ASCENT Project 019

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

University of North Carolina at Chapel Hill

PI: Sarav Arunachalam

PM: Jeetendra Upadhyay

Cost Share Partner: LAWA, EDF, EU-AVIATOR

Objective:

- Develop new aircraft dispersion model (ADM) for assessing local air quality due to aircraft sources during 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 Impacts 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):

- ADM Prototype developed, evaluated against LAX
- Identified roles of meteorology, plume rise, and meander in aircraft dispersion
- New AEDT2ADM emissions processor developed
- Draft manuscripts prepared focusing on (a) role of meteorology in aircraft plume dispersion, and (b) effect of aircraft source characterization in AERMOD
- Plume rise algorithm finalized, and ongoing work to add this into AERMOD's Area source treatment

Future Work / Schedule:

- Continue evaluation for LAX Summer 2012 (Summer 2022)
- Implement chemical conversion (Fall 2022)
- Evaluate at other airports (Spring 2023)
- Finalize v1 of ADM for FAA (Fall 2023)

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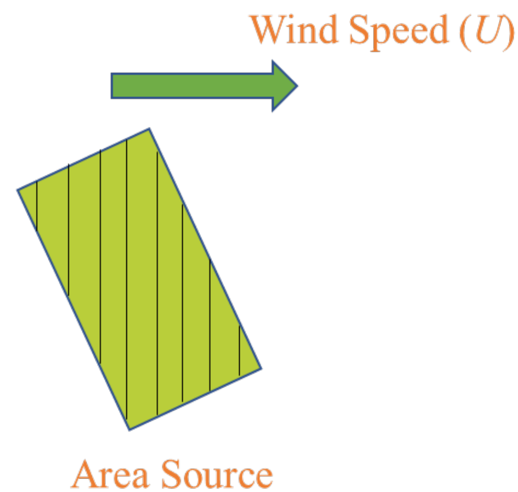
Treatment of Surface Area Sources

- Each area source is a modeled as a set of line sources, perpendicular to the wind. Number of line sources is increased until successive contribution of the area source to a receptor is within a specified error
- Vertical dispersion is modeled with the numerical solution of

$$u(z)\frac{\partial C}{\partial x} = \frac{\partial}{\partial z}\left(K\frac{\partial C}{\partial z}\right)$$



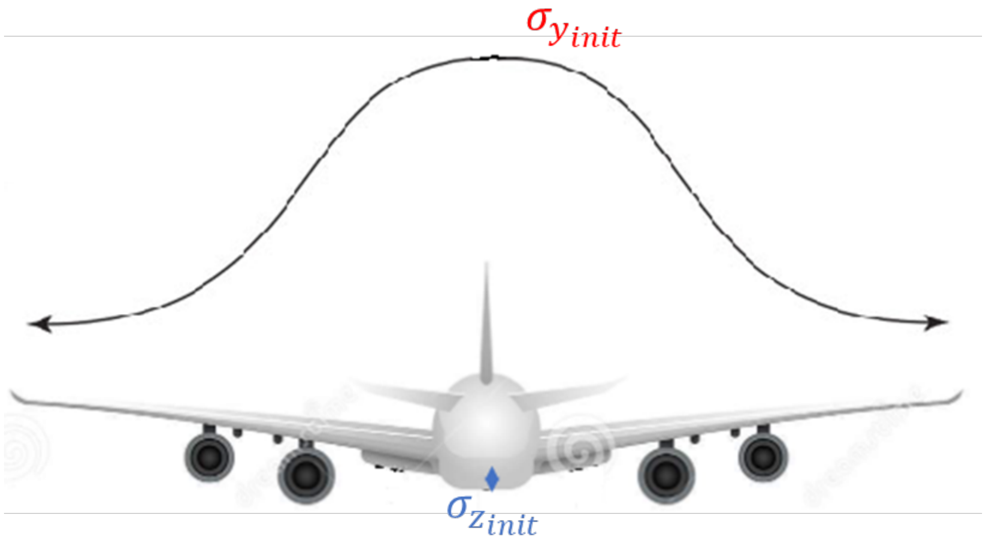
1. Provides excellent description of near surface releases
2. Avoids assumption of Gaussian vertical distribution
3. Eddy diffusivity can be adjusted to account for buoyancy induced mixing

- Horizontal Contribution of each line source treated analytically with horizontal dispersion as *(Venkatram and Horst, 2006)*,

$$\sigma_y = \sigma_v t$$

Treatment of Airborne Sources

- Airborne sources at each layer (total 9 different layers from 0 to 914 m) treated as volume sources with initial horizontal plume ($\sigma_{yinit} = 20\ m$) corresponding to aircraft wingspan, initial vertical plume ($\sigma_{zinit} = 5m$) and buoyancy



- Horizontal and vertical dispersion parameters similar to AERMOD for elevated point releases

Treatment of Plume Rise for Aircraft Source

Plume Rise associated with buoyancy using the formulation applicable to point releases in a neutral atmosphere

$$h_{pb} = \left[\left(\frac{r_0}{\beta} \right)^3 + \frac{3}{2\beta^2} \frac{F_b}{U} t^2 \right]^{1/3} - \left(\frac{r_0}{\beta} \right) \tag{1}$$

r_0 = Initial plume radius,

β = 0.6 (Entrainment Coefficient),

F_b = Buoyancy parameter,

$t = \frac{x_{eff}}{U_{eff}}$,

x_{eff} = Effective distance between area source and receptor

U_{eff} = Effective Wind Speed

Computation of Horizontal Jet Momentum

Plume rise associated with horizontal momentum, h_{pm} is taken to be the radius of the plume

$$
\begin{aligned}
h_{pm} &= r_0 + \alpha x \quad && x \le x_m \\
&= r_m && x > x_m
\end{aligned}
\tag{2}
$$

where x_m is the distance at which the radius reaches its maximum value.

α = Entrainment Constant
r_m = Maximum plume radius (when plume velocity = ambient velocity)
T = Thrust
ρ_a = Ambient Density
U_a = Ambient Velocity
U_p = Velocity inside the plume
r_o = Initial plume radius

$$
x_m = \frac{(r_m - r_0)}{\alpha} \tag{3}
$$

The effect of buoyancy is treated by assuming that it acts independently on the expanding jet plume

Implementation of Plume Rise

Buoyant plume rise interacts with that associated with horizontal momentum through the initial radius, R, in Eqn (1). It is taken to be the average value of the radius of the momentum plume between 0 and x to account for the impact of momentum on the initial radius of the buoyant plume,

$$R = \frac{1}{x}\int_0^x r(x)dx \qquad (4)$$

- α = Entrainment Constant
- r_m = Maximum plume radius (when plume velocity = ambient velocity)
- T = Thrust
- ρ_a = Ambient Density
- U_a = Ambient Velocity
- U_p = Velocity inside the plume
- r_o = Initial plume radius

which yields

$$\begin{aligned} R &= r_0 + \alpha x / 2 \qquad x \le x_m \\ R &= \frac{x_m}{x}\left(r_0 + \frac{\alpha x_m}{2}\right) + r_m\left(1 - \frac{x_m}{x}\right) \qquad x > x_m \end{aligned} \qquad (5)$$

Implementation of Plume Rise (Surface Source)

The buoyancy parameter, F_b, is computed using the below equation. Eqn (1) has to be solved iteratively because the wind speed at plume height is not known *a priori*.

$$F_b = \frac{g}{T_a}\frac{\dot{m}_f H_f (1-\eta_t)}{\pi \rho_e C_p} \qquad (6)$$

F_b = Buoyancy Parameter,
T_a = Ambient temperature,
g = Acceleration due to gravity,
ρ_e = Exhaust Density,
C_p = Specific heat of Exhaust Gases (Air),
H_f = Heating value of fuel,
η_t = Thermal efficiency,
$\dot{m}_f$ = Fuel Burn Rate.

Total plume rise

$$h_p = h_{pm} + h_{pb} \qquad (7)$$

Implementation of Plume Rise (Airborne Source)

Airborne sources are treated as pseudo volume sources with an initial horizontal spread corresponding to the span of the aircraft.

The flight path is divided into airborne segments, each of which is located using the three-dimensional co-ordinates of the beginning (x_b, y_b, z_b), and the end (x_e, y_e, z_e) of the segment. The angle, Θ, that the segment make with horizontal plane is given by

$$\cos\theta = \sqrt{\frac{(x_e - x_b)^2 + (y_e - y_b)^2}{(x_e - x_b)^2 + (y_e - y_b)^2 + (z_e - z_b)^2}} \qquad (8)$$

However, the momentum plume rise h_{pm} is not added to the total plume rise although it is added to the horizontal spread of the plume as $h_{pm}/\sqrt{2}$. In the range, $x_h \leq x_m \cos\theta$, we assume that the plume descends by $h_p = x_h \tan\theta$. Buoyancy governs plume rise beyond $x_h = x_m cos\Theta$, so that plume rise beyond this distance becomes

$$h_p = z_s - x_m sin\Theta + h_{pb} \qquad (9)$$

where z_s is the source height.

Implementation of Plume Rise

Maximum Plume Rise

The rise of the plume associated with buoyancy is limited to the height in the boundary layer at which the standard deviation of the vertical velocity fluctuations, σ_w, is equal to the rate of rise of the plume ${}^{dh_{pb}}/_{dt}$. This height is given by (Weil, 1988)

$$h_{max} = 1.85 \frac{F_b}{U\sigma_w^2} \tag{10}$$

and when the boundary layer is stable, plume rise is limited by the final rise in a stable atmosphere with a potential temperature gradient

$$h_{max} = 2.66 \left(\frac{F_b}{UN^2}\right)^{1/3} \tag{11}$$

where *N* is the Brunt-Vaisala frequency,

$$N = \left(\frac{g}{T_a}\frac{d\theta}{dz}\right)^{1/2} \tag{12}$$

The total plume rise is also limited by the height of the mixed layer.

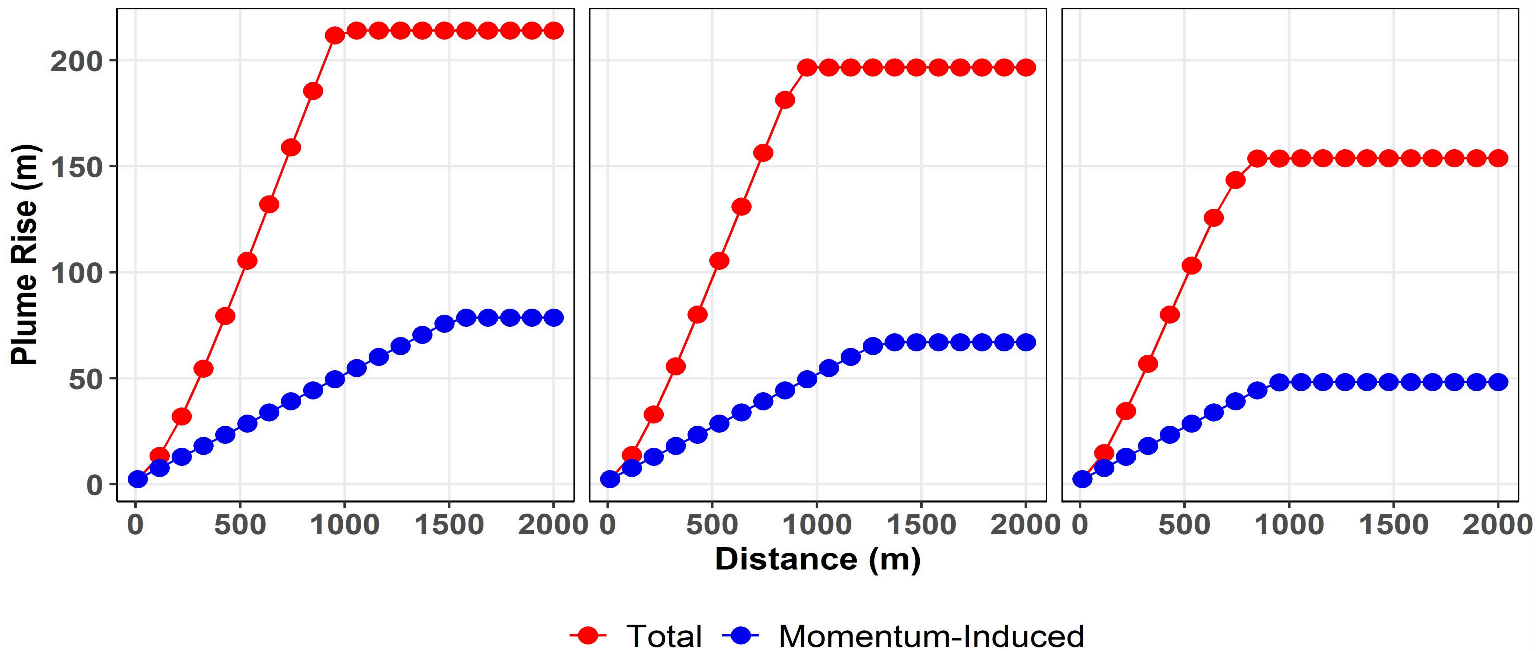
Sample Plume Rise

Meteorological Variables:

$$U = 2.4\,ms^{-1};\ u_* = 0.201\,ms^{-1};\ z_0 = 0.106\,m;\ \sigma_w = 0.25\,ms^{-1};\ L = 54.5\,m;$$

$$z_i = 216\,m;\ z_{ref} = 10\,m; Temp = 284.2\,K; \frac{dt}{dz} = 0.005$$

Initial Plume Radius (r_0): 2 m; Source Height: 2 m



Fuel Burn Rate: 0.262 kg/s; Thrust: 25561.88 N; Air Fuel Ratio: 45; Aircraft Velocity: 34.46 m/s; Bypass ratio: 5.5	Fuel Burn Rate: 0.332 kg/s; Thrust: 35214.23 N; Air Fuel Ratio: 83; Aircraft Velocity: 51.14 m/s; Bypass ratio: 5.5	Fuel Burn Rate: 0.113 kg/s; Thrust: 13210.5 N; Air Fuel Ratio: 106; Aircraft Velocity: 8.33 m/s; Bypass ratio: 5.5

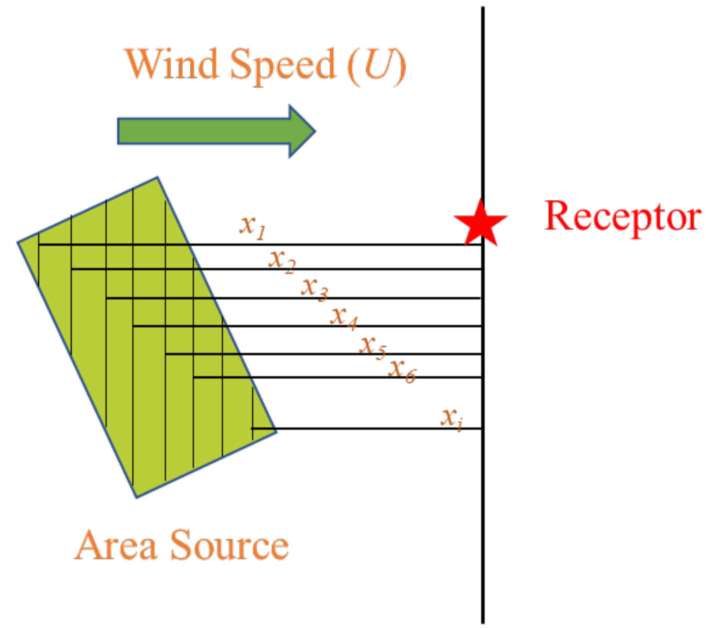
Aircraft Plume Rise is slightly higher as compared to normal stack's plume

Computation of Effective Distance from Area Source

The effective distance from an area source to a receptor is computed by treating the area source as a set of 32 line sources perpendicular to the wind direction at 10 m. These line sources are terminated at the boundaries of the area source.

The effective distance of the area source from the receptor is then computed from

$$x_{eff} = \frac{\sum C_l(x_i) x_i}{\sum C_l(x_i)} \quad (13)$$



where $C_l(x_i)$ is the contribution of a line source at a distance x_i from the receptor.

So x_{eff} weights the distance of the line source from the receptor by the contribution of the line source.

Model Evaluation with LAWA Study Data

- SO_2 concentrations in the vicinity of the airport are dominated by aircraft emissions

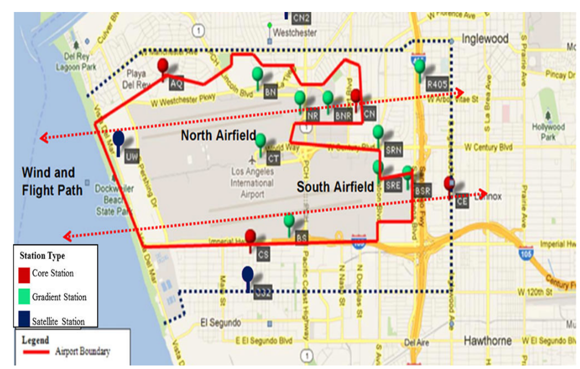
- ADM is evaluated with

  - SO_2 measurements from LAWA study conducted during February 2012 at the AQ, CN, CS, and CE monitors shown in the figure

  - one-hour averages using EPA recommended performance statistics (FB: Fractional Bias based on Robust Highest Concentrations (RHC), and FAC2: Factor of two to the observations)

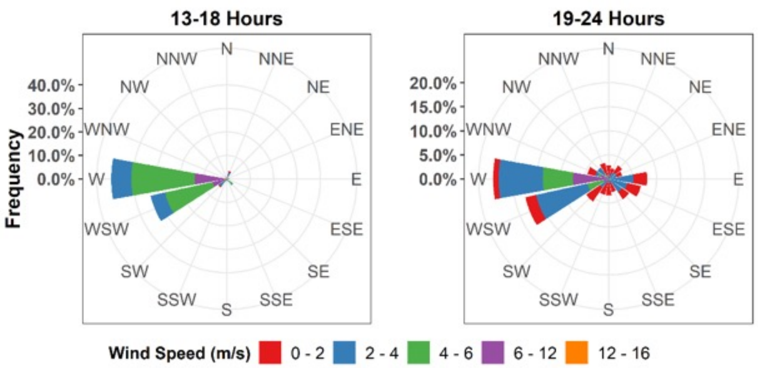
  - using 2 sets of meteorology:
    - <u>Original Meteorology</u> generated by AERMET and
    - <u>Modified Meteorology</u> based on region-specific modifications of AERMET outputs

    Pandey et al, 2022. In Prep



Meteorological Modification in AERMET Output

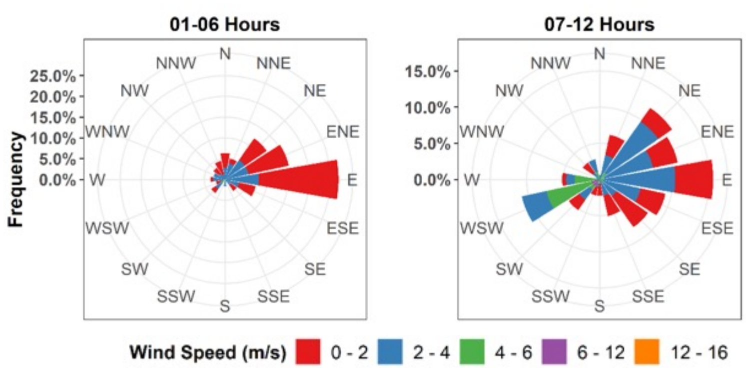
1. To account for shoreline effects at LAX, westerly wind conditions replaced by neutral conditions (specially Monin-Obukhov length (L) and surface friction velocity (u_*))

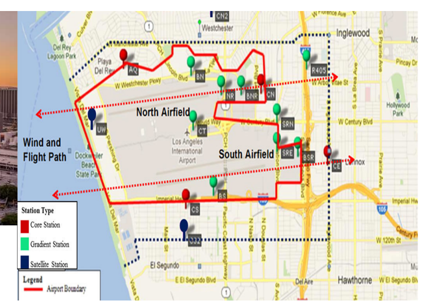


$$u_* = k \frac{U_r}{ln\left(\frac{z_r - z_d}{z_0}\right)},$$

where k is the von-Karman constant, U_r is the wind speed at z_r (reference height), z_0 is the roughness length, and z_d is the zero-plane displacement height

2. Roughness lengths altered when the wind blew from the northeast quadrant to reflect flow passing over LA urban core with tall buildings





Source: Google Image

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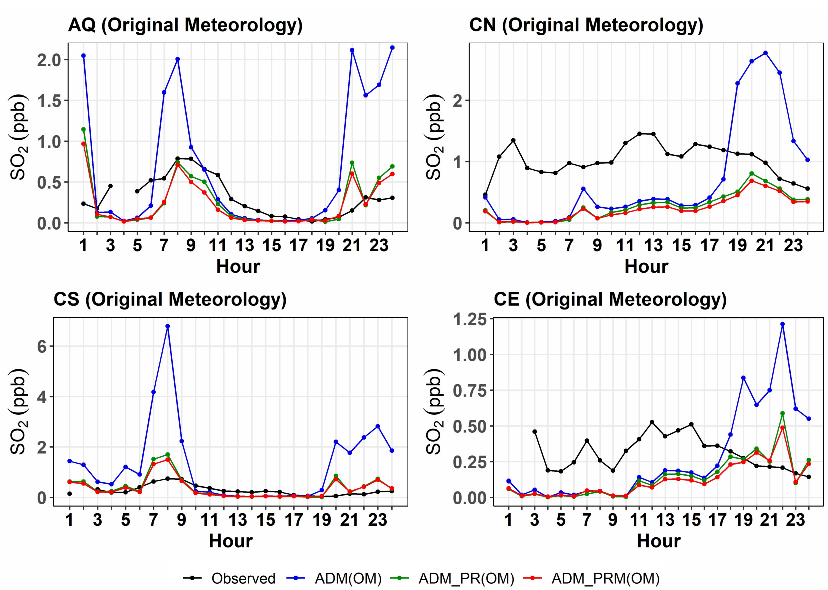
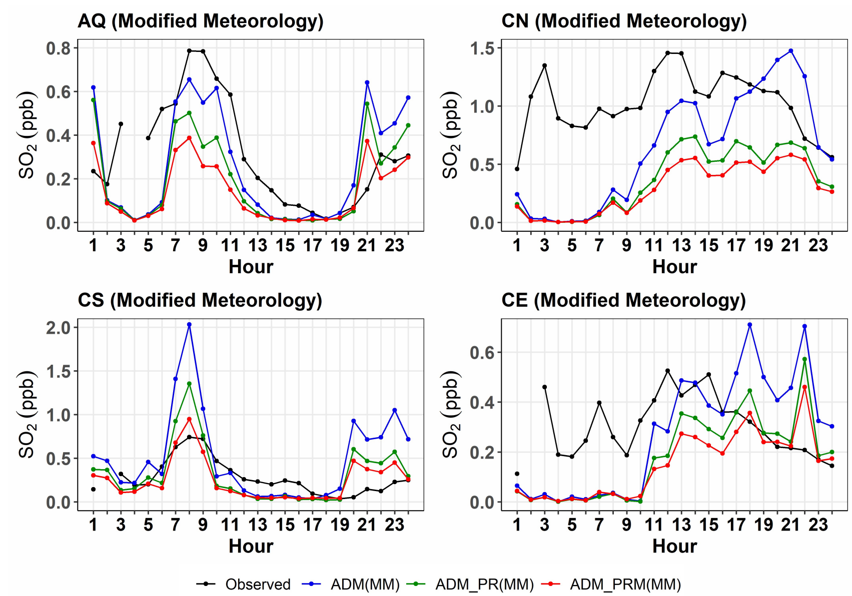
ADM Model Performance at LAX – February 2012 (Only aircraft sources)

Original Meteorology



Improved Meteorology



OM – ORIGINAL MET
MM – MODIFIED MET
ADM – AIRPORT DISPERSION MODEL
PR – PLUME RISE
PRM – PLUME RISE with MEANDER

Pandey et al, 2022. In Prep

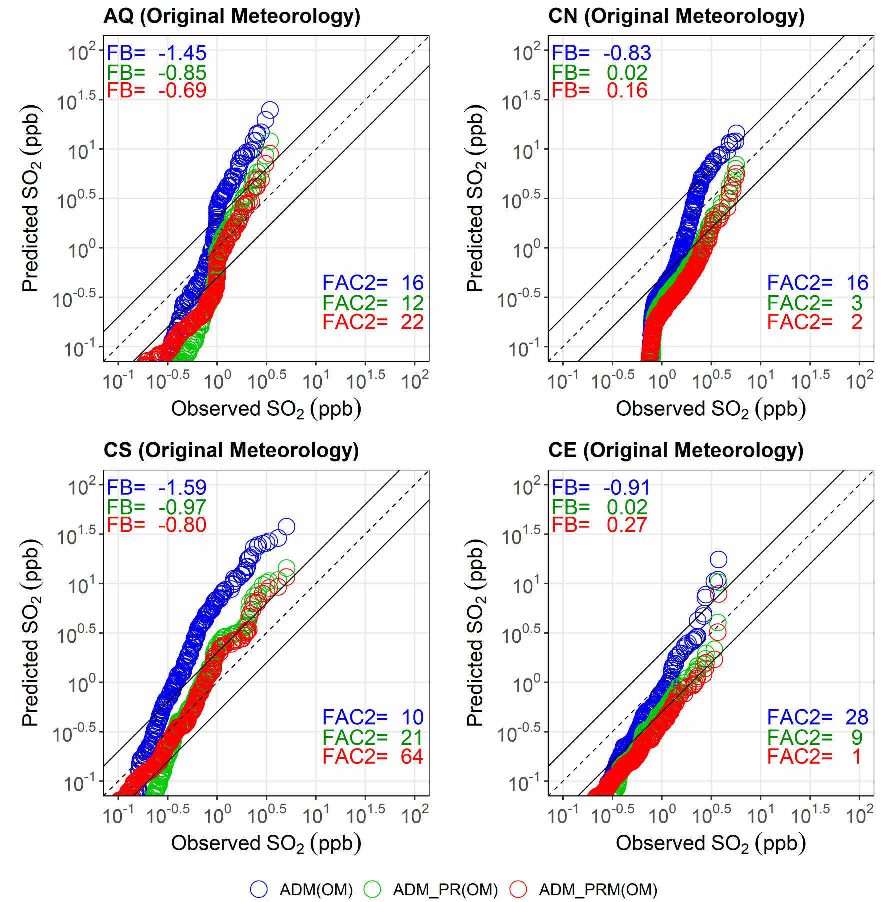
Overpredictions at higher end reduced at all receptors with use of plume rise as well as meander for area sources

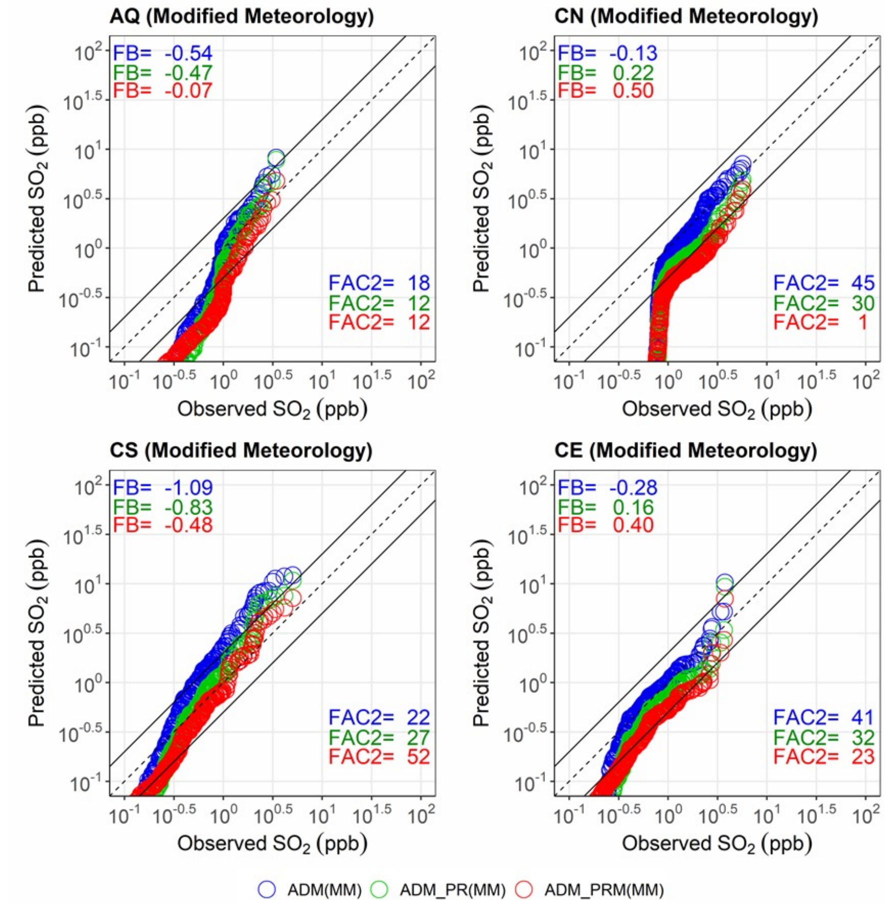
Improved meteorology enables reproducing observed diurnal patterns

ADM Model Performance at LAX – February 2012 (Only aircraft sources)

Original Meteorology

Improved Meteorology





OM – ORIGINAL MET
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PR – PLUME RISE
PRM – PLUME RISE with MEANDER

Pandey et al, 2022. In Prep

High Concentrations are coming close to the one-to-one line with use of plume rise and meander

Improved meteorology reduces the Fractional Bias (FB) based on top 26 robust highest concentrations (EPA recommended measure)

Summary

- ADM code restructured to improve readability and facilitate conversion to other languages
- Input and output formats formalized for different source types
- Surface sources treated as area sources, while airborne sources treated as pseudo volume sources with initial horizontal plume corresponding to aircraft wingspan
- Plume rise computed using horizontal momentum and buoyancy from typical aircraft in area source
- Meander algorithm is used to treat the low and variable wind conditions
- Significant and sustained interactions with the EPA who owns the AERMOD model for updates leading to the Appendix W update (Nov 2023)
- Design documents created for AEDT modification to support ADM and AERMOD
- Started implementing chemical conversions based on the Generic Reaction Set (GRS) and Travel Time Reaction Methods (TTRM) mechanisms (5 – 6 Months)
- Continue evaluation at LAX and additional airports (BOS and EU) (12 – 18 Months)
- Finalize and submit multiple research articles (7 have been identified so far) (6 – 12 Months)

Other Collaborations

- EPA
  - Continued engagement with the EPA during model development specially to add the plume rise for area source in AERMOD, leading to Appendix W Update
  - Weekly and monthly calls to discuss technical issues during AERMOD updates
- EU-AVIATOR
  - Engagement re ongoing field studies for future ADM evaluation
- Boston University (ASCENT NOI 18)
  - Evaluation of observations from ongoing field study at Boston Logan
  - Plan next phase of campaign
  - Scoping of drone-based AQ measurements at Boston Logan
- Presentations / Publications
  - AEC Annual meeting 2021
  - 2 papers at 20th Annual CMAS Conference, October 2021
  - Paper at 38^{th} ITM, Barcelona, Spain, October 2021
  - Publication of AQ/Health benefits of SAF in Commercial Aviation
    - Arter et al, *Environment International*, 2022

Project Team

- S. Arunachalam, ASCENT19 PI
- G. Pandey, Postdoctoral Scholar (Dispersion Model Developer)
- C. Moniruzzaman*, Postdoctoral Scholar (Air Quality Modeler)
- B. Naess, GIS Specialist
- P. Dodda and H. Kim, Ph.D. Students
- Akula Venkatram, UC Riverside (Consultant)

* Not with UNC anymore; looking for a replacement

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