Development of Aviation Air Quality Tools for Airport-Specific Impact Assessment Project 19

Lead investigator: Saravanan Arunachalam, UNC-Chapel Hill
Project manager: Mohammed Majeed, FAA

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Project 019

Development of Aviation Air Quality Tools for Airport-Specific Impact Assessment

University of North Carolina at Chapel Hill

PI: Saravanan Arunachalam

PM: Mohammed Majeed

Cost Share Partner(s): LAWA, EDF, EU-AVIATOR, Barr Foundation

Objective:

- Develop a new aircraft dispersion model (ADM) for assessing local air quality due to aircraft sources during landing and take-off (LTO) cycles.

Project Benefits:

- Improved characterization of air quality due to aircraft sources in the vicinity of the airport
- Directly feeds into AEDT development
- Support for NEPA Analyses and HIA studies
- Enhances EPA's AERMOD Regulatory model
- Inputs for ICAO-CAEP Impact Science Group (ISG)

Research Approach:

Focus on 3 key aspects of LAQ Modeling

- Source characterization
- Physical Processes
- Chemical Processes

Develop a series of options for testing and implementing in a 2-year timeline

- Prototype and preliminary evaluation at LAX for Winter and Summer 2012
- Apply to other case studies in the US and EU

Major Accomplishments (to date):

- Gridded ADM developed and evaluated against LAX
- Identified roles of meteorology, plume rise, and meander in aircraft dispersion
- New AEDT2ADM emissions processor developed
- Role of meteorology in aircraft plume dispersion published
- Aircraft plume rise algorithm published, implemented into AERMOD's source code, released as an ALPHA option in AERMODv23132 by EPA
- Aircraft plume rise evaluation and AREA source meander published
- Aircraft plume rise algorithm is updated and evaluated against LAX and BOS
- Draft manuscripts prepared focusing on (a) Aircraft plume rise, (b) ADM chemistry, (c) effect of aircraft source characterization in AERMOD, and (d) ADM development

Future Work / Schedule:

- Finalize and publish refined AERMOD Plume Rise algorithm (Winter 2025)
- Continue evaluation for LAX2012 and BOS Summer'24 season (Winter 2025)
- Continue evaluation for BOS Winter'24 season (Spring 2026)
- Implement chemical conversion (Winter 2025)
- Finalize v1 of ADM for FAA (Spring 2026)

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Introduction

- Motivation
  - Airports need a dispersion modeling system that incorporates all physical and chemical processes related to LAQ (Local Air Quality) around airports
- Known limitations in AERMOD *(Arunachalam et al, 2017; ACRP Report 179)*
  - Identified issues related to:
    - Source representation: area vs. volume vs. line *(Pandey et al., AQAH 2024)*
    - Lack of AREA source meander *(Venkatram et al., JA&WMA 2024)*
    - Lack of plume rise for hot buoyant plumes *(Pandey et al., Atmos. Environ. 2023)* *(Pandey et al., JA&WMA 2024)*
    - Shoreline effects for marine boundary layer *(Pandey et al., Atmos. Environ. 2022)*
    - Limited treatment of chemistry *(Huy et al., 2025, In Prep)*
    - Time Scale – Sub-Hourly Approach
- Objectives – long term, short term
  - To develop an improved aircraft dispersion model that addresses the above issues for U.S. regulatory compliance purposes *(Pandey et al, 2025, In Prep)*
  - To enhance the aircraft plume rise algorithm within AERMOD and evaluate against LAX-2012 and BOS-2024 studies *(Pandey et al, 2025, In Prep)*

Enhancement in AERMOD dispersion modeling

- Enhancement in AERMOD aircraft plume rise feature for conversion from ALPHA to BETA* designation
  - Modify the algorithm to reflect real-world conditions better and re-implement within AERMOD
  - Validate these enhancements using the LAX airport study as well as the BOS airport study
  - Detailed modeled vs observed evaluation using EPA-recommended statistics
- To better understand the contribution of surface vs. airborne emissions to local air quality using AERMOD
  - Performed a detailed analysis using the LAX airport study
  - Performed an analysis by reducing the number of sources at the surface to see the effect on model performance at LAX airport
- Enhance AERMOD for NO_2 modeling
  - Implemented the GRS7 scheme that better handles the VOC emissions

* ALPHA and BETA are specific designations for EPA regulatory models

Aircraft Plume Rise Algorithm (AERMOD: Updated Algorithm)

Buoyancy parameter

$$Fo = \frac{g}{T_a}\frac{Q_e}{U_p}\frac{1}{\pi\rho_e C_p}$$

where;
g = Acceleration due to gravity, Q_e = Heat rejection (from energy balance)*,
T_a = Ambient temperature, U_p = Exhaust velocity,
ρ_e = density of the exhaust, C_p = Specific heat.

Plume rise due to buoyancy, z_p, is governed by

$$\frac{dz_p}{dt} = w_p$$

**where w_p is the buoyancy-induced vertical velocity given by, combining the momentum and energy balances on the plume element.

$$\frac{d}{dt}\left(r^2 w_p\right) = Fo$$

**Radius of plume r grows through the combined effect of shear between the rising plume and the surrounding air and atmospheric turbulence

$$\frac{dr}{dt} = \beta w_p + \sigma_w$$

where $\beta = 0.6$ is an entrainment constant, and σ_w is standard deviation of vertical velocity fluctuations of surrounding atmosphere.

The maximum height of the plume is limited by the height of the boundary layer. During stable conditions, plume rise is limited by the stable potential temperature gradient.

**The radius of the plume grows in response to the effects of both horizontal motion caused by exhaust momentum and the vertical motion caused by buoyancy.

*Note: Calculation of heat rejection is categorized in two ways, one for turbine-based engines and the second for piston-based engines.

***Once the exhaust plume leaves the engine, it is treated in a frame of reference fixed to a stationary observer.

Aircraft Plume Rise Algorithm (AERMOD)

Comparison of existing and new aircraft plume rise algorithm

Feature	Existing Algorithm (AERMODv24142) (Old) - As published in Pandey et al, 2024	Updated Algorithm (AERMODv24142_v1) (New) - Revisions since then for BETA
Plume Rise Modules	Uses a semi-empirical model based on separate, pre-defined equations for stable (ASBLRIS) and unstable (ACBLPRD, ACBLPRN, ACBLPR3) conditions.	Uses a Lagrangian plume trajectory model for both stable and unstable conditions (PLUME_TRAJ subroutine). It simulates the plume rise step by step as it moves downwind.
Momentum Plume Rise	Integrates momentum plume rise as a separate MOMENTUM_PLUMERISE subroutine and then adds it to the buoyancy rise calculation in ASBLRIS and ACBLPRD.	Explicitly separates momentum and buoyancy plume rise in the PLUME_TRAJ subroutine. It integrates the contributions of both to determine the final plume trajectory.
Buoyancy Flux (Fb)	AFLUXES subroutine calculates buoyancy flux without dividing the exhaust velocity.	AFLUXES subroutine calculates the buoyancy flux based on heat rejection (QEE) and exhaust velocity (VE), also by dividing the exhaust velocity.
Source Angle/Airborne Sources	Explicitly calculates a horizontal displacement HDISP for airborne sources based on a source angle, which is then used to adjust the final plume rise. This suggests an attempt to model the initial trajectory more accurately for airborne releases.	Using the same approach as surface sources, not using the source angle.
Computational Method	Uses analytical equations for plume rise, which are simpler and faster to compute. For unstable conditions, it uses Weil's (1993) model for direct, indirect, and penetrated plumes.	Uses a numerical integration in PLUME_TRAJ to simulate the plume's evolution over a downwind distance. This is computationally more intensive but offers greater flexibility.

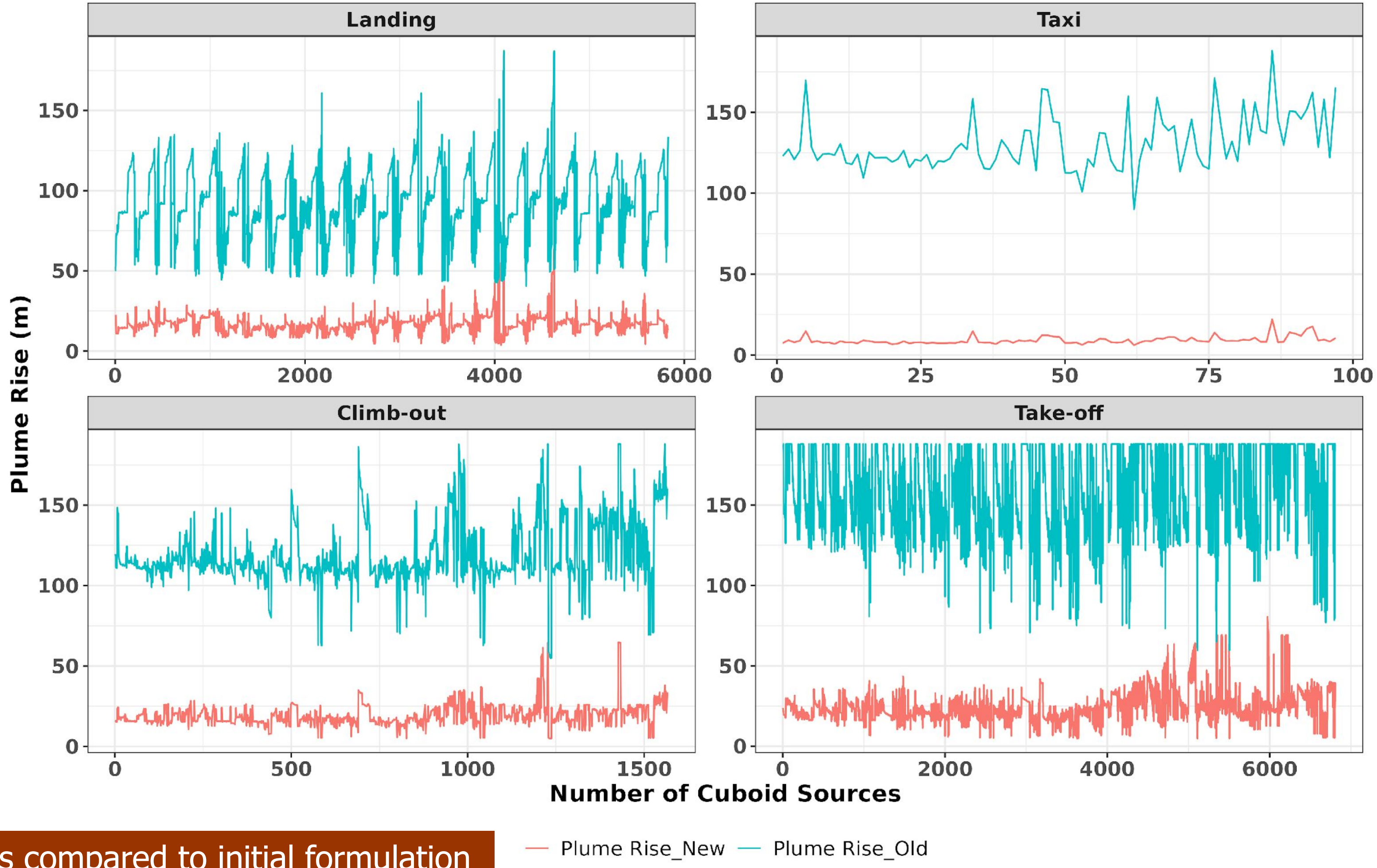
Aircraft Plume Rise Algorithm (AERMOD)

Plume Rise values for each mode

Here, for a single met condition, plume rise is calculated for different combinations of engine parameters

Meteorological variables:

Wind Speed = 3.5 m/s
Temp = 298.15 K
Zo (Surface Roughness) = 0.03 m
Monin-Obukhov Length = 100 m
U* (Surface Friction Velocity) = 0.5 m/s
Zi (Mixing Height) = 200 m



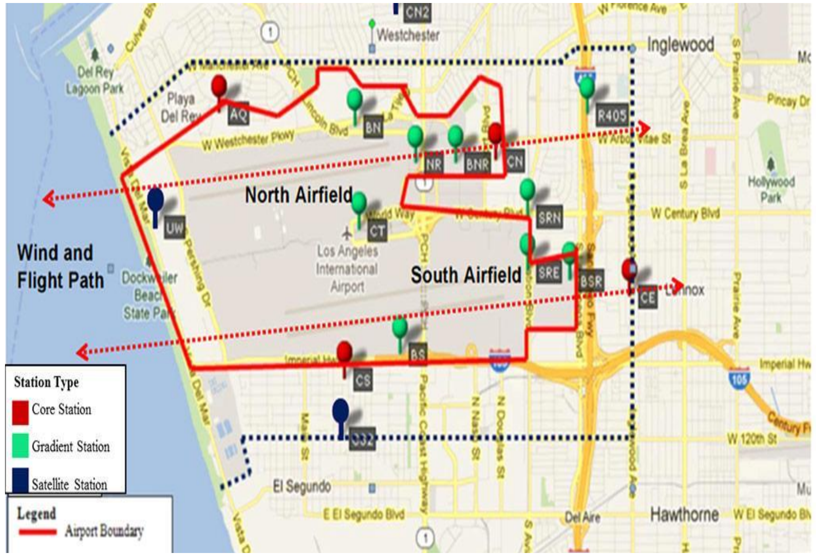
Updated/New plume rise values are significantly less compared to initial formulation

Aircraft Plume Rise Algorithm (AERMOD Evaluation: LAX and BOS)

- SO_2 concentrations in the vicinity of the airport are dominated by aircraft emissions (given fuel S content)
- AERMOD is evaluated with
  - SO_2 and NO_x measurements from the LAWA study conducted during 2012 at the AQ, CN, CS, and CE monitors; and the Boston (BOS) study conducted during 2024 at Revere, Saratoga, and Evans sites are shown in the figures
  - Observed and modeled concentrations are also analyzed in hourly time bins as well as the wind direction bins

LAX Study 2012

Los Angeles International Airport



Pandey et al, Atmos. Environ., 2022; Arunachalam el at. 2017, ACRP report 179

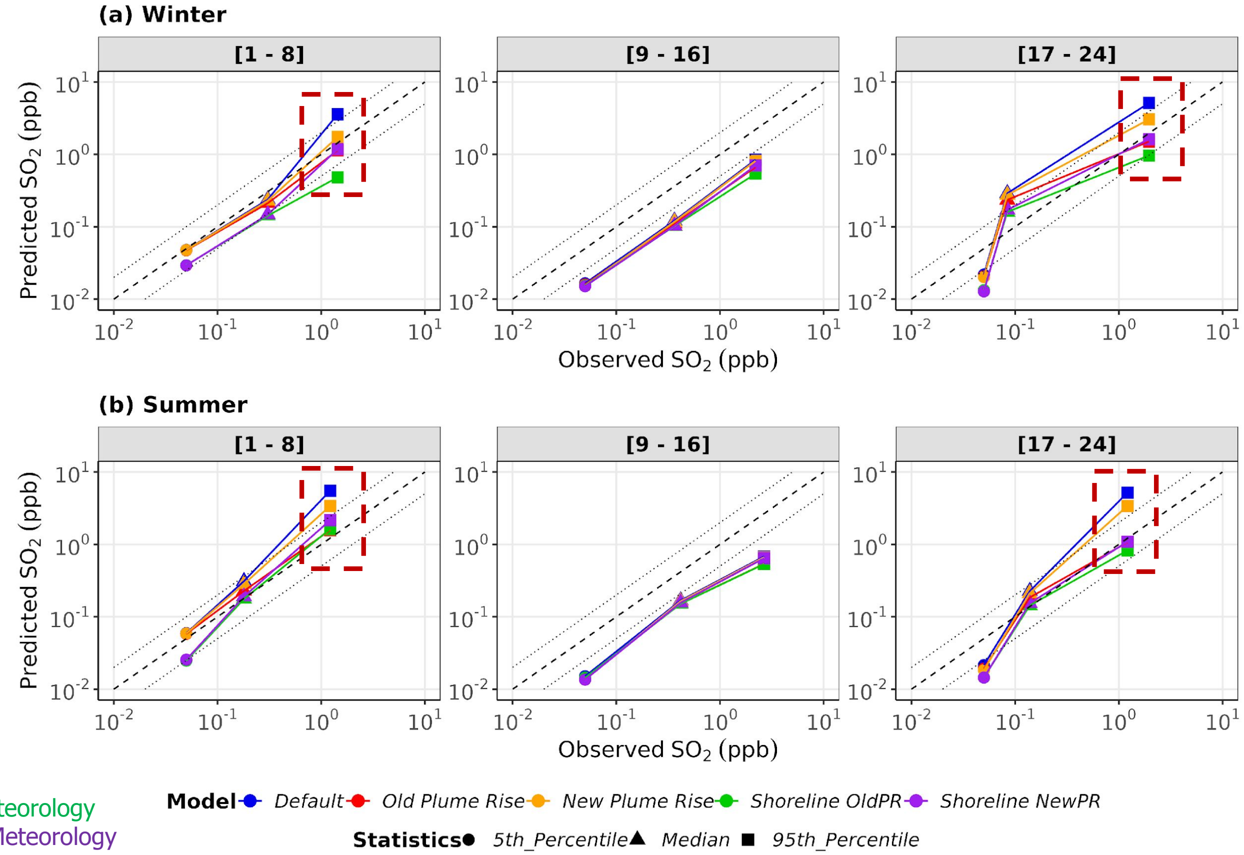
BOS Study 2024

Boston Logan International Airport

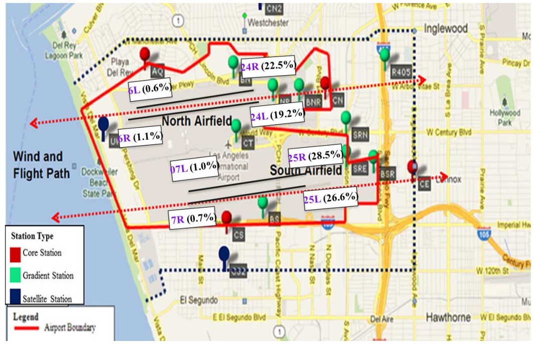
Pandey et al, 2025 (In Prep)

Aircraft Plume Rise Algorithm (AERMOD Evaluation: LAX)

Hourly time bins



PR: Plume Rise
Default: AERMOD without PR
Old Plume Rise: AERMOD with Old PR
New Plume Rise: AERMOD with New PR
Shoreline OldPR: Old Plume Rise with Shoreline Meteorology
Shoreline NewPR: New Plume Rise with Shoreline Meteorology



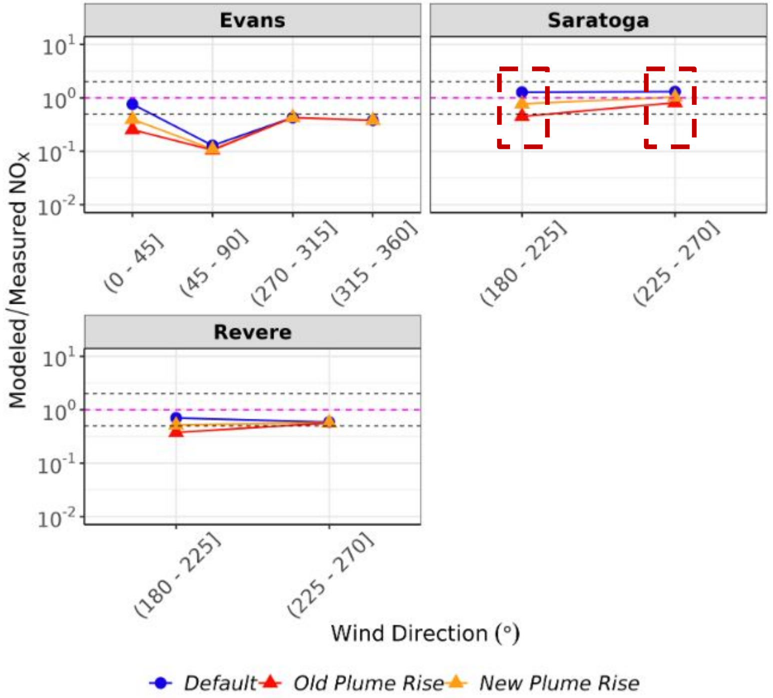
Distributions of measured concentration distributions compared with modeled values. Concentrations correspond to values combined from all four sites.

Early morning (1 – 8) and late evening (17 – 24) hourly concentrations improved significantly in both seasons, whereas the daytime (9 – 16) bin still driven with daytime shoreline meteorology (neutral met can improve it); All scenarios underpredict daytime concentrations

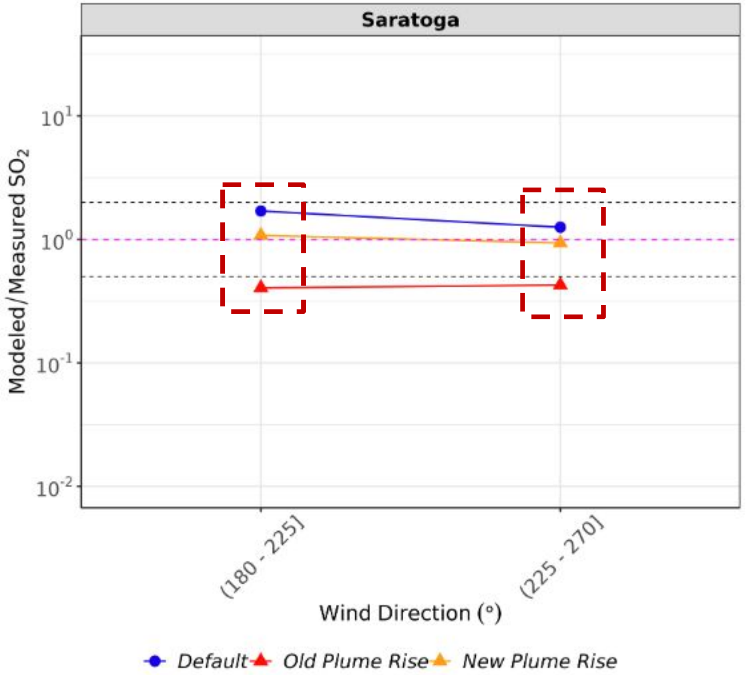
Aircraft Plume Rise Algorithm (AERMOD Evaluation: BOS)

Wind direction bins

NOx



SO_2



PR: Plume Rise
Default: AERMOD without PR
Old Plume Rise: AERMOD with Old PR
New Plume Rise: AERMOD with New PR

Ratio of modeled to measured NO_X and SO_2 concentrations averaged over wind direction bins

Predictions during airport-related wind direction bins are significantly improved, especially for SO_2

*Next slide onwards: Implementation of GRS7 in AERMOD

Implementation of GRS7 NO_2 chemistry in AERMOD

GRSM

$$NO_2 + h\nu \xrightarrow{O_2} NO + O_3$$

$$NO + O_3 \rightarrow NO_2$$

AERMOD currently includes only 2 reactions

GRS7

$$ROC + h\nu \xrightarrow{O_2} RP + ROC \quad (1)$$

$$RP + NO \rightarrow NO_2 \quad (2)$$

$$NO_2 + h\nu \xrightarrow{O_2} NO + O_3 \quad (3)$$

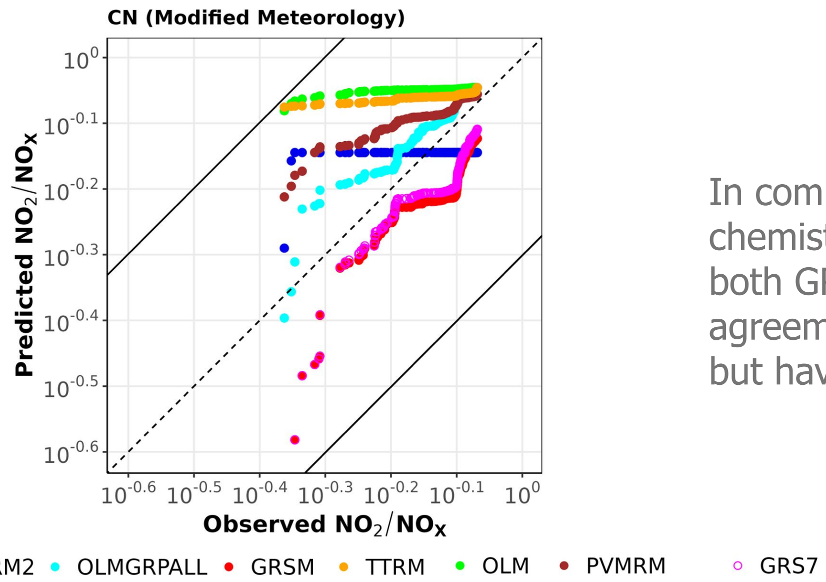
$$NO + O_3 \rightarrow NO_2 \quad (4)$$

$$RP + RP \rightarrow RP \quad (5)$$

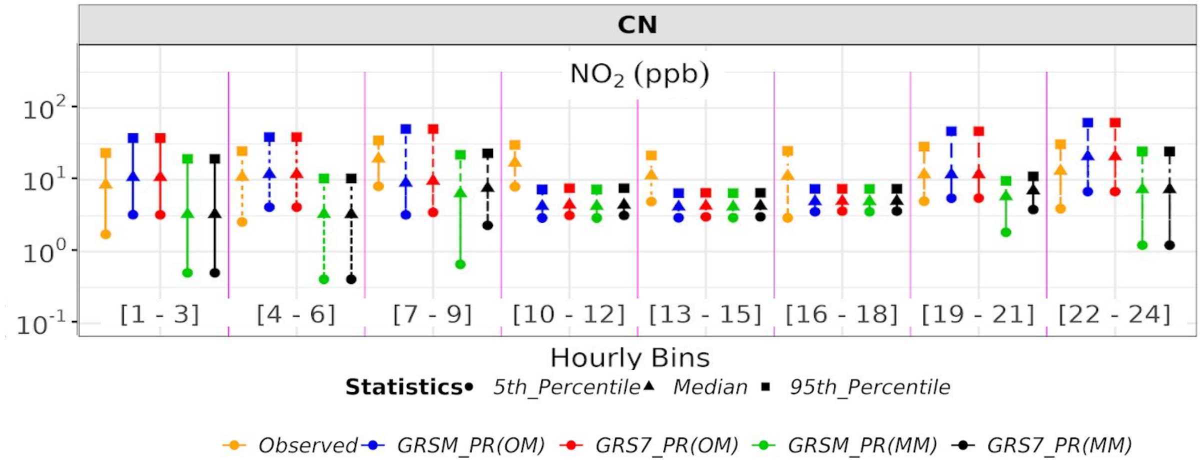
$$RP + NO_2 \rightarrow SGN \quad (6)$$

$$RP + NO_2 \rightarrow SNGN \quad (7)$$

Enhanced approach



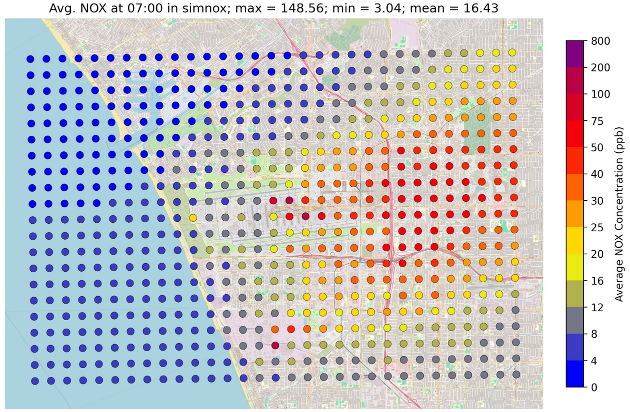
In comparison to performances of simpler chemistry options (ARM2, OLM, TTRM), both GRSM and GRS7 have better agreement with observed NO_2/NO_X ratio but have weaker performance for NO_2.



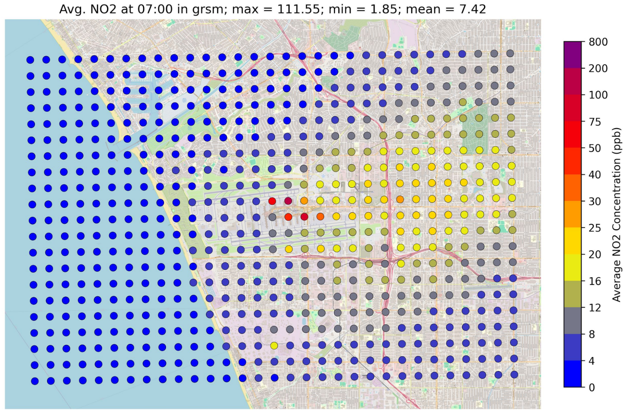
- Differences between GRS7 vs. GRSM are largest in the morning hours (7 – 9 am local time), which is also when observed NO_2 is highest
- During these hours, background O_3 is still low, and so VOCs' role in NO_X photolysis cycle becomes important

Simulated NO_2 GRSM vs. GRS7 (AERMOD)

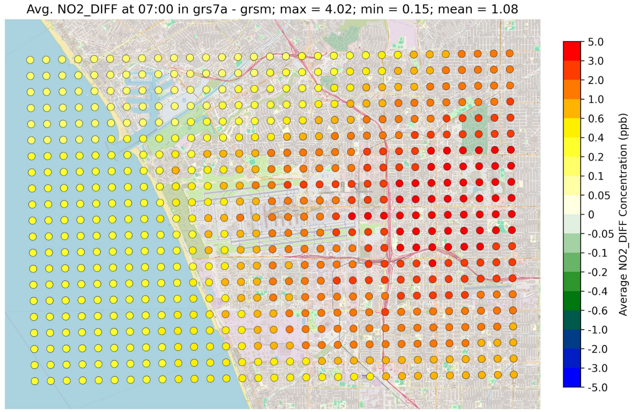
Simulated NOx



Simulated NO_2 with GRSM



Sim. NO_2 diff.: GRS7 - GRSM



Marginal difference in simulated NO_2 between GRSM and GRS7 are attributed to close distance between receptors and emission sources)

- In AERMOD simulation over 10 km x 15 km receptor grids, differences in simulated NO_2 between GRS7 and GRSM are larger at distances > 3 km from the center of LAX (eastward of I-405)
- Largest NO_2 is typically simulated at LAX's terminals and runway, which, because of short chemistry age, are not where the largest NO_2 differences were simulated.
- These findings confirm the importance of age in NO_X chemistry.
- The impact of VOC on NO_X-to-NO_2 conversion becomes larger if enough time is given for chemical reactions to take place.

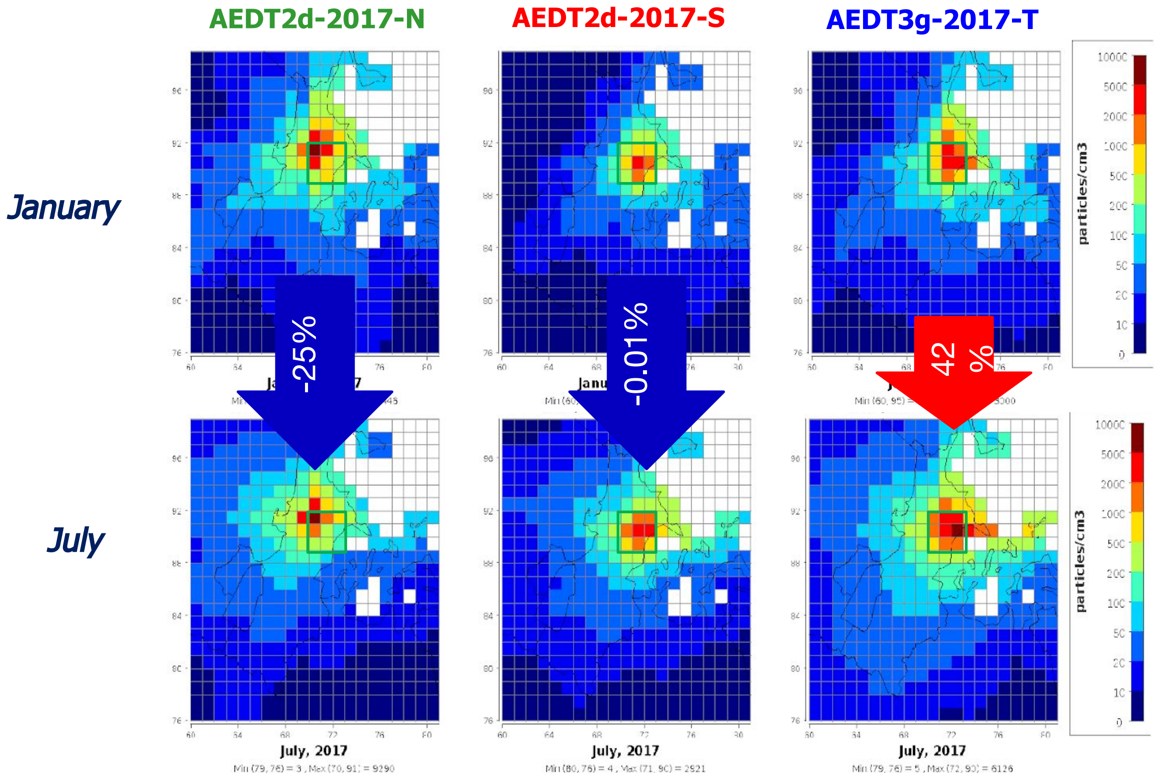
Travel time at each monitoring station (in hours)

Station	Average	Median	95th percentile	Maximum
CE2	1.66	1.48	3.39	4.97
CE	0.36	0.27	0.97	1.83
CS	0.72	0.53	2.09	3.63
CN	0.37	0.25	1.08	2.30
AQ	0.76	0.48	2.24	4.46

*Next slide onwards: CMAQ Boston Airport UFP study

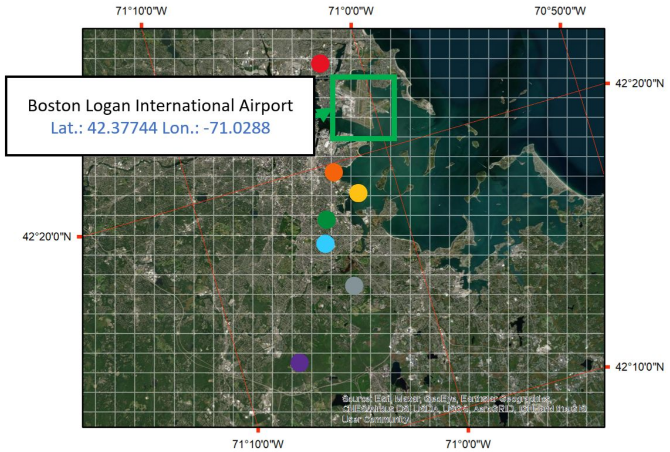
Boston Airport UFP Study (CMAQ)

- Seasonal KBOS contribution to UFP ($\Delta C_{AAC} = C_{KBOS} - C_{NoKBOS}$)



UFPNC monthly contribution of KBOS with 3 scenarios during Jan (top) and July (bottom) 2017

ΔC_{AAC} = Airport Absolute Contribution (monthly mean)
C_{KBOS} = Concentration of KBOS emissions from different Aircraft Emission Inventories
C_{NoKBOS} = Concentration of no KBOS emissions (Background concentration)



- CMAQ modeling at high resolution of 1.3 km^2
- Aircraft-specific aerosol size distribution treatment
  GMDSD (Geometric Mean Diameter and Standard Deviation) *(Moore et al., 2017)*

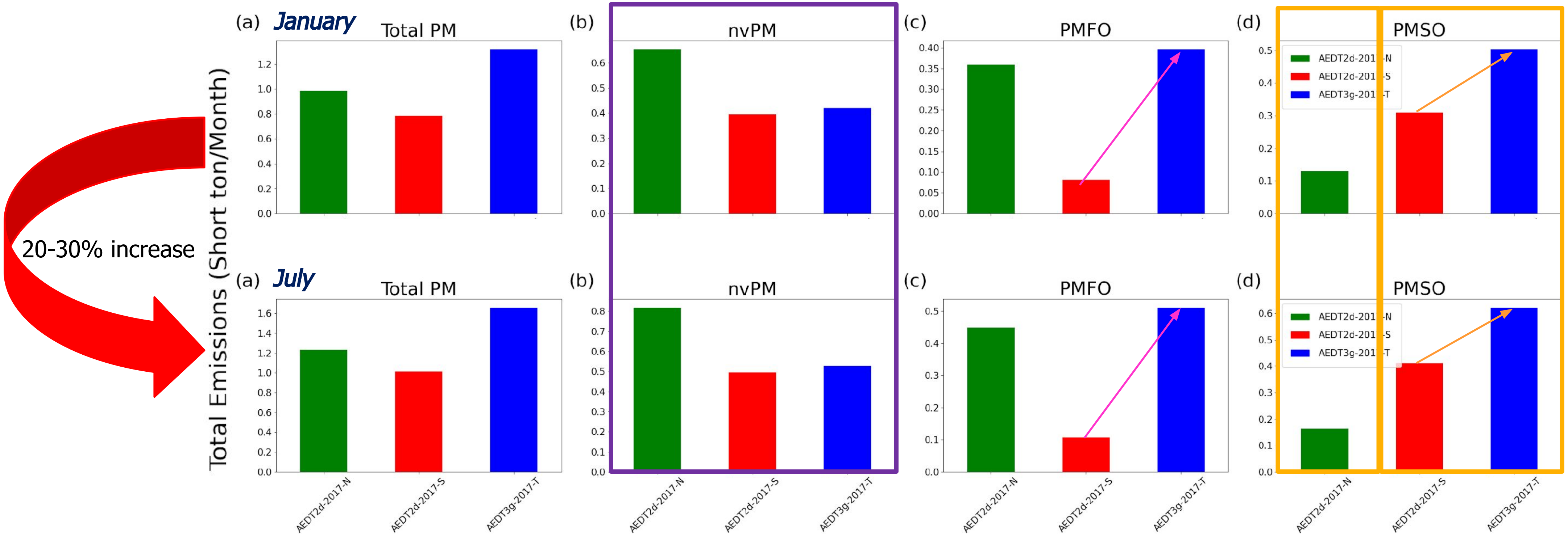
Emissions scenarios

AEDT2d-2017-N: 2017 NEI with KBOS
AEDT2d-2017-S: Straight-line Segment data by Volpe
AEDT3g-2017-T: Threaded Tract (TT) data

AEDT2d-2017-N: UFP decreases by 3,160 #/cm^3 (25%) in July, despite higher total PM emissions (more flights as well), compared to January
AEDT2d-2017-S: Little UFP seasonal difference (21 #/cm^3) (0.01%)
AEDT3g-2017-T: UFP increases by 3,130 #/cm^3 (42%) in July compared to January
☐ Seasonal differences likely attributed to differing rates in **Nucleation Particle Formation (NPF) & PM emission composition (next slide*)**

Boston Airport UFP Study (CMAQ)

- Seasonal differences attributed to PM composition in Emission Inventories



- Non-volatile PM (nvPM) is generated at the source, such as engine exhaust
- Volatile PM (vPM) is generated through gas-to-particle conversion (nucleation) and condensation on nvPM

January: UFP driven mainly by nvPM
July: UFP enhanced by Volatile Organic PM (**PMFO**) and Volatile Sulfate PM (**PMSO**)

AEDT3g-2017-T has higher PMFO and PMSO than **AEDT2d-2017-S** with Similar nvPM ☐ ~42% more UFP in July
AEDT2d-2017-N shows low UFP in July (low PMSO), indicating PMSO more influential than PMFO☐ vPM plays a significant role in UPF in July, compared to January

Summary

AERMOD

- Significant and sustained interactions with the EPA to convert the aircraft plume rise option from ALPHA to BETA
- Ongoing work to make plume rise algorithm more realistic
- Evaluated the updated plume rise algorithm for LAX (winter and summer) and BOS (summer/spring) airports
- Ongoing work to repeat evaluation at Boston airport for summer '24 and spring '25 periods, including running AEDT
- Evaluate the GRS7 scheme for LAX/BOS Airport (3 – 4 Months)

ADM

- Initial versions of ADM and GADM previously developed, but paused given focus on AERMOD implementation
- But ongoing evaluation shows scope for further improvement in the Gridded ADM structure for source characterization
- Started implementing chemical conversions based on the Generic Reaction Set (GRS) and Travel Time Reaction Methods (TTRM) mechanism (6 – 9 Months)
- Continue evaluation at LAX and additional airports such as BOS or other (CLE?) (3 – 4 Months)
- Finalize and submit multiple research articles (4 identified so far) (6 – 12 Months)

CMAQ

- Continued assessment of UFP using models and measurements at Boston Logan

Publications

- Publication of shoreline effects of meteorology, plume rise algorithm, source characterization, plume rise evaluation, and area source meander (Pandey et al, 2022 (AE); 2023 (AE); 2024 (AQAH), 2024 (JA&WMA); and Venkatram et al, 2024 (JA&WMA))

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- UNC Institute for the Environment
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  - H. Kim, Ph.D. Student
- University of California at Riverside
  - Akula Venkatram, UC Riverside (Consultant)

Other Collaborations

- EPA
  - Continued engagement with the EPA during model development, especially to move the plume rise in AERMOD as a BETA/Regulatory option, leading to the Appendix W Update
- EU-AVIATOR
  - Engagement re ongoing field studies for future ADM evaluation
- FAA Volpe Center
  - Revisions to AEDT and AEDT modeling for the Boston study
- Boston University (ASCENT NOI 18)
  - Evaluation of observations from ongoing field study at Boston Logan
  - Scoping of drone-based AQ measurements at Boston Logan for pilot study

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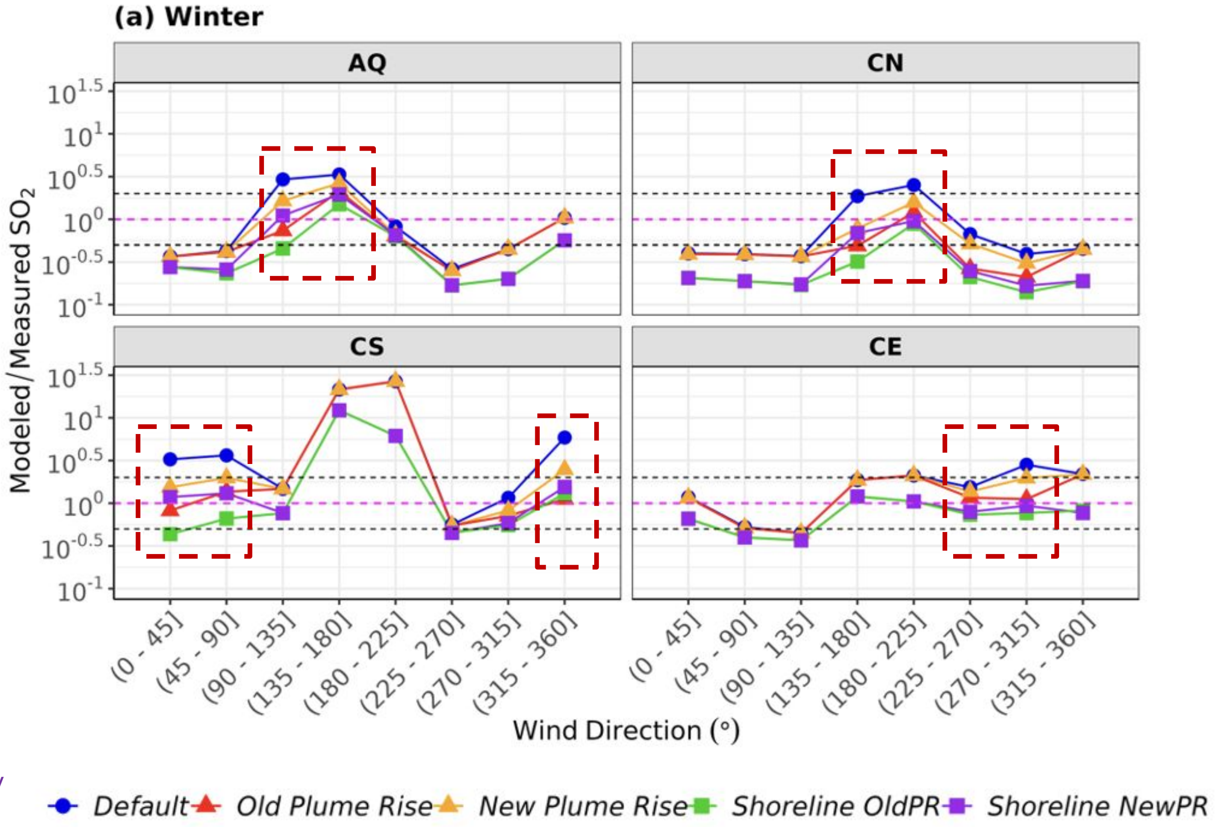
Aircraft Plume Rise Algorithm (AERMOD Evaluation: LAX)

Wind direction bins



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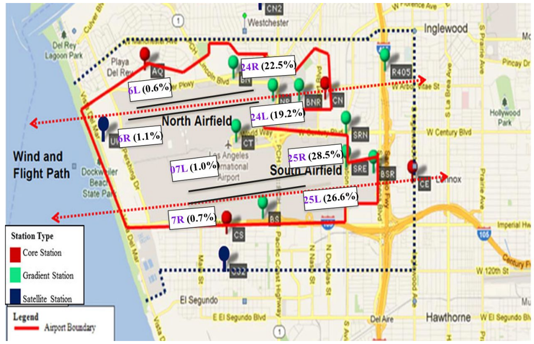
New Plume Rise: AERMOD with New PR
Shoreline OldPR: Old Plume Rise with Shoreline Meteorology
Shoreline NewPR: New Plume Rise with Shoreline Meteorology



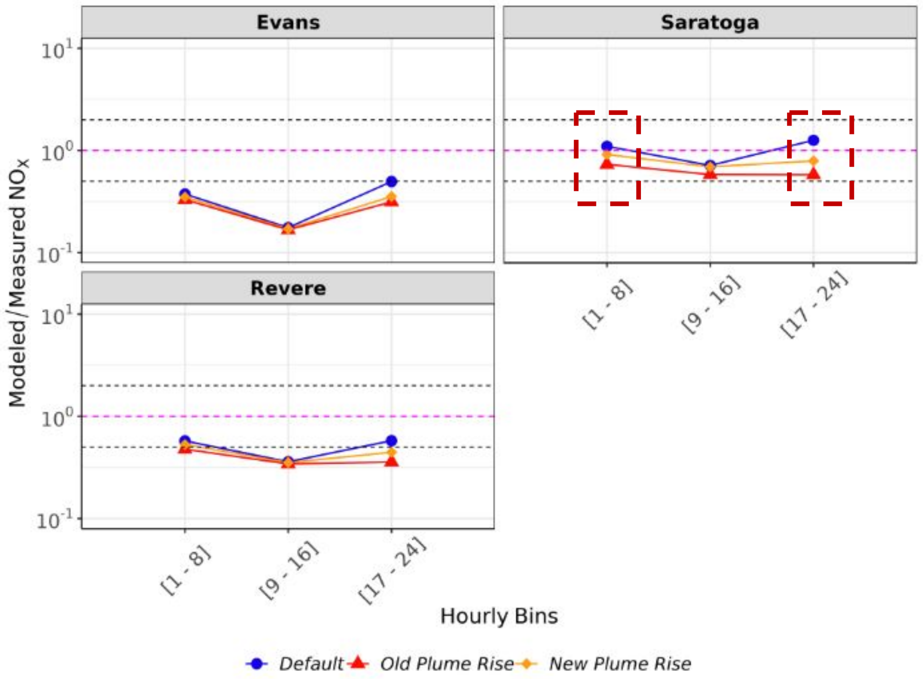
Ratio of modeled to measured SO_2 concentrations averaged over wind-direction bins at the four sites (AQ, CN, CS, and CE) during winter season

Concentrations with the new plume rise and shoreline met are better predicted in airport-related wind direction bins

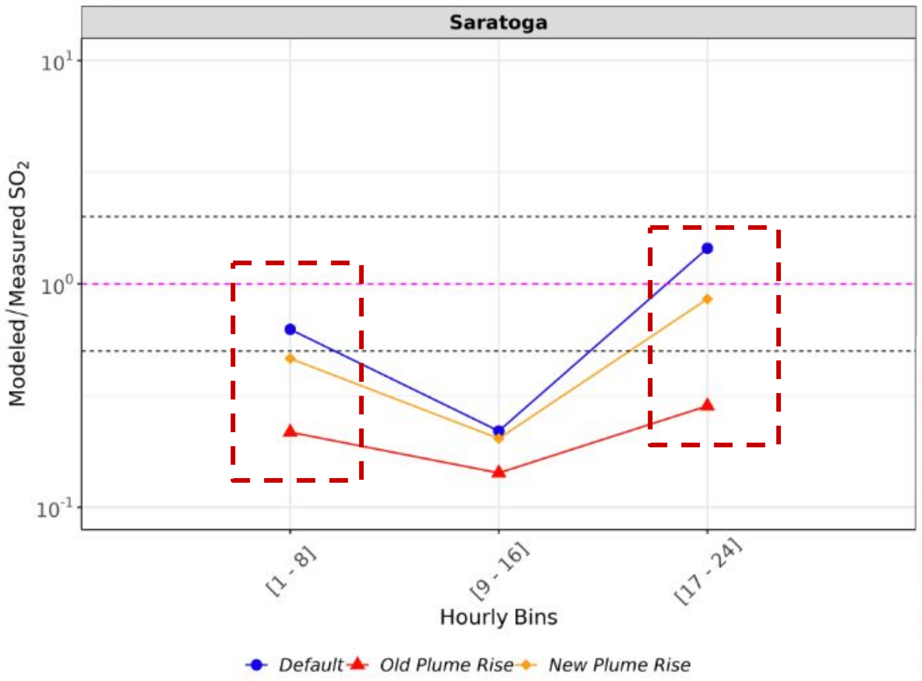
Aircraft Plume Rise Algorithm (AERMOD Evaluation: BOS)

Hourly time bins

NOx



SO_2



PR: Plume Rise
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New Plume Rise: AERMOD with New PR

Ratio of modeled to measured NO_X and SO_2 concentrations averaged over hourly time bins

Early morning (1 – 8) and late evening (17 – 24) hourly predictions are improved slightly, but more improvement can be seen during hours when sites directly impacted by aircraft activity