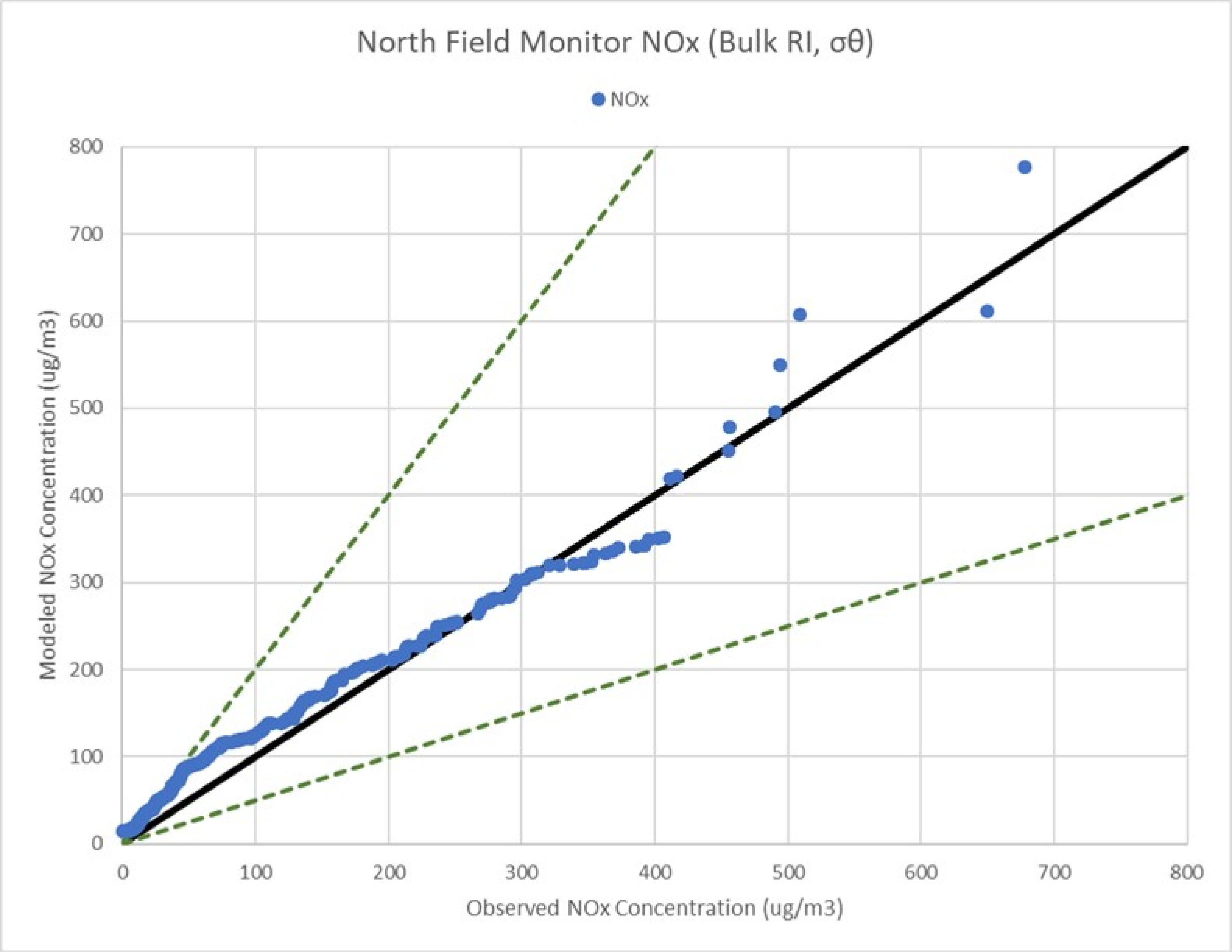
- In general, the use of the TTRM option results in better performance for monitors close to the source; lower or no effect at more distant monitors as expected
- TTRM generally results in unbiased predictions or modest overpredictions for the NO2/NOx ratio for very near-field receptors
- TTRM improves NO_2/NOx ratio over a large range of NOx concentrations for affected monitors
- The Tier 3 approaches (without TTRM) overpredict the NO_2/NOx ratio less than ARM2, as expected
- TTRM should be paired with another method (e.g., a Tier 3 method) and then lower of the two concentrations should be used on an hourly / source / receptor basis

Appendix

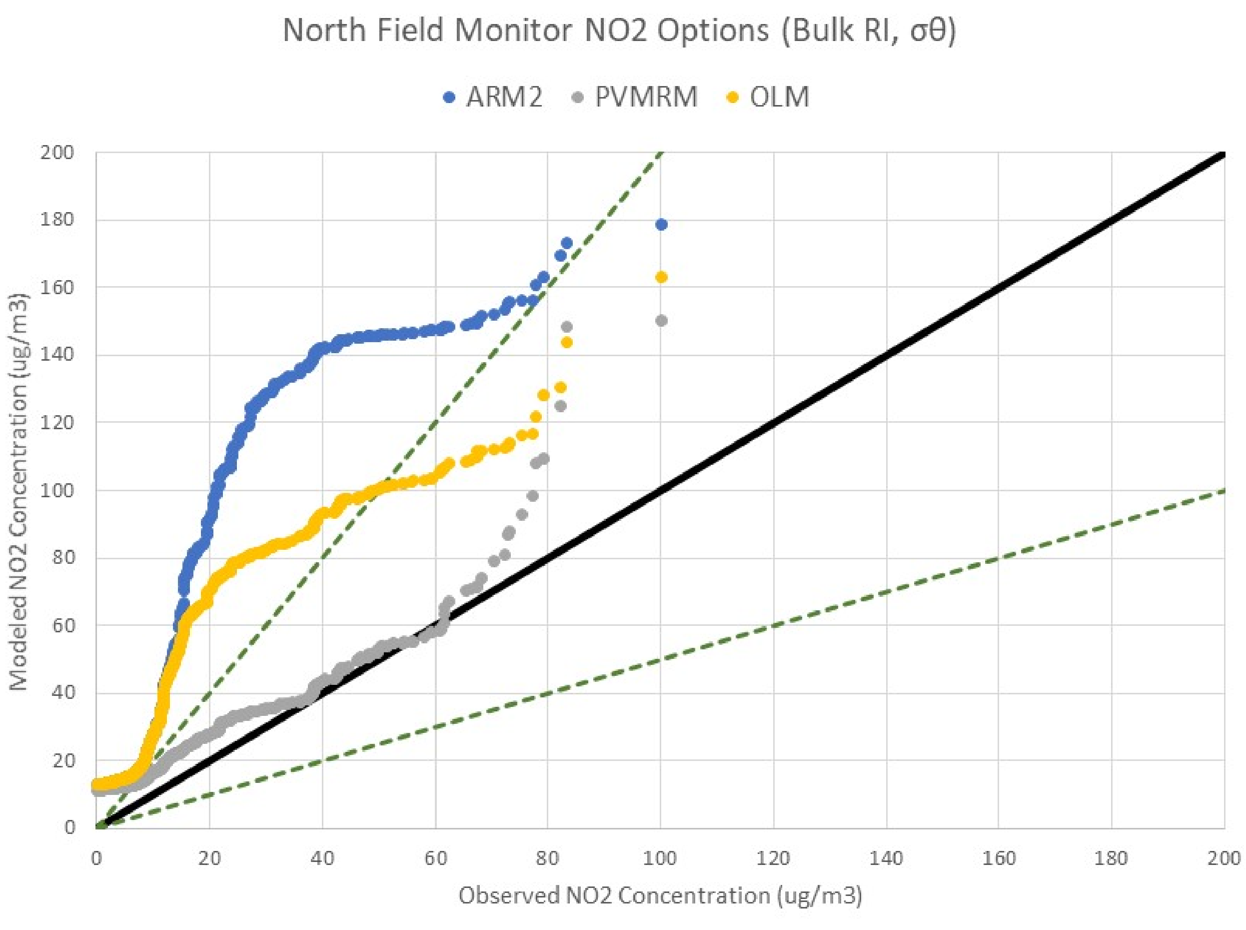
– Details of the modeling results for Balko with the addition of TTRM are provided in this appendix.

Q-Q Plots for North Field: NOx and NO_2

NOx



NO_2



Note: for this monitor, TTRM does not change the Q-Q plot results for NO_2.

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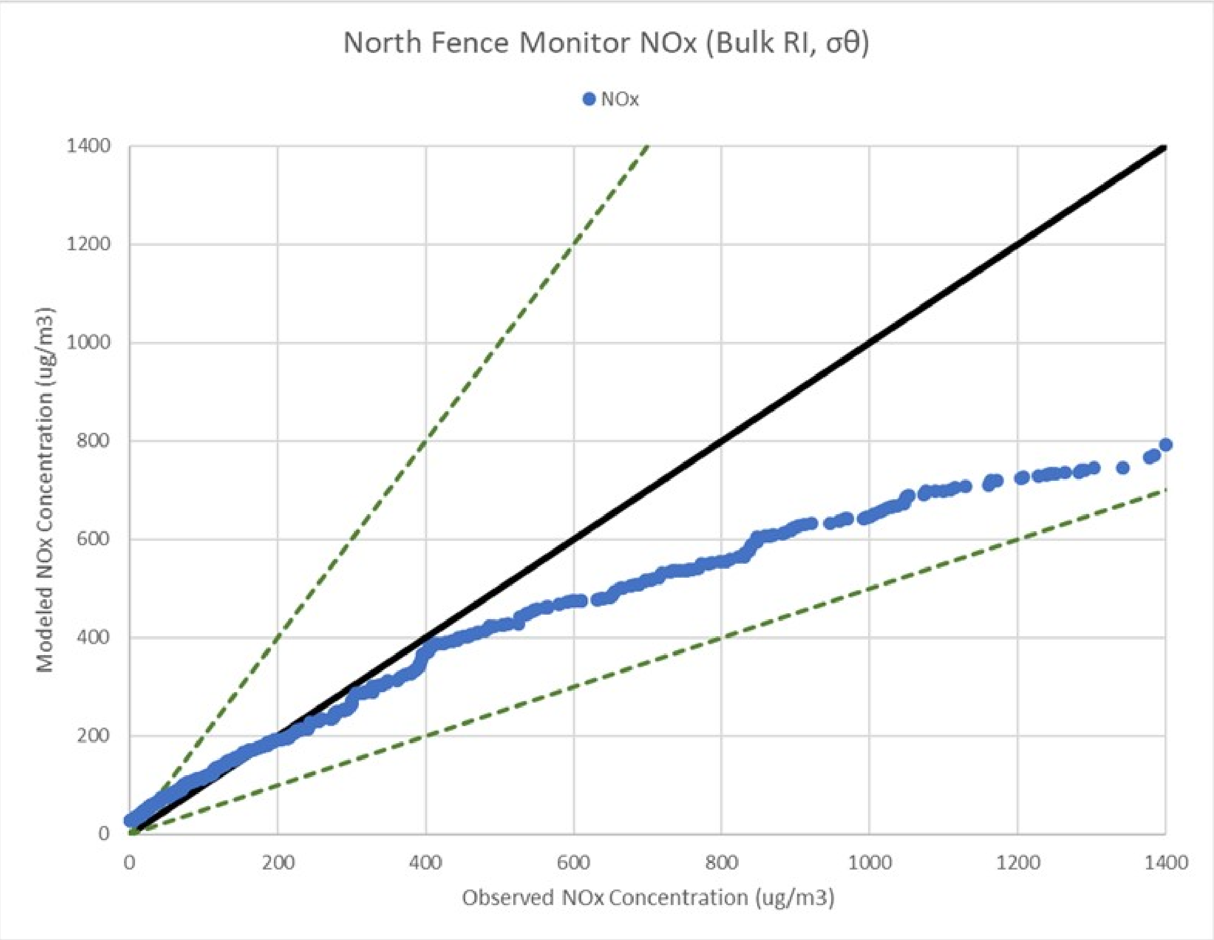
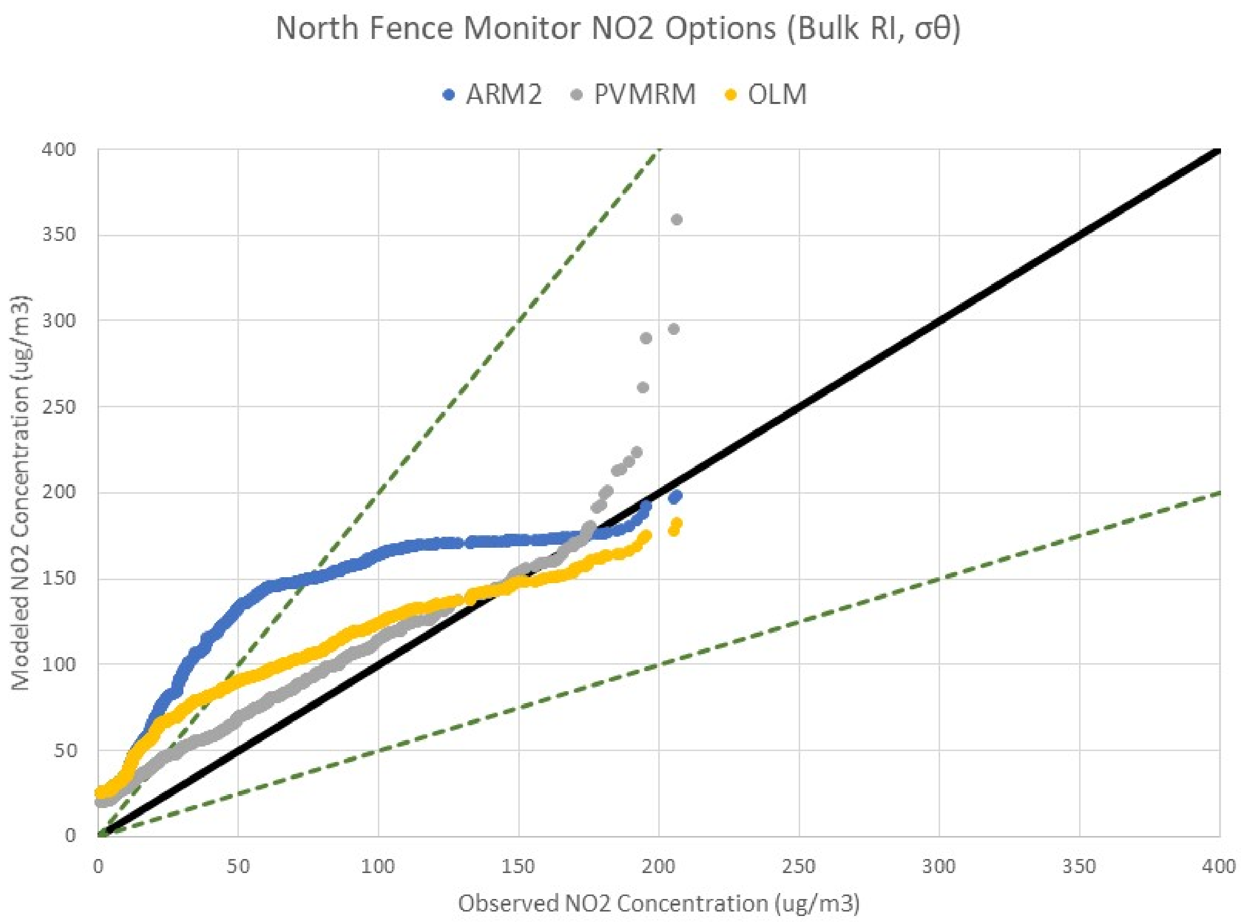
Q-Q Plots for North Fence: NOx and NO_2

NOx	NO_2





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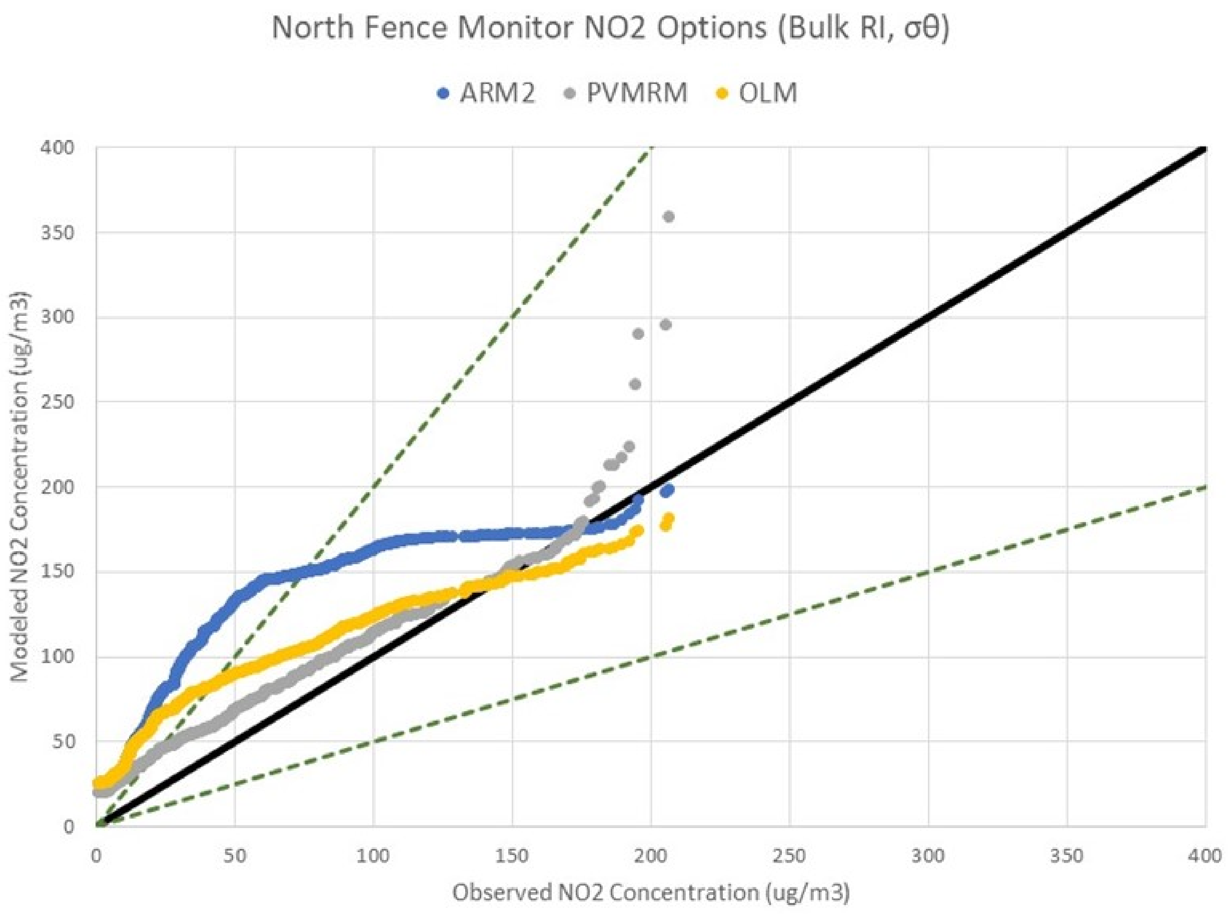
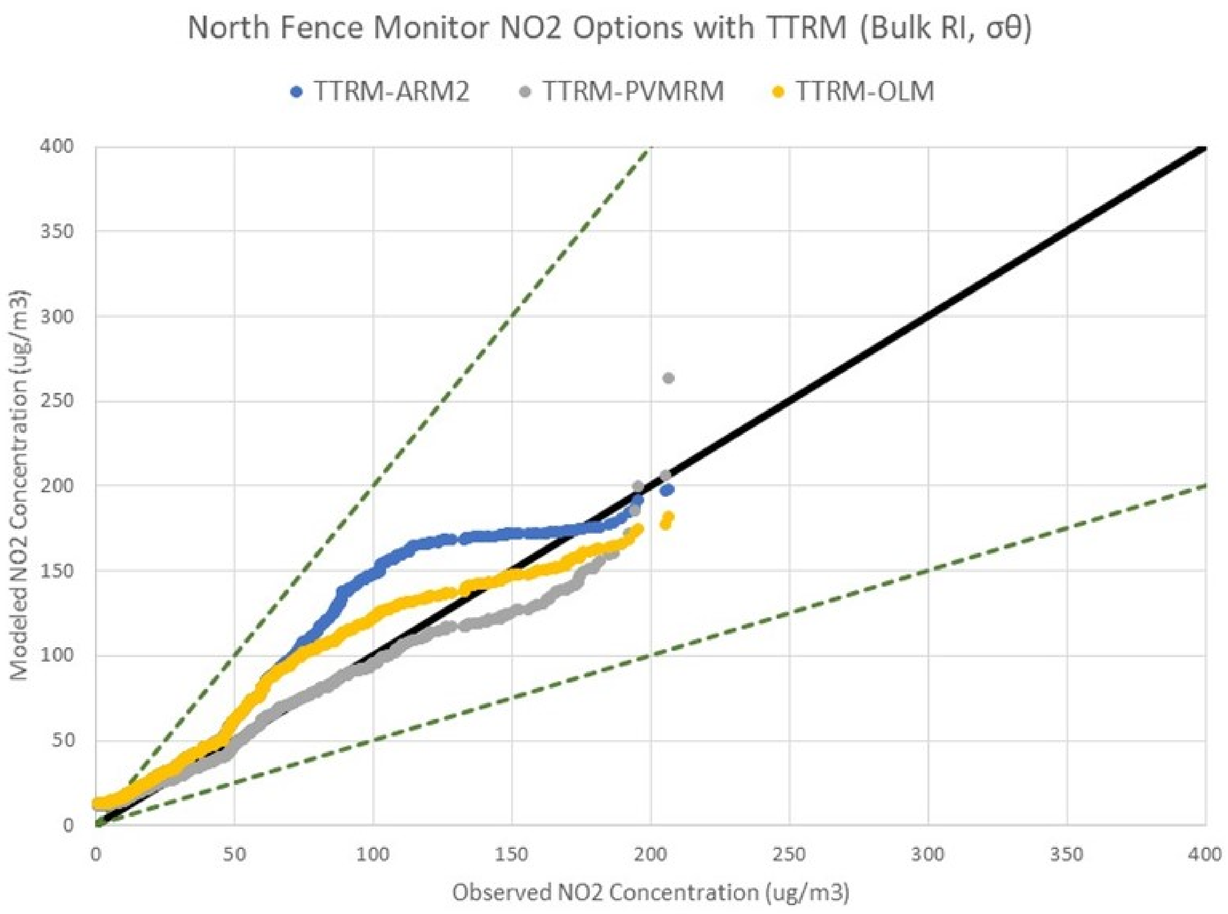
Q-Q Plot for North Fence: NO_2 with TTRM Added on the Right

Without TTRM



Includes TTRM Enhancement



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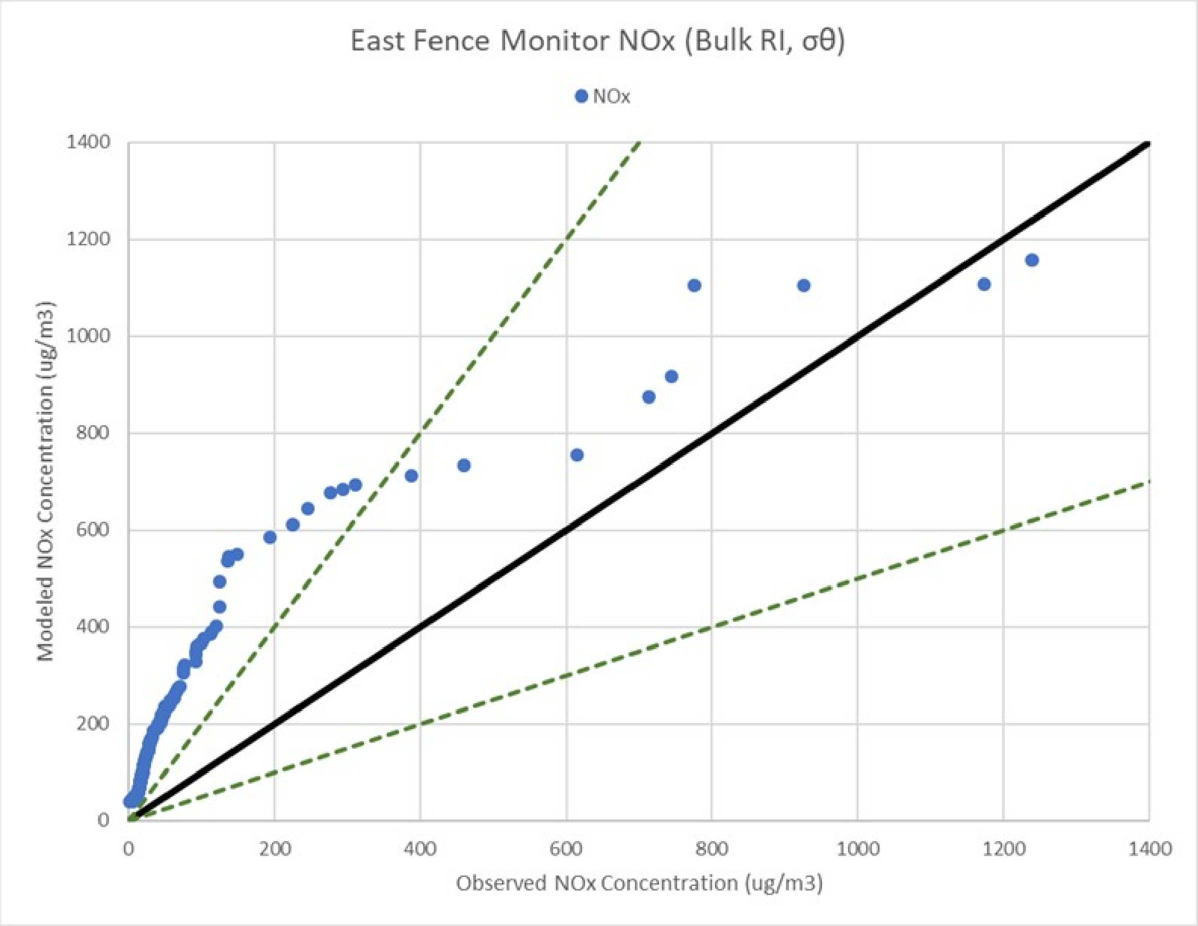
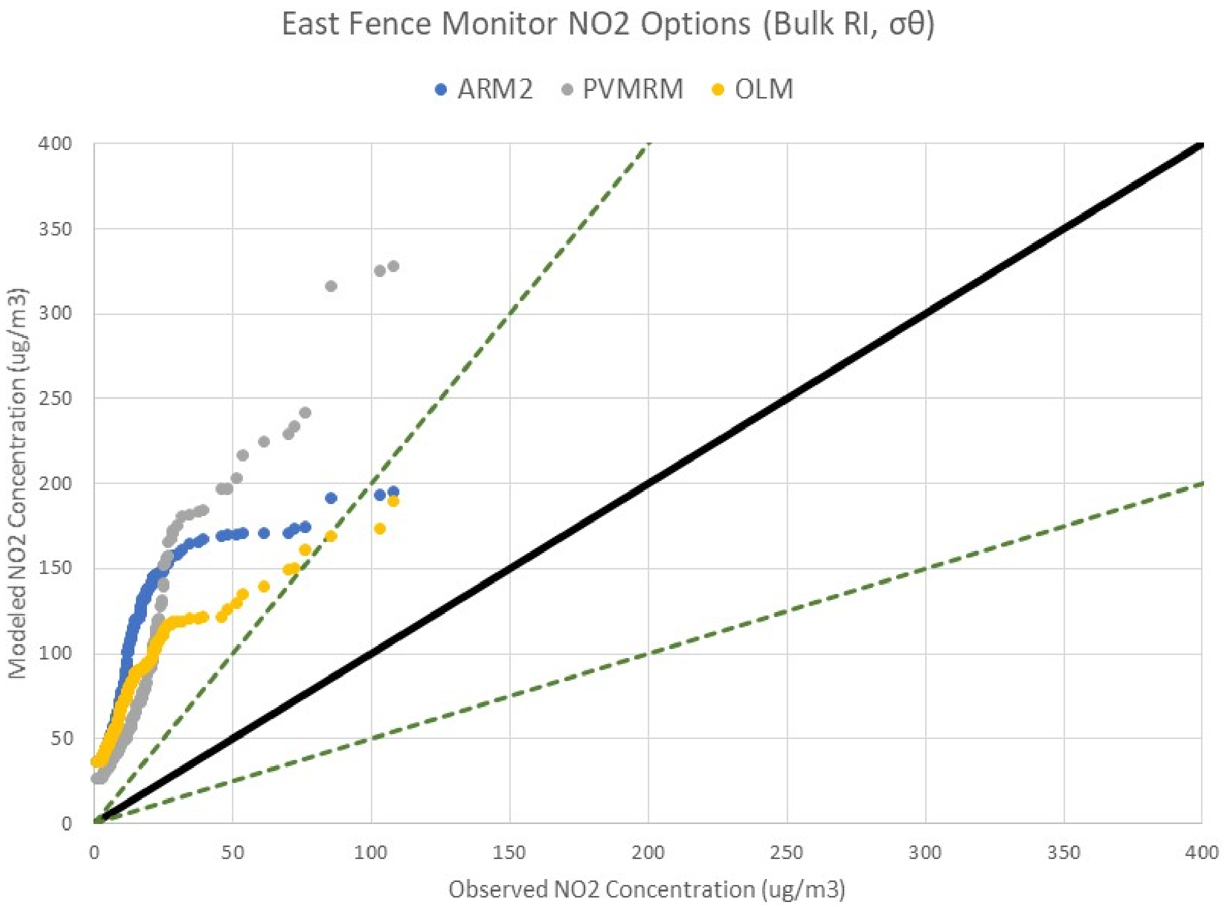
Q-Q Plots for East Fence: NOx and NO_2

NOx



NO_2



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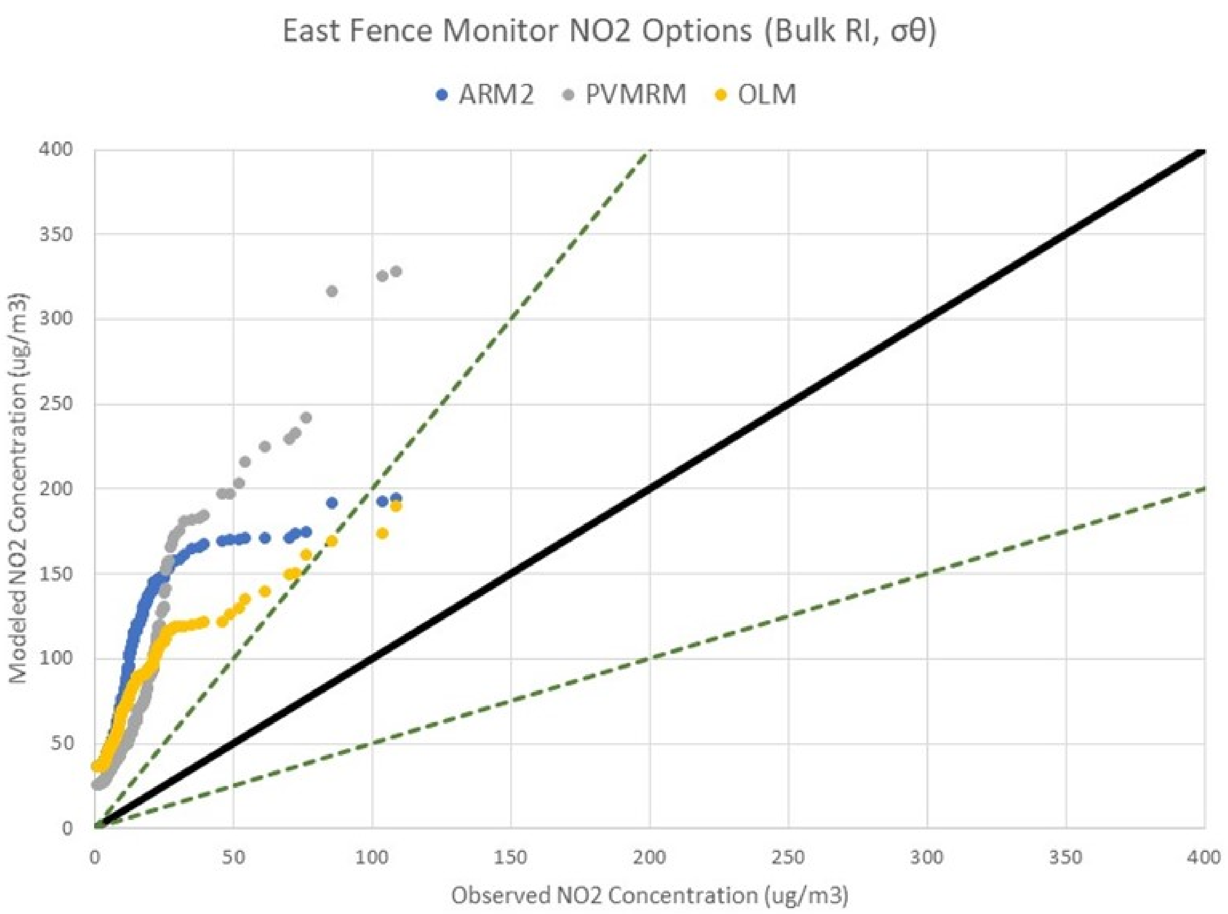
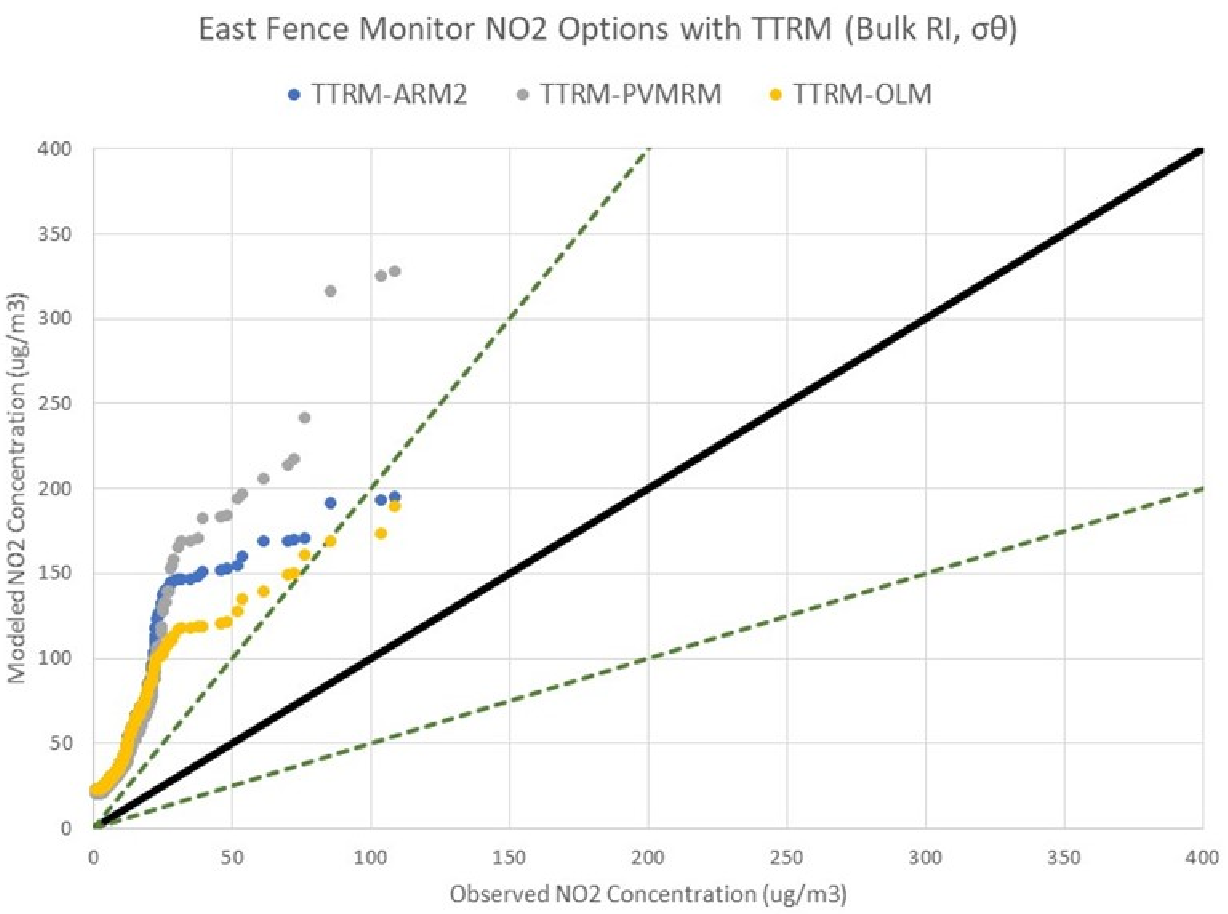
Q-Q Plot for East Fence: NO_2 with TTRM Added on the Right

Without TTRM

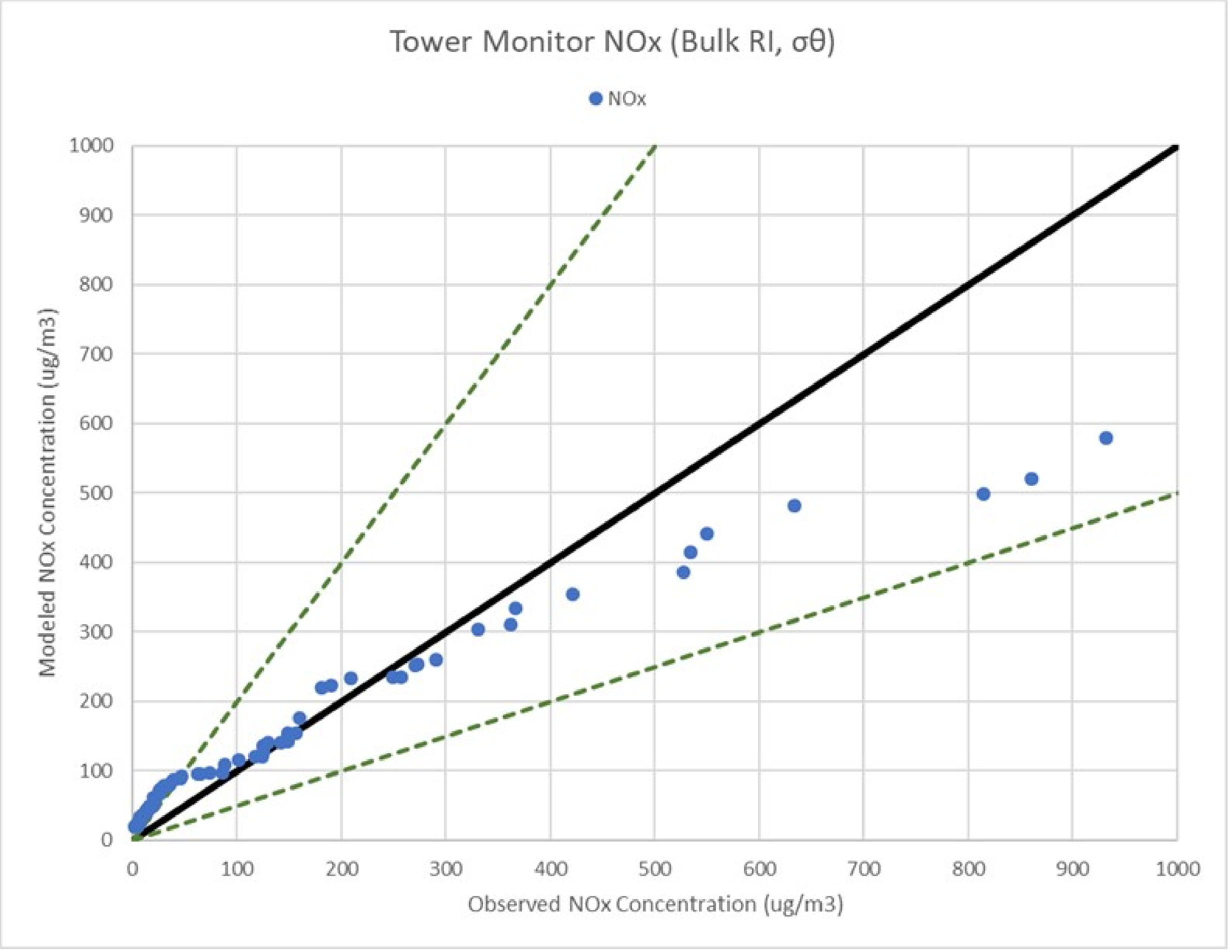


Includes TTRM Enhancement



Q-Q Plots for Tower: NOx and NO_2

NO_2



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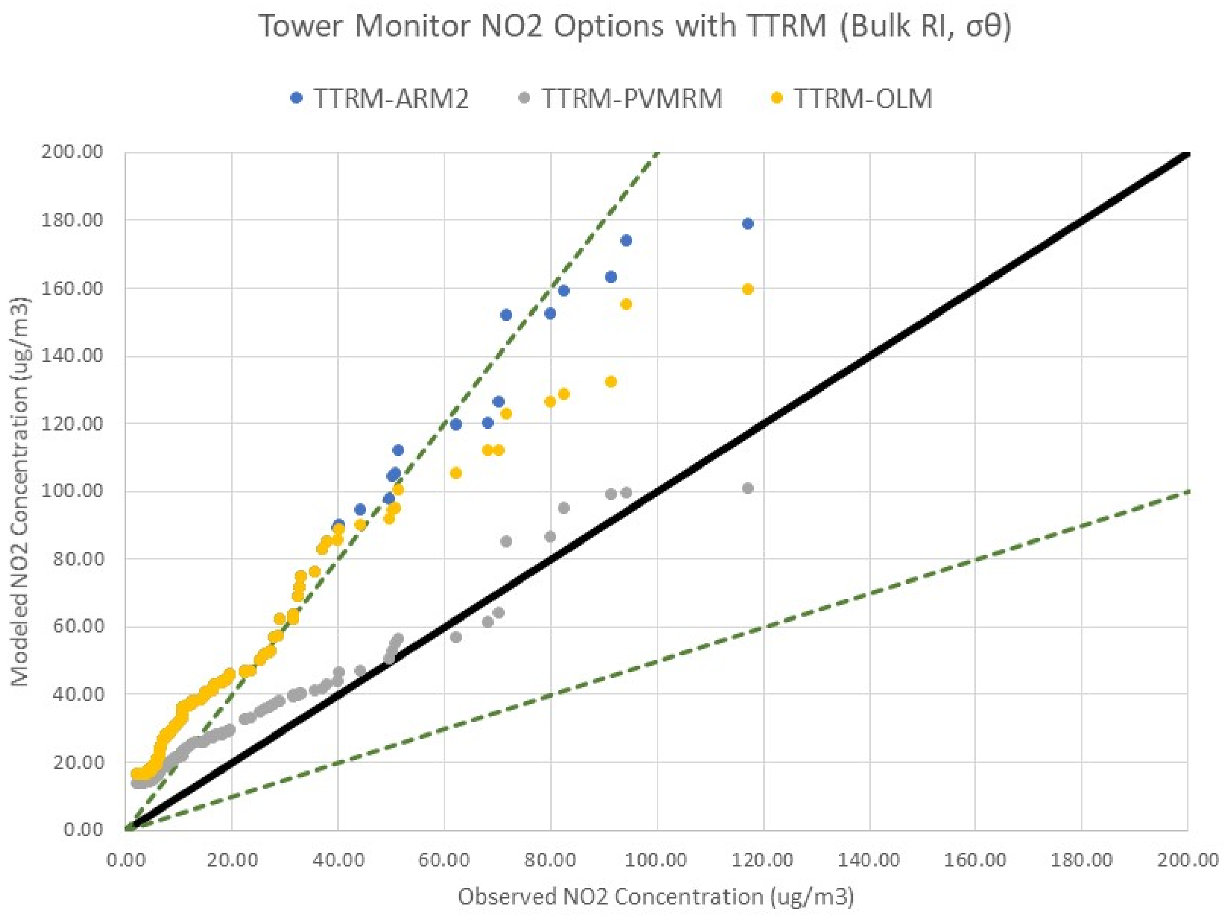
Q-Q Plot for Tower: NO_2 with TTRM Added on the Right

Without TTRM

Includes TTRM Enhancement



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Further Analysis to Remove Effect of NOx Bias

- The real model performance issue is the ratio of NO_2/NOx
- We show plots of observed as well as predicted NO_2/NOx for each model
- The NO_2/NOx ratio is expected to decrease as observed NOx increases
- The plots show the NO_2/NOx ratio on the y axis and observed NOx on the x axis

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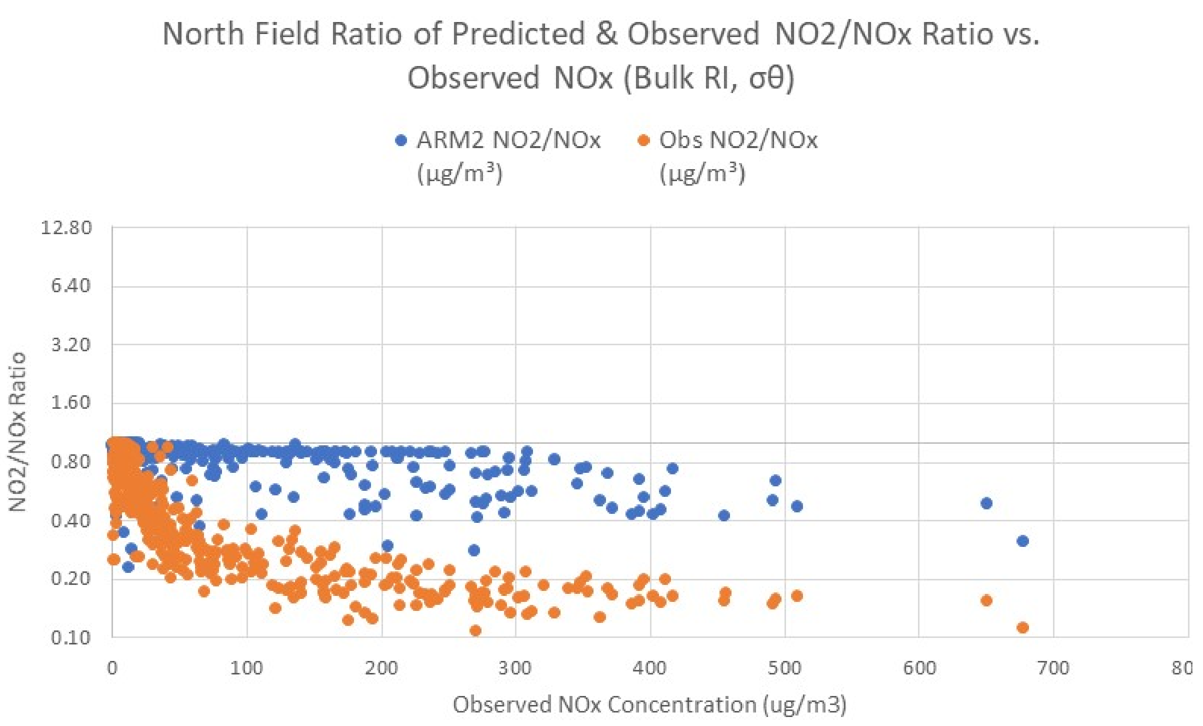
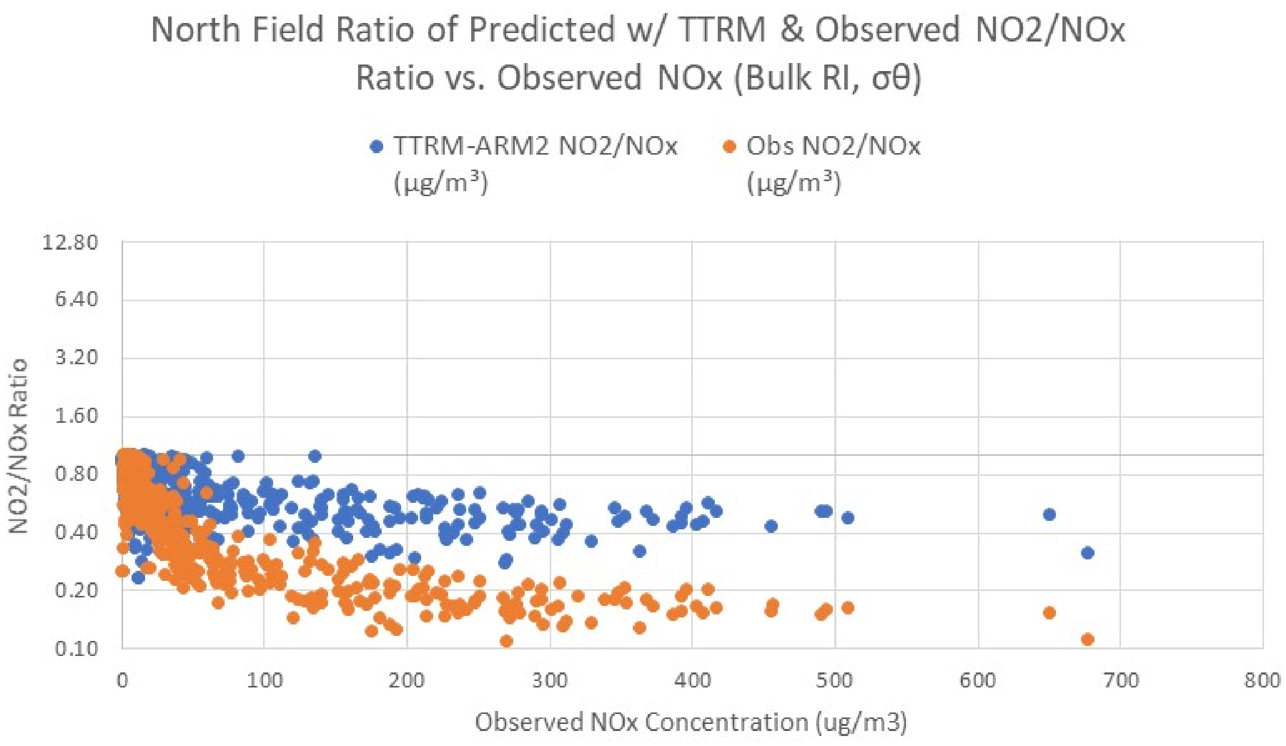
North Field: NO_2/NOx Ratio vs. NOx for ARM2 and ARM2 + TTRM

ARM2



ARM2 + TTRM



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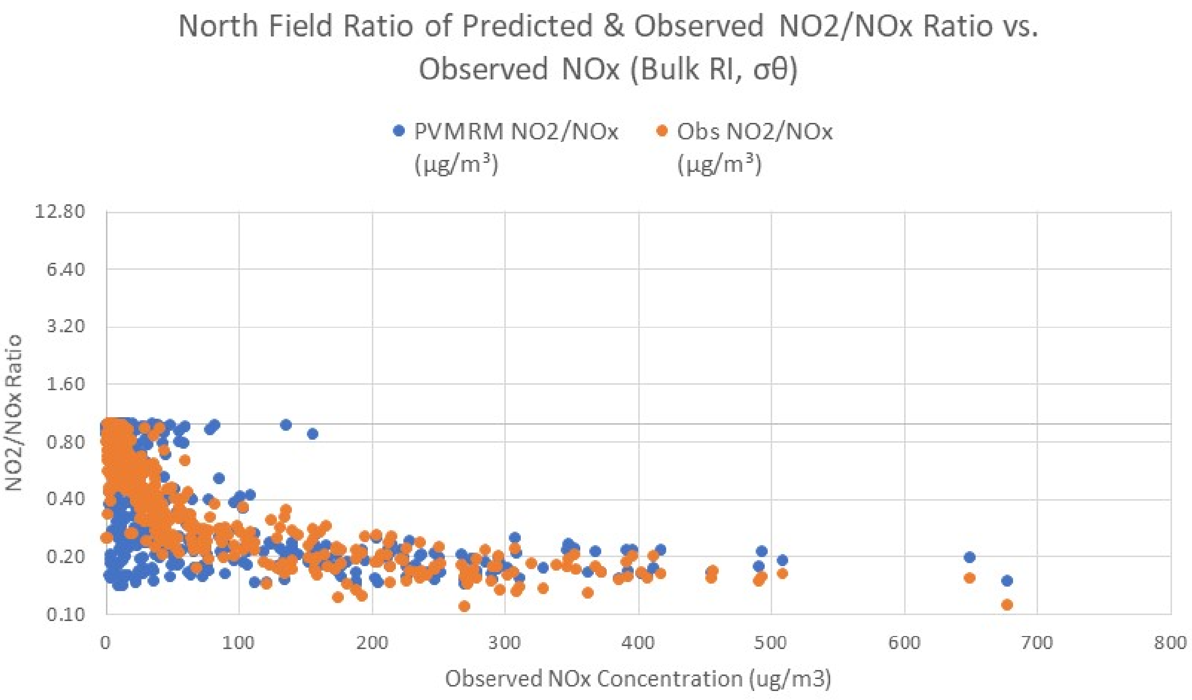
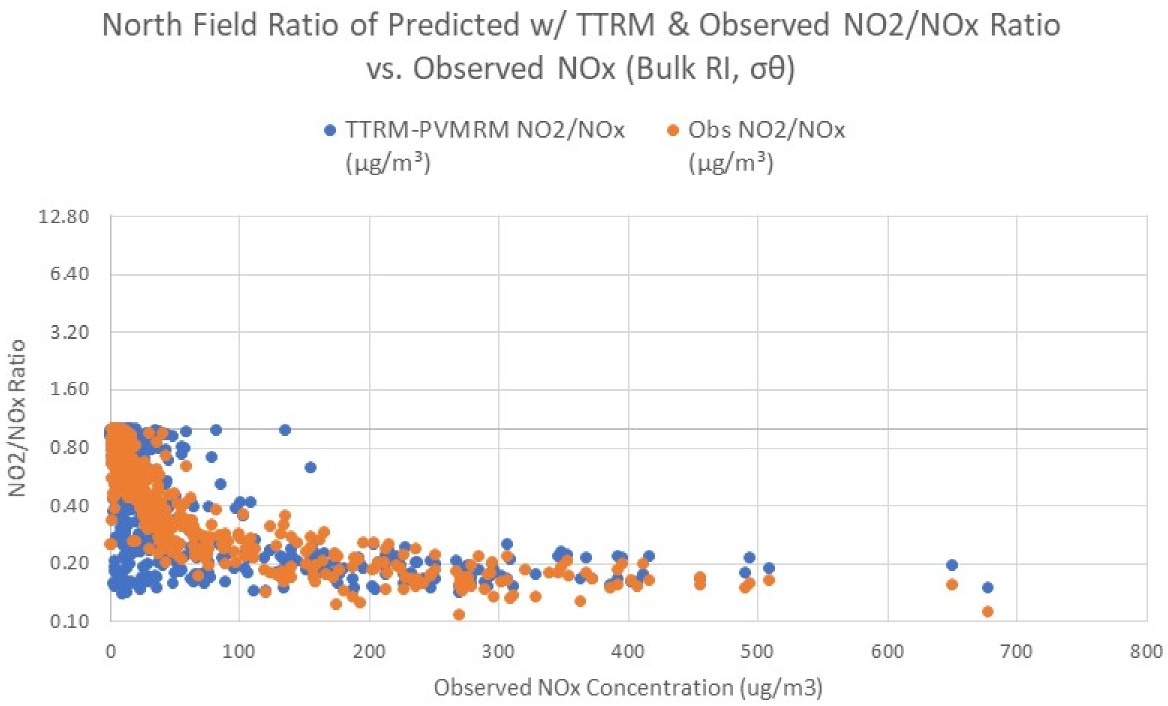
North Field: NO_2/NOx Ratio vs. NOx for PVMRM and PVMRM + TTRM

PVMRM

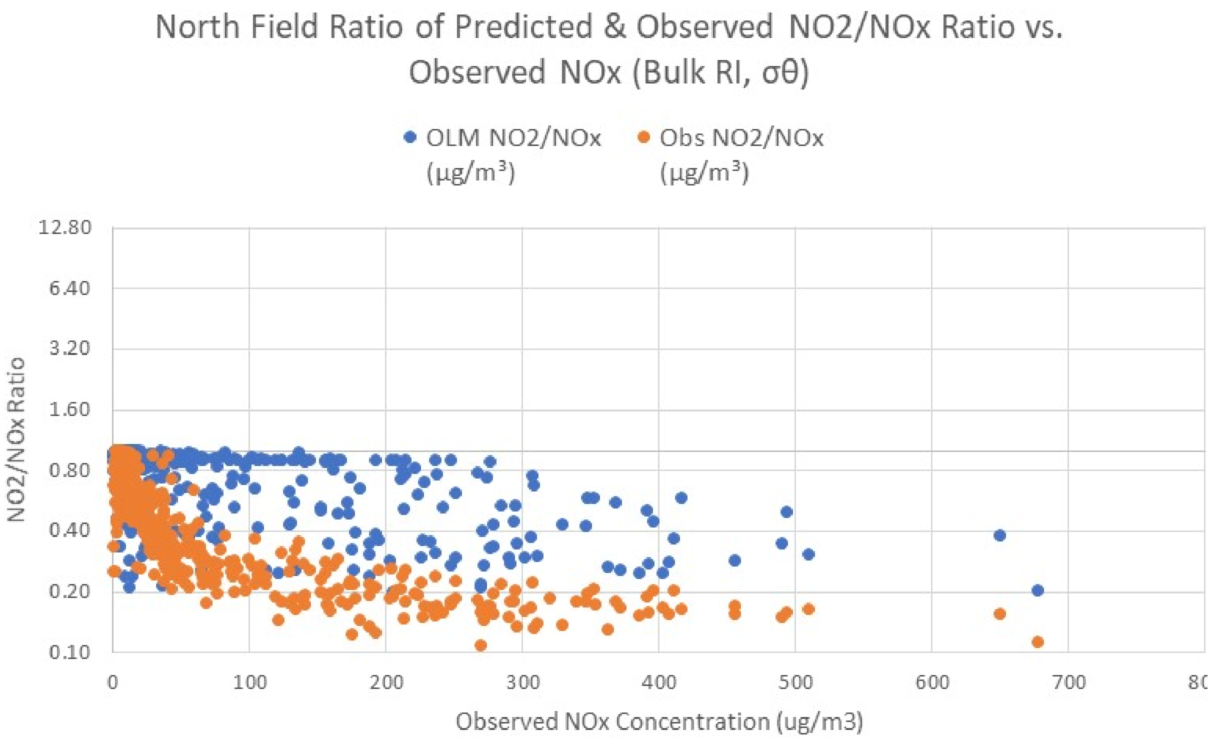


PVMRM + TTRM

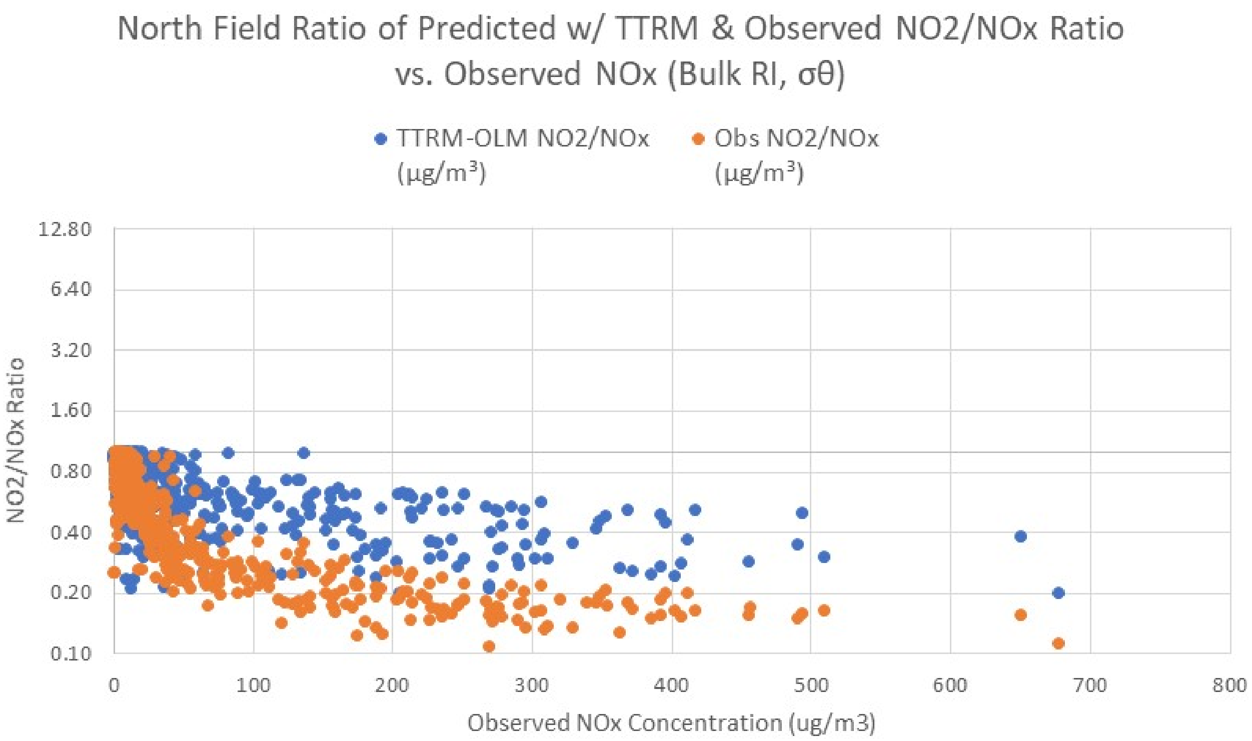


North Field: NO_2/NOx Ratio vs. NOx for OLM and OLM + TTRM

OLM

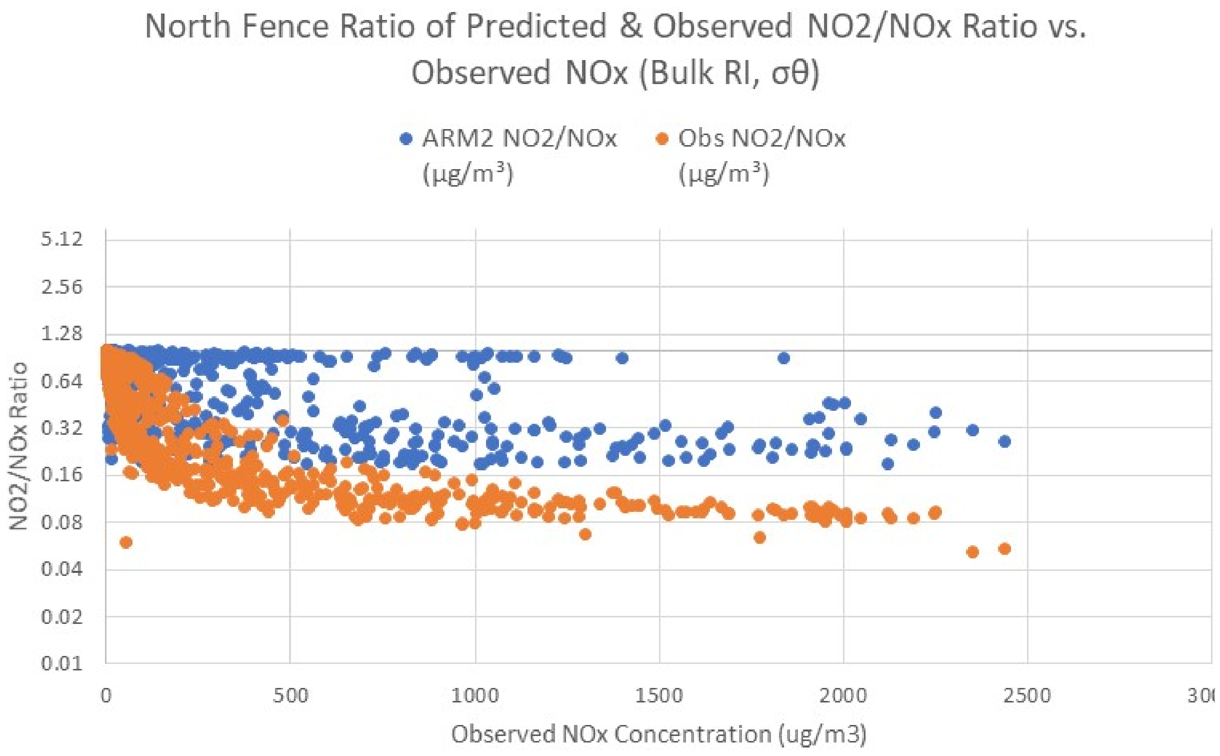


OLM + TTRM

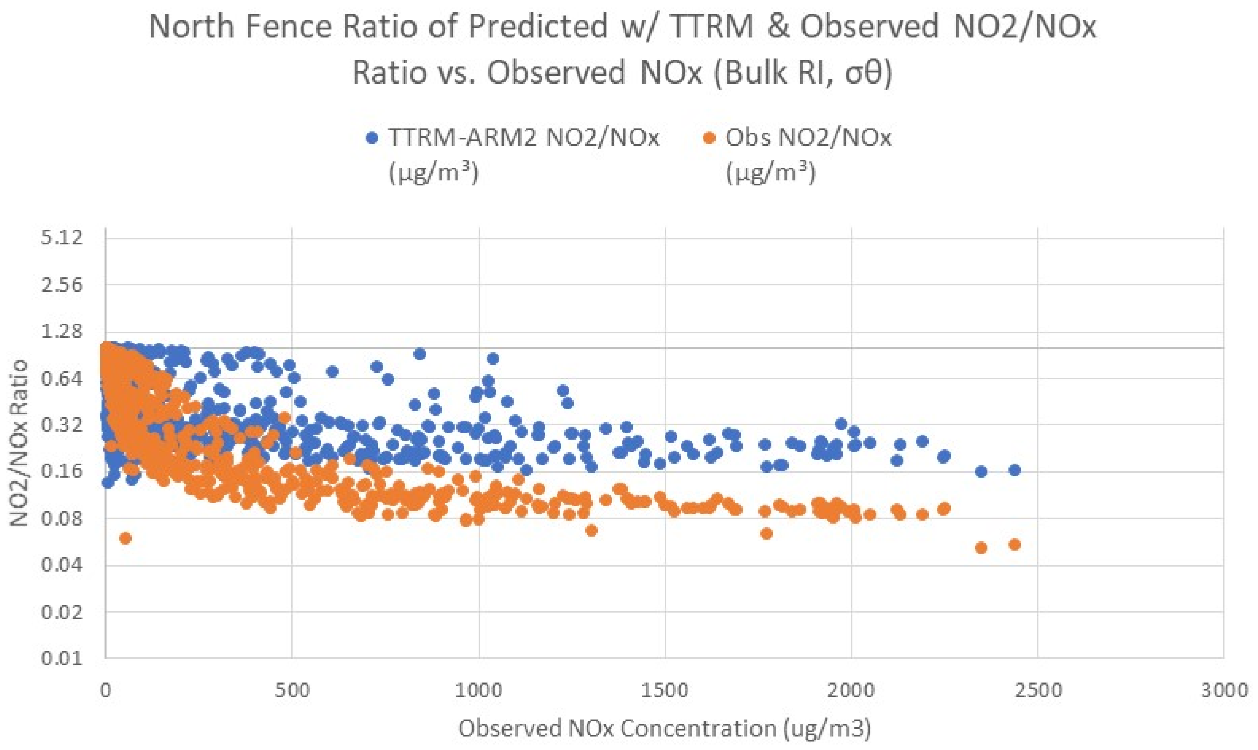


North Fence: NO_2/NOx Ratio vs. NOx for ARM2 and ARM2 + TTRM

ARM2



ARM2 + TTRM



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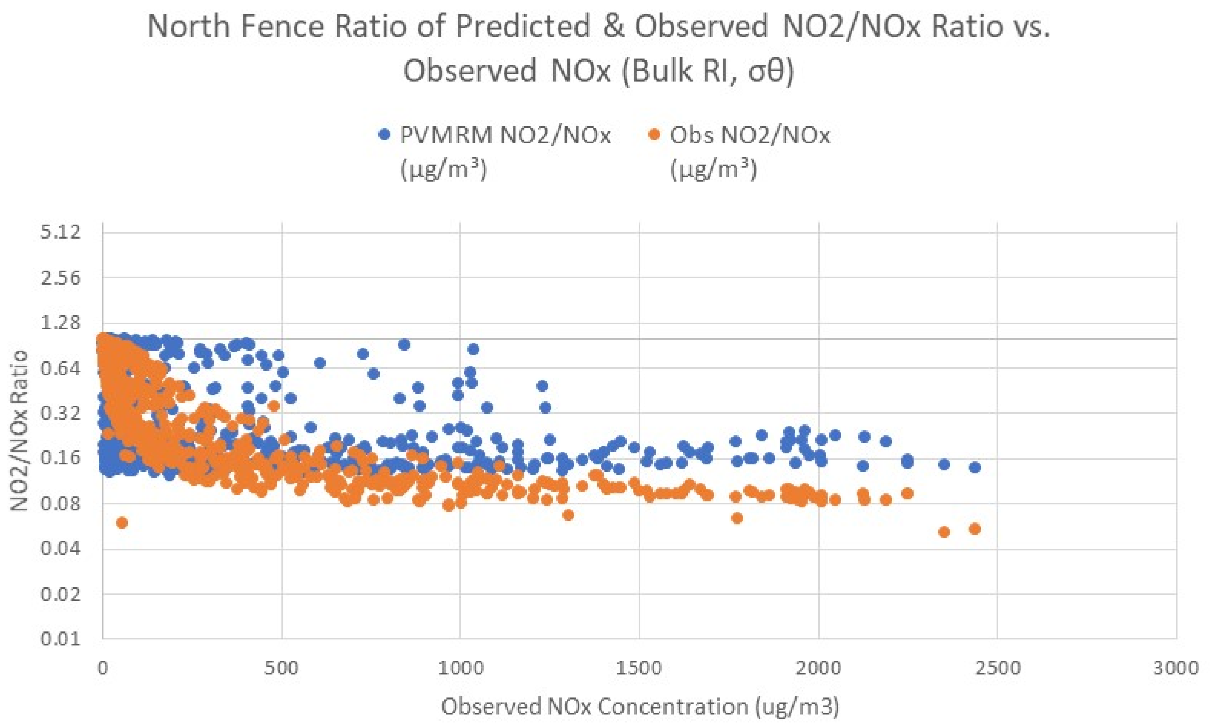
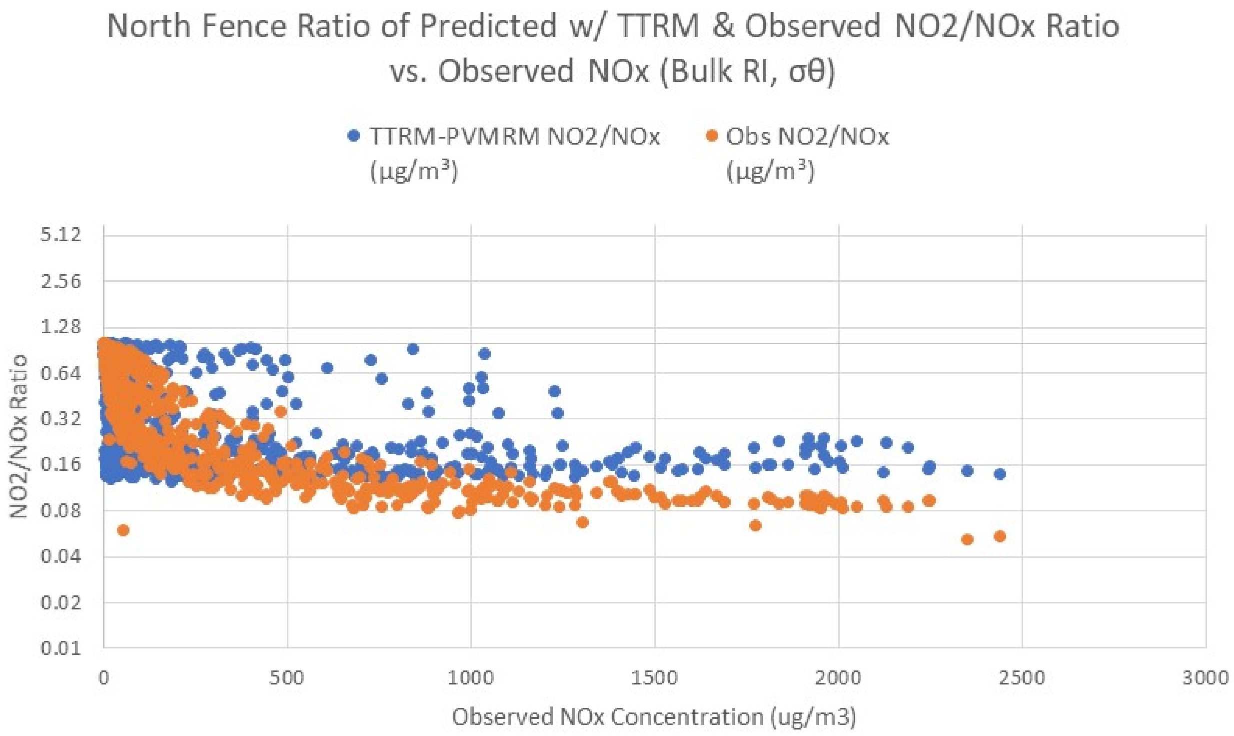
North Fence: NO_2/NOx Ratio vs. NOx for PVMRM and PVMRM + TTRM

PVMRM



PVMRM + TTRM



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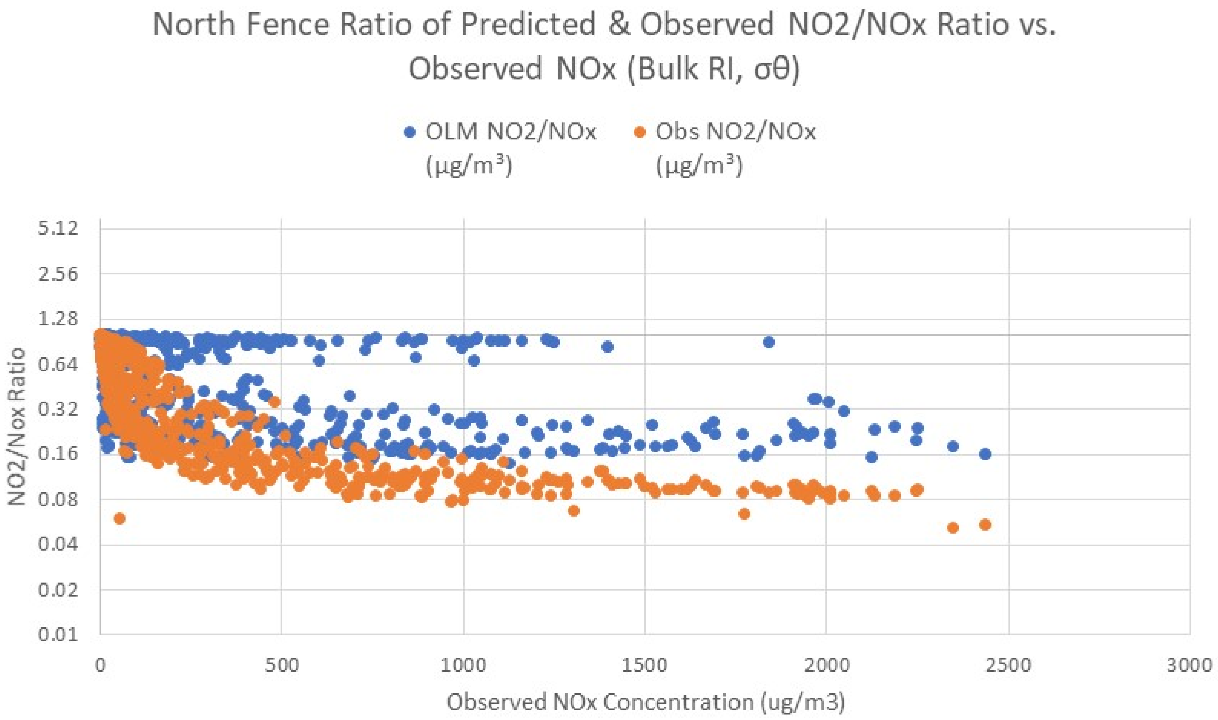
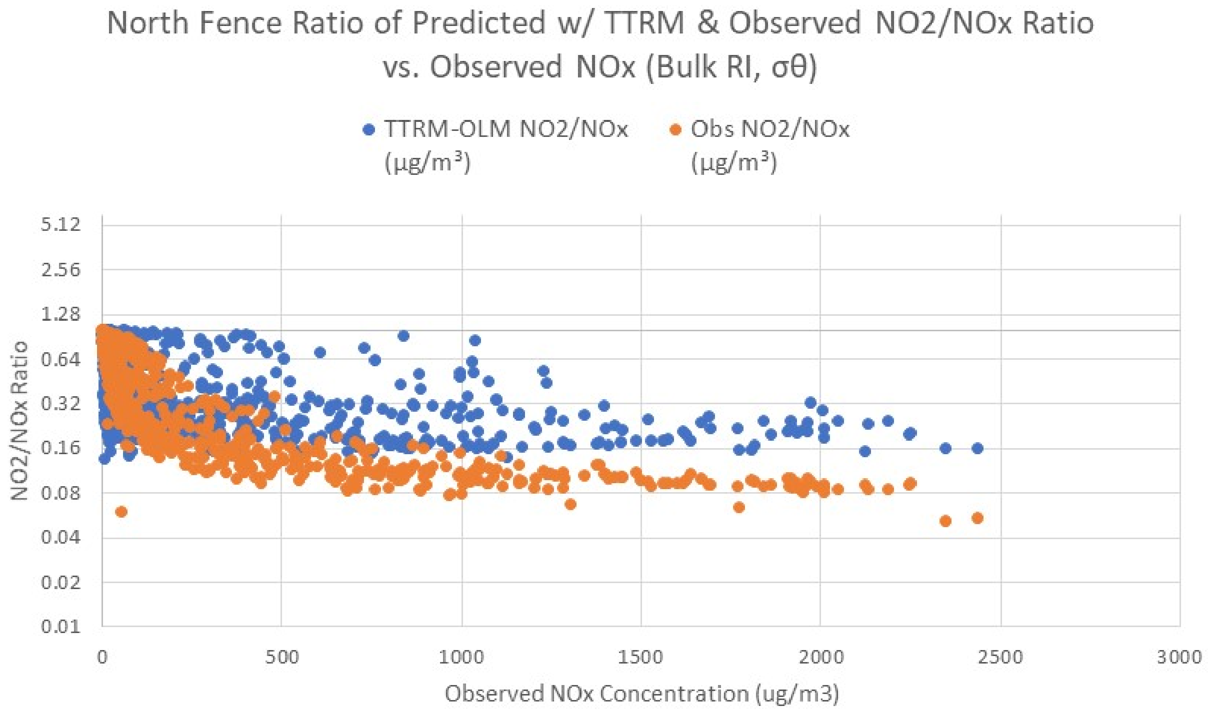
North Fence: NO_2/NOx Ratio vs. NOx for OLM and OLM + TTRM

OLM



OLM + TTRM



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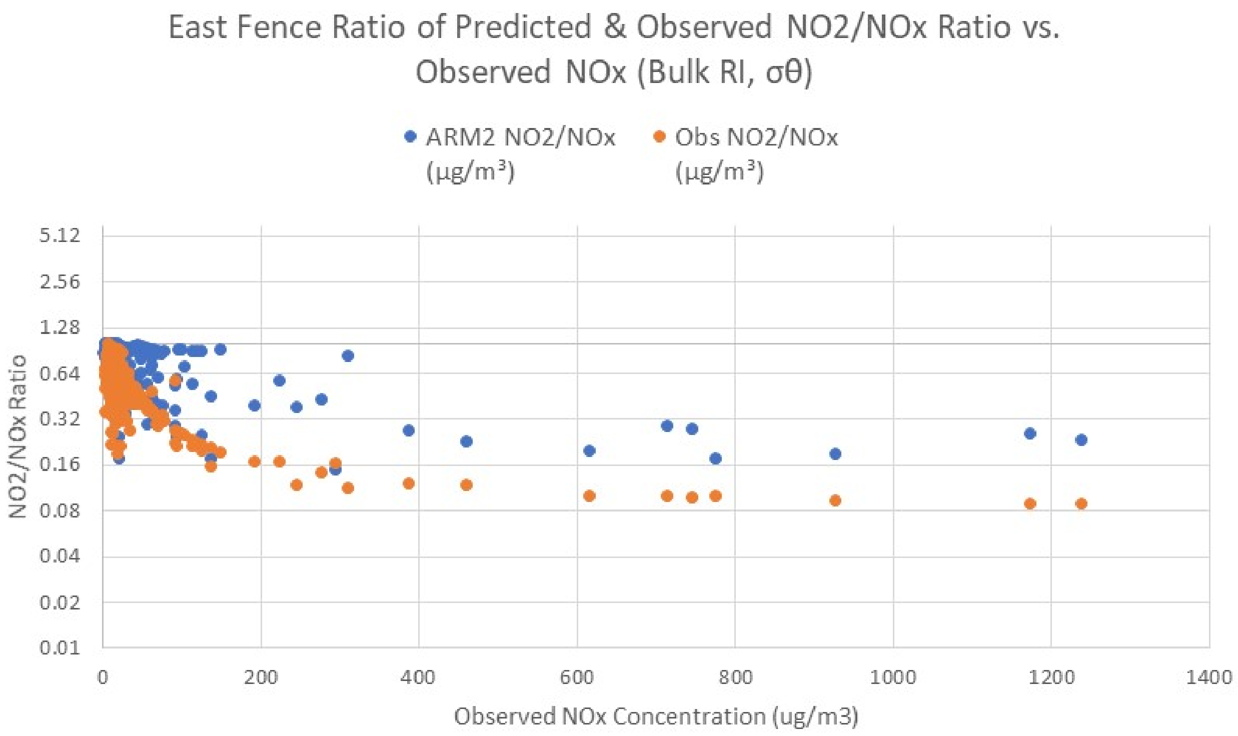
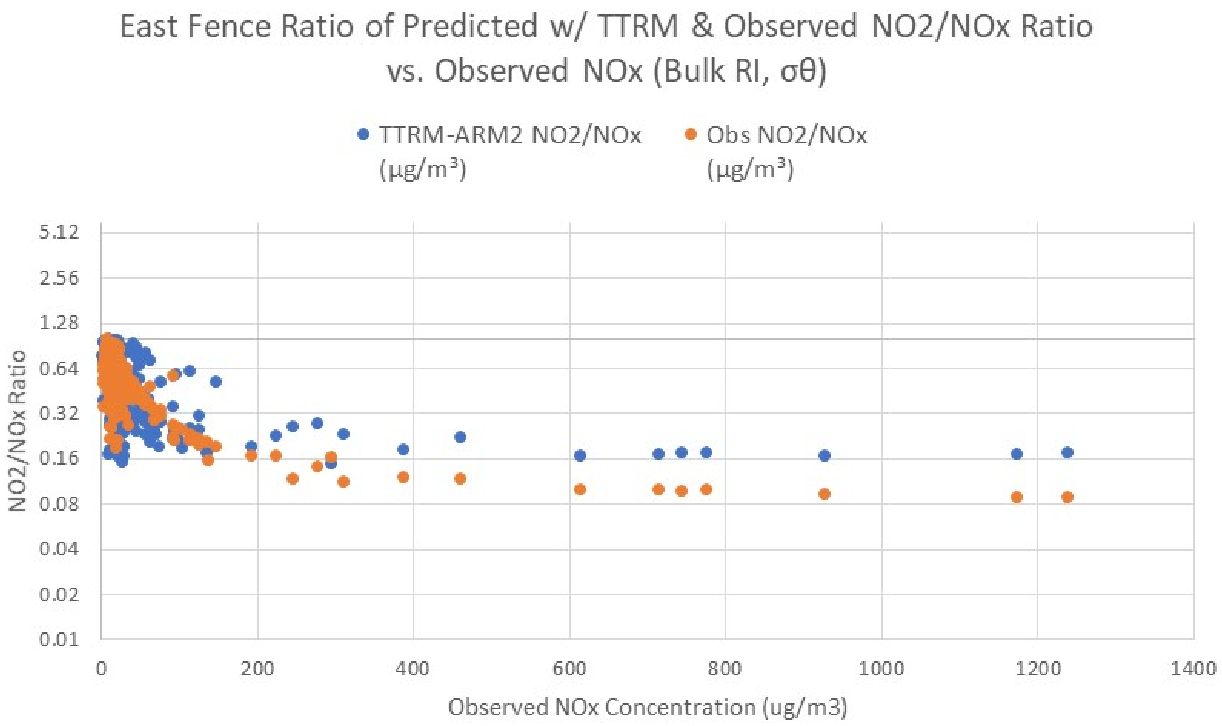
East Fence: NO_2/NOx Ratio vs. NOx for ARM2 and ARM2 + TTRM

ARM2

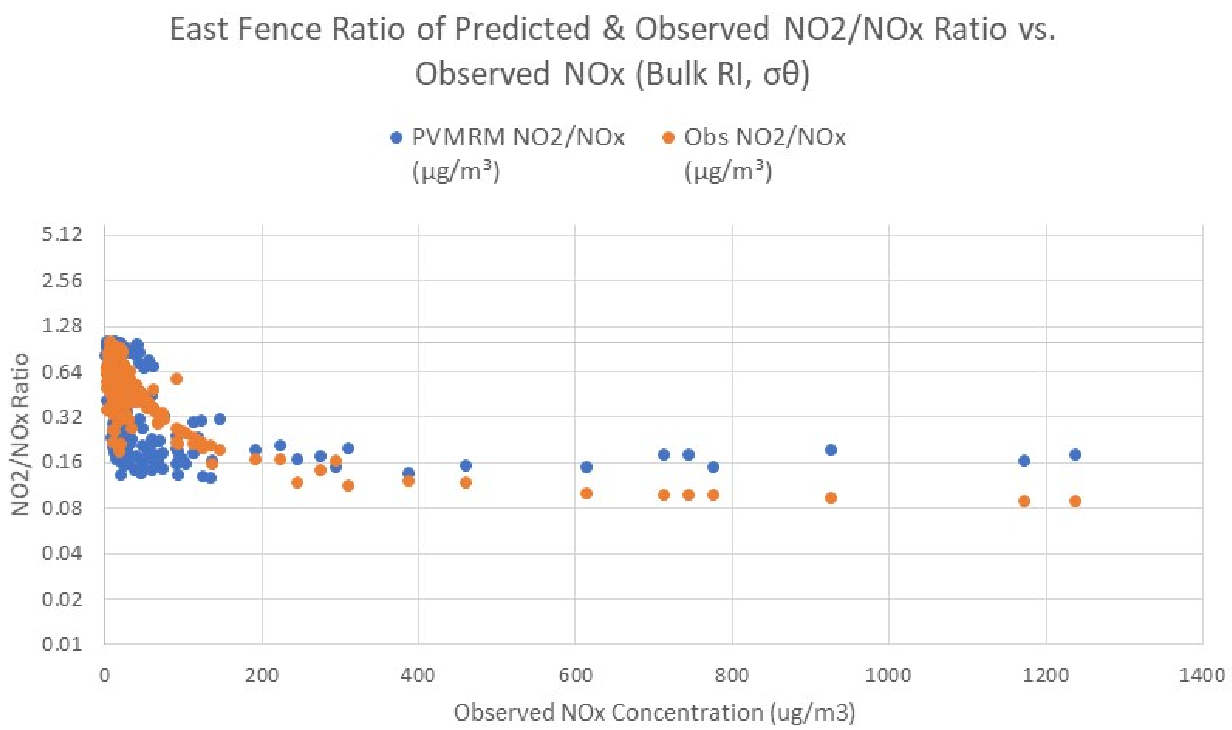


ARM2 + TTRM

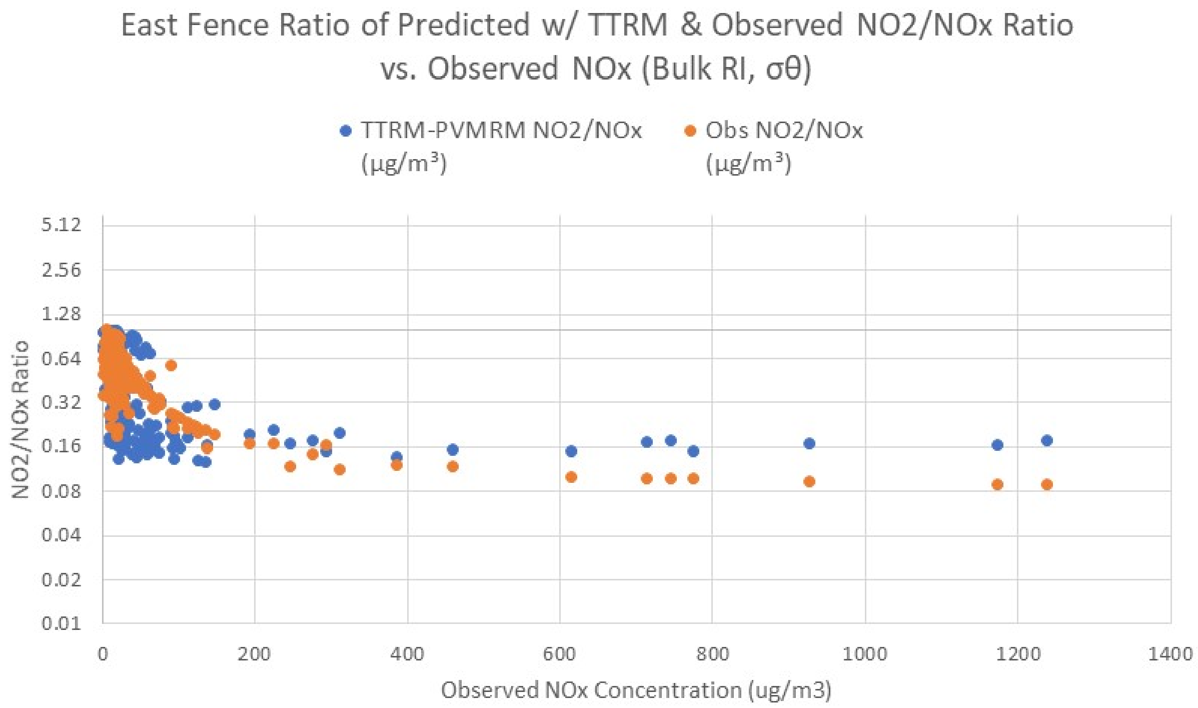


East Fence: NO_2/NOx Ratio vs. NOx for PVMRM and PVMRM + TTRM

PVMRM

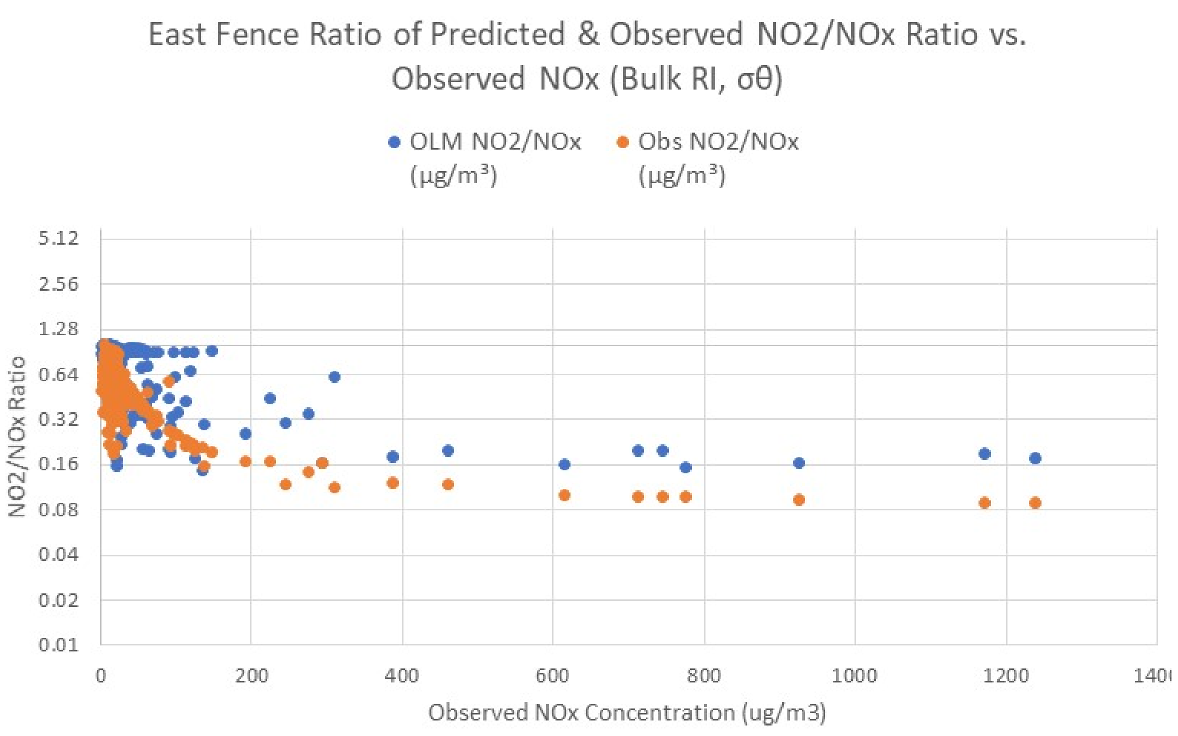


PVMRM + TTRM

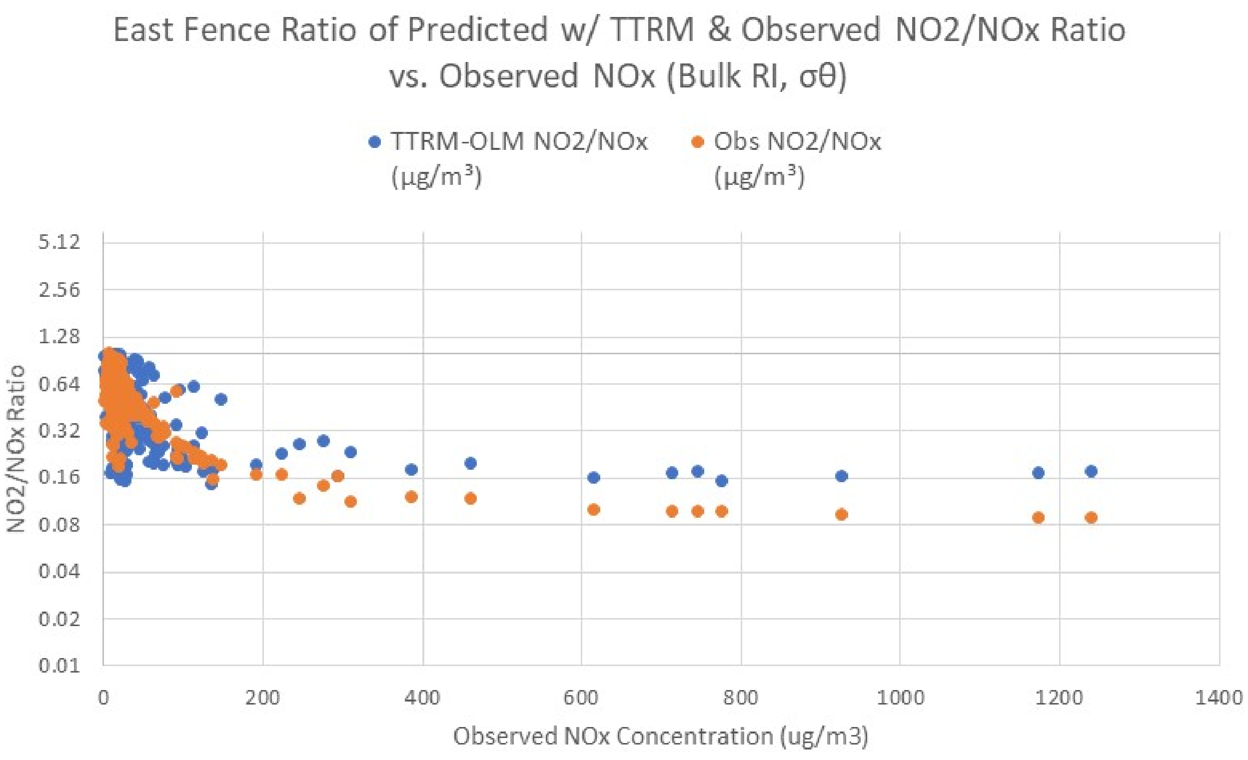


East Fence: NO_2/NOx Ratio vs. NOx for OLM and OLM + TTRM

OLM

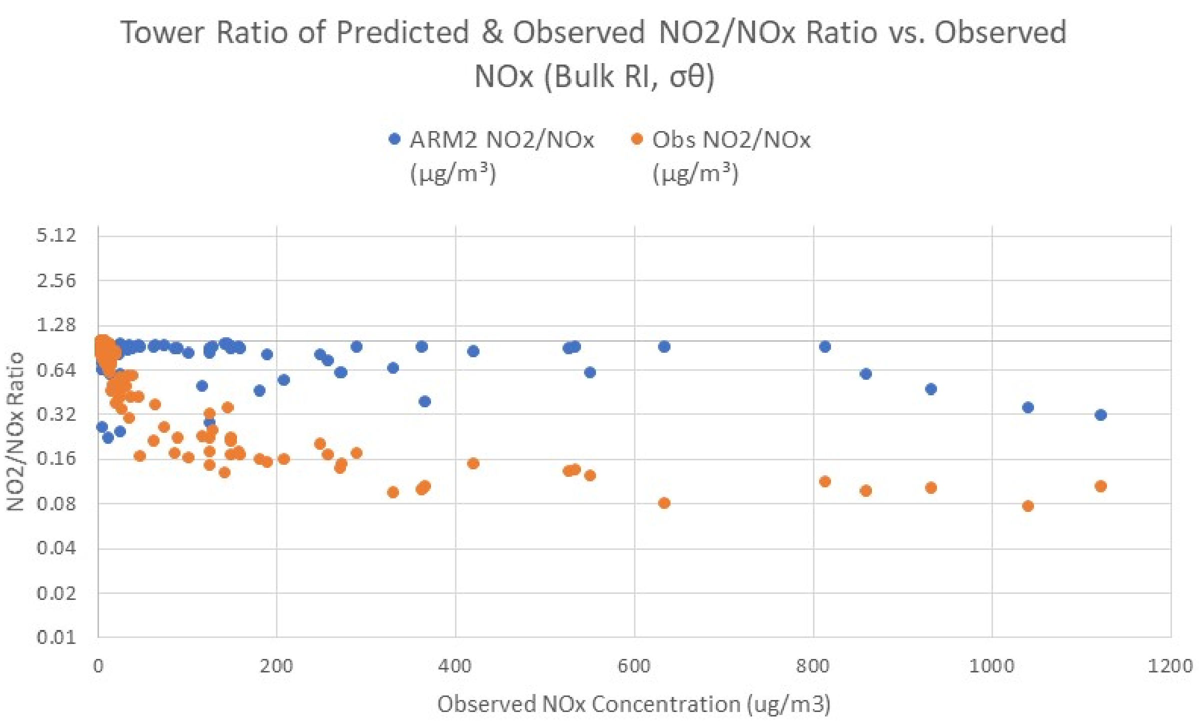


OLM + TTRM

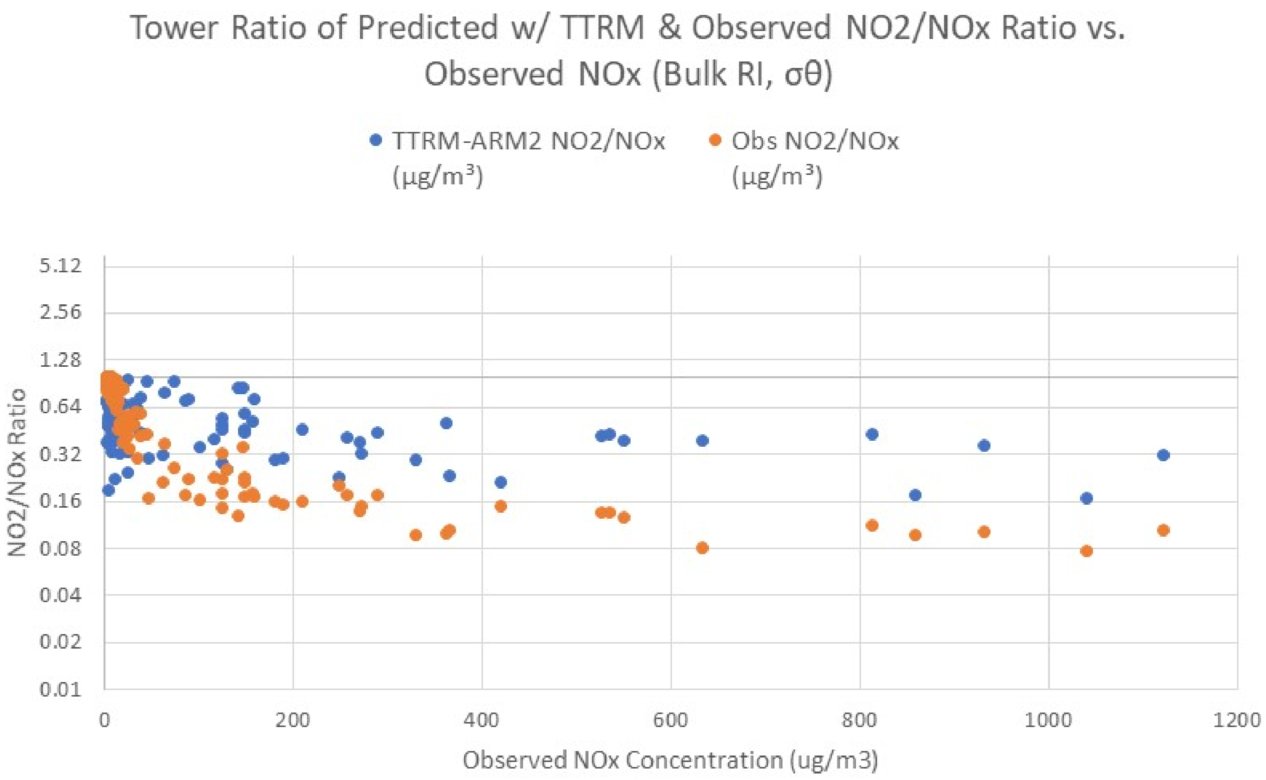


Tower: NO_2/NOx Ratio vs. NOx for ARM2 and ARM2 + TTRM

ARM2

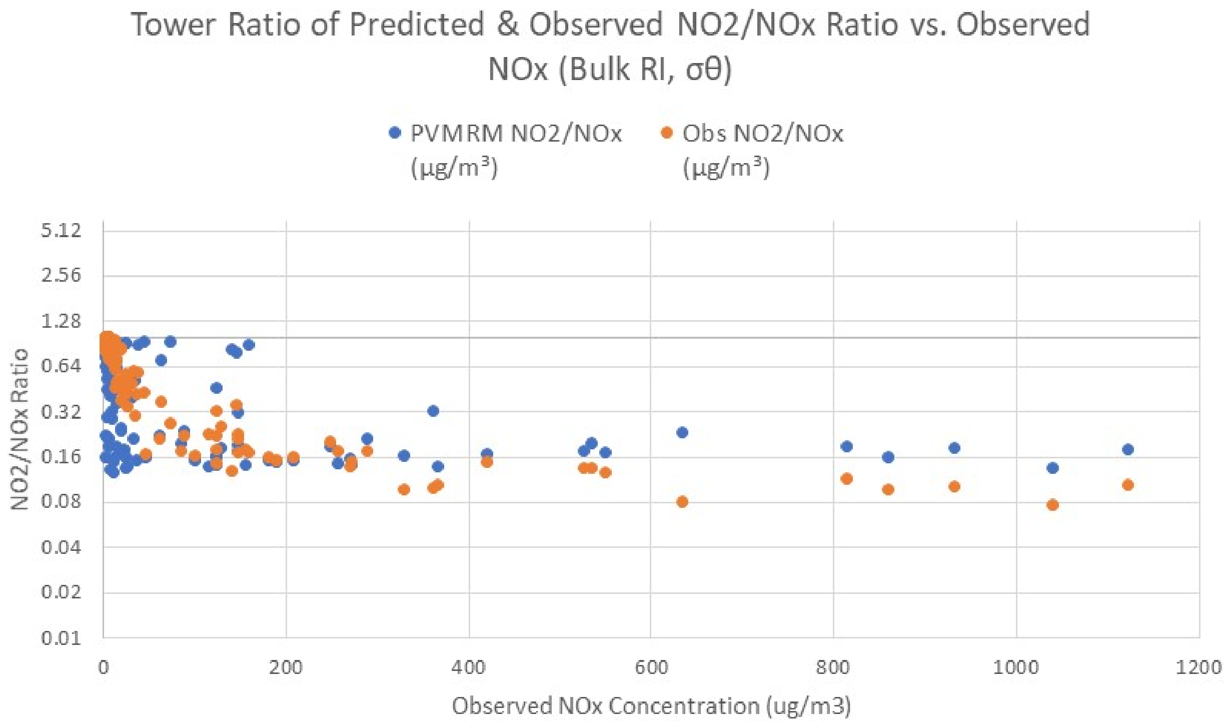


ARM2 + TTRM

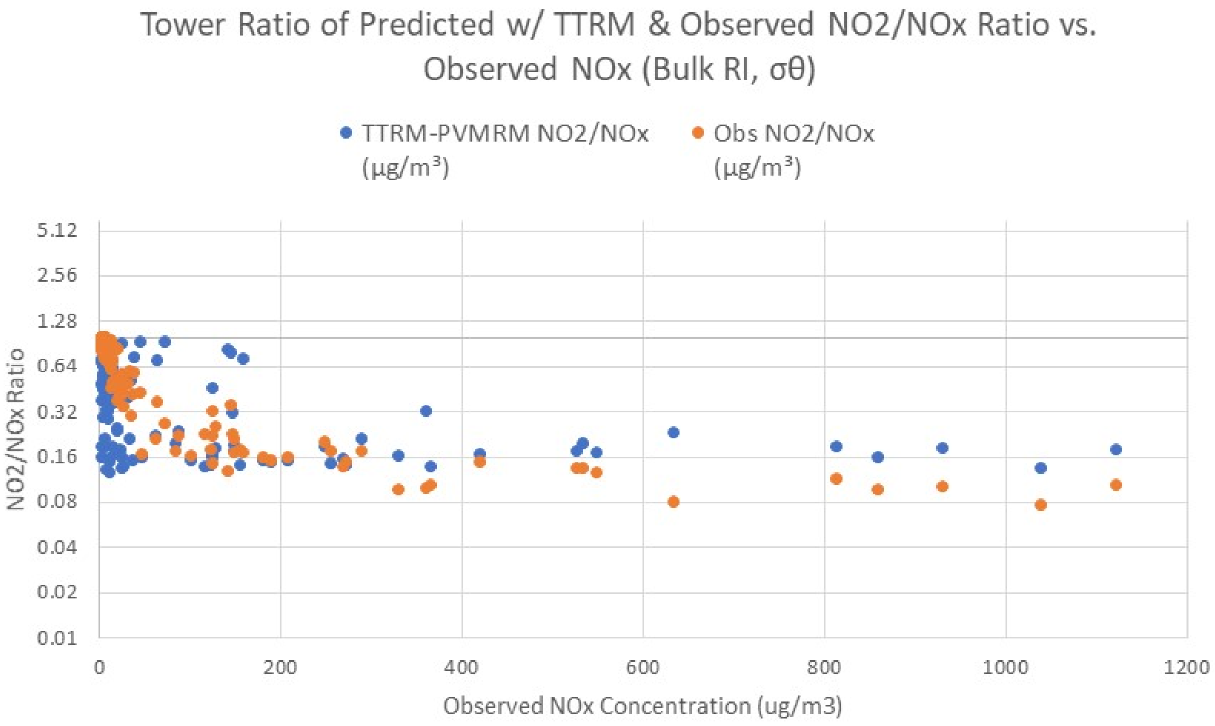


Tower: NO_2/NOx Ratio vs. NOx for PVMRM and PVMRM + TTRM

PVMRM



PVMRM + TTRM



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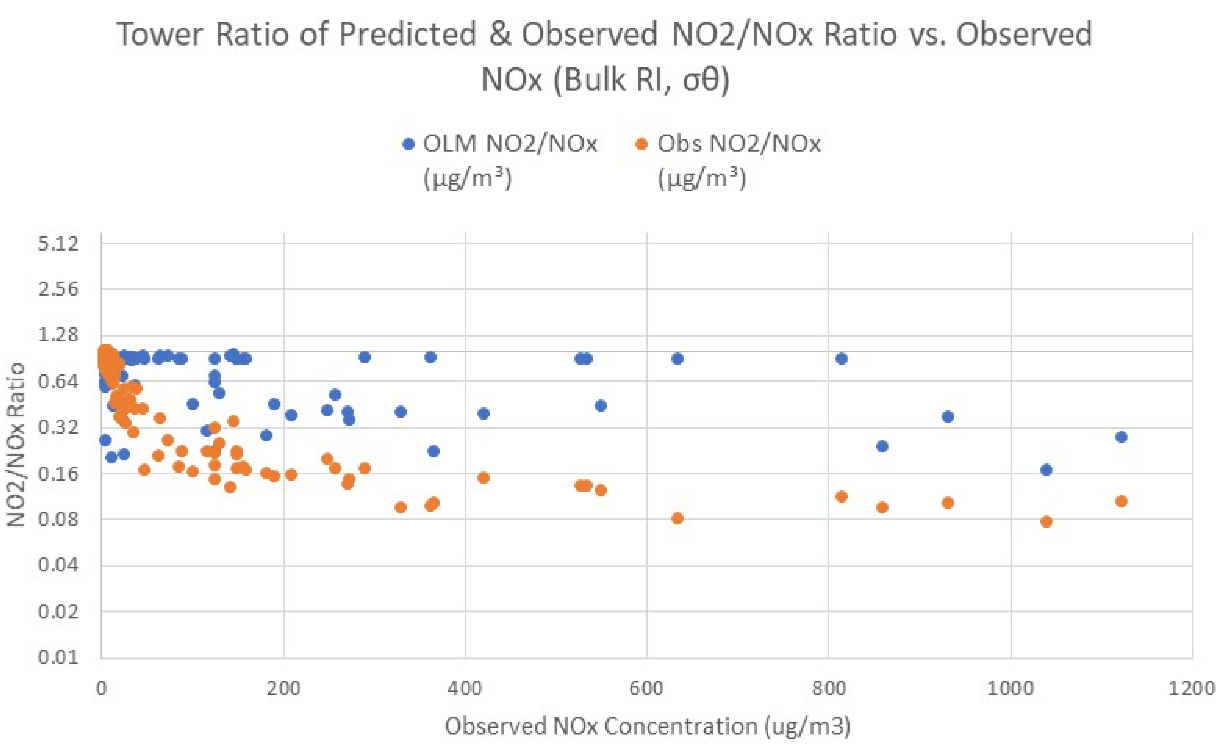
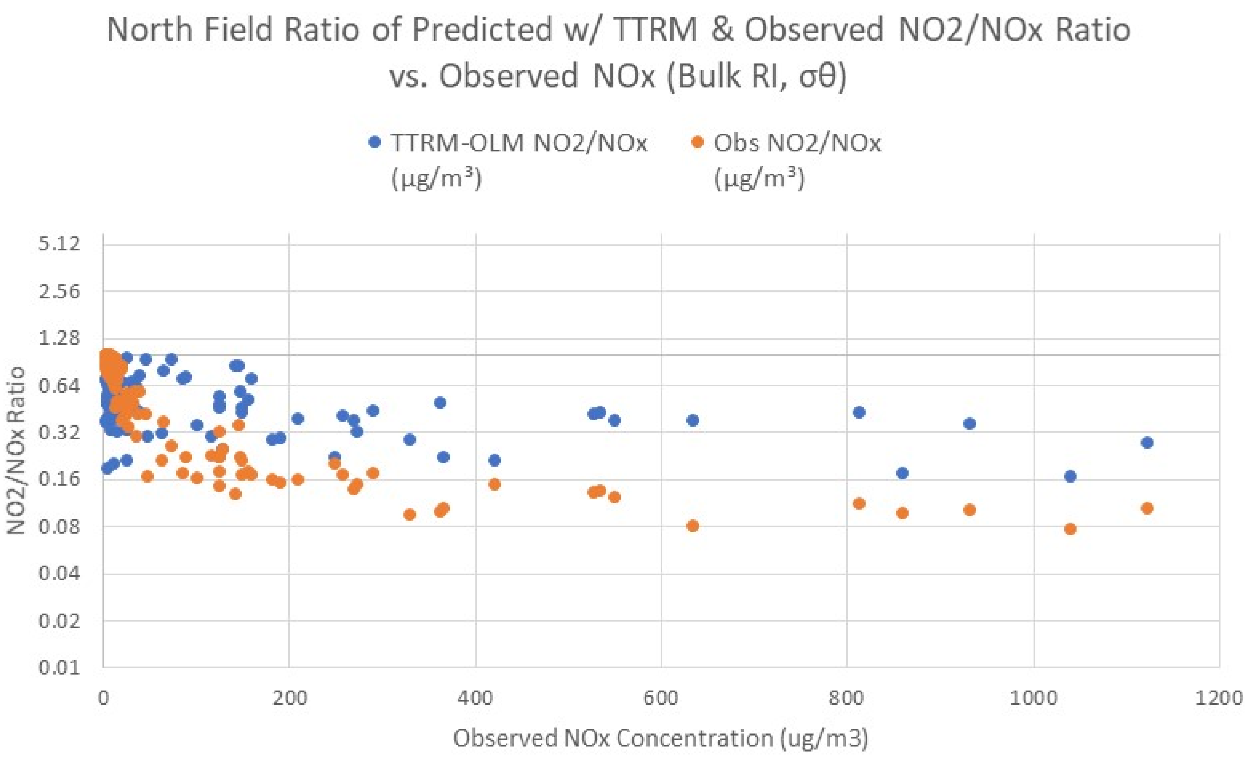
Tower: NO_2/NOx Ratio vs. NOx for OLM and OLM + TTRM

OLM



OLM + TTRM



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