Technical Report Documentation Page

1. Report No.
j.atmosenv.2022.119506

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Evaluating AERMOD with measurements from a major U.S. airport located on a shoreline

5. Report Date
November 2022

6. Performing Organization Code

7. Author(s)
Gavendra Pandey, Akula Venkatram, Saravanan Arunachalam

8. Performing Organization Report No.

9. Performing Organization Name and Address
Center of Excellence for: Alternative Jet Fuels and Environment

The University of North Carolina at Chapel Hill, United States

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
13-C-AJFE-UNC-007, 014

12. Sponsoring Agency Name and Address
Federal Aviation Administration
Office of Environment and Energy

13. Type of Report and Period Covered
Journal Article

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
The impact of airport operations on air quality is a key public health concern for the population surrounding an airport. Air pollution regulations require the assessment of this impact using dispersion models. Modeling dispersion of aircraft-related sources poses challenges because of the large number and variety of airport sources, which include aircraft, ground operation vehicles, and traffic in and out of the airport, most of which are mobile. Emissions from aircraft sources are transient, buoyant, and occur at different heights from the ground. Quantifying these emissions as well as modeling the governing processes is challenging. An added complexity occurs when the airport is situated near a shoreline where meteorological conditions are far from being spatially uniform. These features that characterize the dispersion of airport emissions are being incorporated into the AERMOD model in this paper. This paper examines the impact of shoreline meteorology and urban effects on dispersion by comparing model estimates of SO2 with corresponding measurements made during a field study conducted at the Los Angeles International Airport (LAX) during winter and summer of 2012 at all the four core sites (AQ, CN, CE, and CS) as a part of the LAX Air Quality Source Apportionment Study (AQSAS). We modified outputs from AERMOD's meteorological preprocessor AERMET to account for 1) the formation of the internal boundary layer that is formed when stable air from the ocean flows onto the warmer land surface of the airport, and 2) urban roughness effects on winds flowing from Los Angeles, east of the airport. Simulations with unmodified AERMET yielded concentrations that were substantially higher than the concentrations at AQ and CS and much lower than those at CN and CE. Model performance improved when AERMOD used the modified meteorology. The fraction of model estimates within a factor of two of the observations improved from 34 to 84% at the CS site and CE site, by up to 79% in winter season whereas in summer, FAC2 values are almost comparable at all the sites. The ratio of robust highest modeled values to measured values improved from 7.72 to 2.53 and 4.92 to 1.94 in winter and summer seasons respectively.

17. Key Words
AERMOD; Air quality; IBL; LAX-Airport; Shoreline effect; Urban, ASCENT

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages

22. Price

Atmospheric Environment 294 (2023) 119506

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Evaluating AERMOD with measurements from a major U.S. airport located on a shoreline

Gavendra Pandey [a], Akula Venkatram [b], Saravanan Arunachalam [a,*]

[a] Institute for the Environment, The University of North Carolina at Chapel Hill, United States
[b] University of California at Riverside, United States

ARTICLE INFO

Keywords:
AERMOD
Air quality
IBL
LAX-Airport
Shoreline effect
Urban

ABSTRACT

The impact of airport operations on air quality is a key public health concern for the population surrounding an airport. Air pollution regulations require the assessment of this impact using dispersion models. Modeling dispersion of aircraft-related sources poses challenges because of the large number and variety of airport sources, which include aircraft, ground operation vehicles, and traffic in and out of the airport, most of which are mobile. Emissions from aircraft sources are transient, buoyant, and occur at different heights from the ground. Quantifying these emissions as well as modeling the governing processes is challenging. An added complexity occurs when the airport is situated near a shoreline where meteorological conditions are far from being spatially uniform. These features that characterize the dispersion of airport emissions are being incorporated into the AERMOD model in this paper. This paper examines the impact of shoreline meteorology and urban effects on dispersion by comparing model estimates of SO_2 with corresponding measurements made during a field study conducted at the Los Angeles International Airport (LAX) during winter and summer of 2012 at all the four core sites (AQ, CN, CE, and CS) as a part of the LAX Air Quality Source Apportionment Study (AQSAS). We modified outputs from AERMOD's meteorological preprocessor AERMET to account for 1) the formation of the internal boundary layer that is formed when stable air from the ocean flows onto the warmer land surface of the airport, and 2) urban roughness effects on winds flowing from Los Angeles, east of the airport. Simulations with unmodified AERMET yielded concentrations that were substantially higher than the concentrations at AQ and CS and much lower than those at CN and CE. Model performance improved when AERMOD used the modified meteorology. The fraction of model estimates within a factor of two of the observations improved from 34 to 84% at the CS site and CE site, by up to 79% in winter season whereas in summer, FAC2 values are almost comparable at all the sites. The ratio of robust highest modeled values to measured values improved from 7.72 to 2.53 and 4.92 to 1.94 in winter and summer seasons respectively.

1. Introduction

The impact of airport operations on air quality is a key public health concern for the population surrounding an airport. Air pollution regulations require the assessment of this impact using dispersion models. AERMOD (Cimorelli et al., 2005) is a state-of-the-art dispersion model that the U.S. Environmental Protection Agency (USEPA) recommends for estimating the air quality impact of emissions when the receptor of concern is approximately less than 50 km from the source (EPA, 2005). Consequently, several studies have used AERMOD to estimate the impact of airport-related emissions on the air quality of surrounding areas. These studies include.

1. estimating the impact of airport-related emissions on ambient air quality in and around the airports: Makridis and Lazaridis (2019); Groma et al. (2018); Kuzu (2017); Arunachalam et al. (2017); Doird (2015); Penn et al. (2015); Simonetti et al. (2015); Steib et al. (2007); and Wayson et al. (2003).
2. examining the relative roles of aircraft operations such as landing and takeoff and taxiing on emissions and air quality: Feinberg and Turner (2013); Kim et al. (2012); Carr et al. (2011); and Barrett and Britter (2008).
3. forecasting air quality around airports: Tian et al. (2019); Sabatino et al. (2011); and Zhou and Levy (2009).

---

* Corresponding author. Institute for the Environment, The University of North Carolina at Chapel Hill, Chapel Hill, NC, 27510, United States.
E-mail address: sarav@email.unc.edu (S. Arunachalam).

https://doi.org/10.1016/j.atmosenv.2022.119506
Received 13 August 2022; Received in revised form 6 November 2022; Accepted 17 November 2022

4. evaluating the performance of AERMOD in describing measured concentrations of airport-related pollutants: Tetra Tech (2013); Steib et al. (2008); and Martin (2006).

Although AERMOD has been applied to estimating the air quality impact of airport emissions (Makridis and Lazaridis (2019); Penn et al., 2015), it has not been formally evaluated with relevant measurements to determine the uncertainty in model results in this type of application. This evaluation is important because AERMOD does not account for unique features of airports and airport emissions that might be important in estimating the air quality impact of airports. These features are listed below:

1. Airport emissions are transient, lasting for minutes, such as those during take-off and landing. AERMOD assumes constant emission rates during an hour.
2. Emissions from aircraft have significant horizontal momentum associated with thrust generated by aircraft engines. The plume rise formulation in AERMOD neglects this feature.
3. Aircraft move over the airport while emitting pollutants. AERMOD assumes a fixed location for the sources and characterizes these sources as AREA sources.
4. AERMET, AERMOD's meteorological processor, assumes that the atmospheric boundary layer is horizontally homogeneous. This assumption is not likely to be valid at airports located on shorelines or in the middle of an urban area.

Because AERMOD does not account for these features explicitly, it is necessary to estimate the uncertainty in model results by comparing model estimates to observations made during a field study. The objective of this paper is to 1) present the results from such a comparison using data from a field study conducted at the Los Angeles International airport in 2012, and 2) examine the change in model performance when the meteorological inputs are modified to reflect the airport's proximity to the ocean and downtown Los Angeles.

In this study, we examine the performance of AERMOD using SO_2 measurements at the four sites shown in Fig. 1. This choice is based on the observation that most sources in the vicinity of LAX emit little SO_2 compared to that from aircraft; SO_2 emissions from aircraft can be quantified well because they correspond to the sulfur content of aircraft fuel. One major source of SO_2 near the aircraft is a Shell oil refinery (Chevron) located southwest of the airport. The emissions from this source are relatively well quantified and can be excluded from the analysis, if necessary, by considering wind directions that transport its emissions to the four sites used to evaluate AERMOD's performance. The next section describes the field study, conducted at LAX, which provided the data used in evaluating AERMOD.

2. The LAWA field study

Los Angeles International Airport (LAX) is situated within the South Coast Air Basin (Basin). Because this airport is close to residential areas located to the north, south, and east the impact of airport operations on air quality is a significant public health concern. To understand the extent of the impact of the airport on surrounding areas, Los Angeles World Airports (LAWA) conducted the Los Angeles Source Apportionment Study (LAX AQSAS Phase III) in 2012 in two different six-week field monitoring campaigns: the "winter measurement season" from 1/31/12 to 3/13/12 and the "summer measurement season" from 7/18/12 to 8/28/12 (Tetra Tech, 2013).

There are two main airfields: South Airfield and North Airfield, each with two runways, in the LAX airport. During the field study, NO_x, SO_2, $PM_{2.5}$, CO, and BC (Black Carbon) were measured at three different types of sites, four "core", four "satellite" and nine "gradient", with different time scales for both the seasons (Fig. 1). Extensive air quality observations were measured at the four core sites, the Air Quality (AQ) site, the Community North (CN) site, the Community South (CS) site, and the Community East (CE) site. The core monitoring site AQ is located at the South Coast Air Quality Management District (SCAQMD) Hastings site, which was northwest of the airport in Playa del Rey. The CN core monitoring site was installed at Westchester about 1.5 km east of the North Airfield. The CS core monitoring site was placed at the former Imperial Avenue School in El Segundo, about 200 m from the LAX southern boundary. The fourth core monitoring site CE was installed at Lennox about 1.5 km east of the South Airfield and approximately half km east of the I-405 Freeway (Fig. 1) (Tetra Tech, 2013) (Arunachalam et al., 2017).

During the LAX AQSAS Phase III study, the SO_2 concentrations consisted of 1-min averages at the four core monitoring sites, AQ, CN, CS, and CE. They were measured with Thermo Model 43i TLE SO_2 analyzers, which are capable of measuring ambient SO_2 concentrations as low as 50 parts per trillion (ppt). The SO_2 analyzer was operated on the 0–500 ppb range during the winter season and 0–50 ppb range during the summer season, with a minimum detection level (LOD) of 0.1 ppb for both seasons (Tetra Tech, 2013).

We aggregated these 1-min values to construct 1-h averages for comparison against AERMOD results in this study for a total of 84 days during winter (02/01/2012–03/13/2012) and summer (07/18/2012–08/28/2012) seasons at the LAX Airport. We replaced values below the lower detection limit with 0.05 ppb (half of the LOD of 0.1 ppb) (Cohen and Ryan, 1989) and then aggregated them into hourly averages.

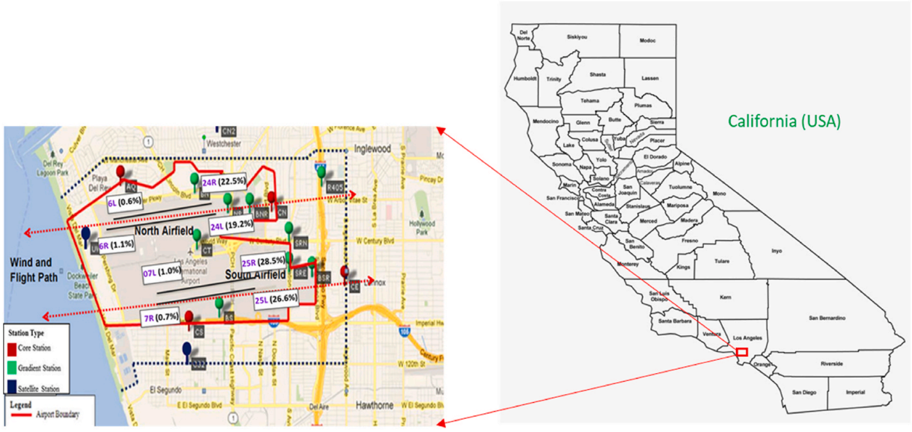

Fig. 1. Locations of core, gradient, and satellite monitoring stations at LAX during AQSAS Phase III (Adapted from Arunachalam et al., 2017; ACRP Report 179).

3. Application of AERMOD

AERMOD (version 22112) is a steady-state model that does not account for the unique nature of aircraft sources at an airport. The emissions during landing and takeoff (LTO) of aircraft are transient, buoyant, and occur at different heights from the ground. Quantifying these emissions and accurately modeling the governing dispersion and transport processes is a challenge. An added complexity is that LAX is situated near a coastal region where meteorological conditions are far from being spatially uniform, which is assumed in the meteorological processor, AERMET, that is used to construct the micro-meteorological inputs for AERMOD.

We treated the emissions from airport sources as area sources located at different heights above the ground. Originally, area sources in AERMOD were designed to model the emissions from a fixed/stationary source with a large surface area. In the literature, area sources have also been used to represent ground roll operation emissions (e.g., runways and taxiways), and elevated aircraft sources (e.g., imaginary surfaces elevated above the ground along the path of landing and take-off). Area sources are recommended in several studies to represent aircraft sources in AERMOD because they are the source type for other transportation sources, though recent versions of AERMOD have a line source algorithm to treat on-road traffic sources.

For this analysis, we used SO_2 emissions from the Emissions and Dispersion Modeling System (EDMS) (Martin, 2006) emission inventory of LAX, which accounts for all the airport and non-airport sources for winter (02/01/2012–03/13/2012) as well as summer (07/18/2012–08/28/2012) seasons of 2012. EDMS accounts for emissions from aircraft, auxiliary power units (APU), ground support equipment (GSE), and stationary sources. The combination of EDMS and AERMOD has been used for the majority of airport air quality assessments in the United States (Arunachalam et al., 2017). Since May 2015, the Aviation Environmental Design Tool (AEDT) (FAA, 2014) has replaced EDMS for such assessments.

The meteorological inputs for the winter and summer 2012 seasons were generated with AERMET using the KLAX (Los Angeles Airport) surface observations (WBAN 722590), and KNKX (San Diego Marine Corps Air Station) upper air soundings (WBAN 722900).

During the winter season, the late night to morning winds were from the north-east until around 8:00 a.m. During the daytime and the nighttime, the LAX airport was consistently downwind of Los Angeles city as winds were westerly or onshore during this time (Fig. 2 (a)). Fig. 2 (a) shows that more low wind (≤ 2 m/s) cases occurred during 01–08 h as compared to 09–24 h. Out of 1008 h or 42 days in winter season, 534 h (or 53%) had winds from north-west and south-west directions.

In 42 days (1008 h) of the summer season, there were 899 h (or approximately 90%) when the winds were westerly. As in the winter season, the summer season had also more westerly winds during 09–24 h and low winds during 01–08 h (Fig. 2 (b)).

In both seasons, westerly winds resulted in higher contributions from on-airport sources especially aircraft sources at the CN and CE monitoring sites, whereas off-airport sources (such as I-405 traffic and some parking lots) affected these sites when the winds were not westerly.

We first applied AERMOD using the standard outputs from AERMET, which we refer to as Original Meteorology (OM). We then modified the outputs from AERMET to account for shoreline and urban effects. We refer to this meteorological input set as Modified Meteorology (MM). Details on constructing MM are described next.

3.1. Modified meteorology to account for shoreline and urban effects

AERMET uses measurements of wind speed, temperature, cloud cover, roughness length, and albedo to generate the micrometeorolog-

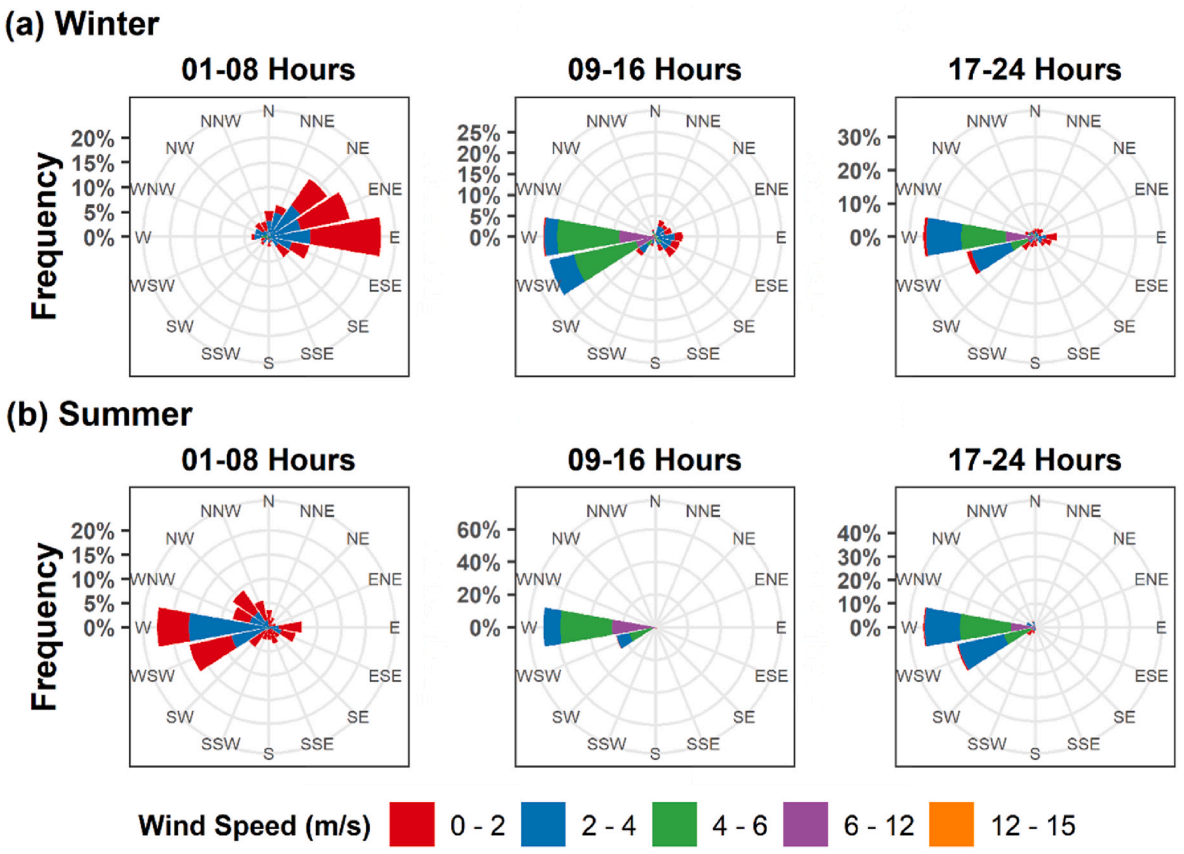

Fig. 2. Wind rose plots (a) winter, and (b) summer seasons of 2012, showing frequency of counts by direction.

ical variables: 1) friction velocity $u_*,\ m/s$, 2) the surface heat flux, H_0, $\frac{W}{m^2}$, 3) the convective velocity scale, $w_*,\ m/s$, 4) the stable boundary layer height, *sbl*, *m*, 5) the convective boundary layer height, *pbl*, *m*, and 6) the Monin-Obukhov (MO) length, *L*, *m*. These variables depend on the values of the surface roughness length, z_0, and the Bowen ratio, *Bo*, which is the ratio of the sensible heat flux to the latent heat flux. The micrometeorological inputs for AERMOD are contained in the AERMET surface (.sfc) and profile (.pfl) files, the outputs of AERMET.

The meteorology at LAX is affected by two major processes that are not accounted for in AERMET. The first is related to the location of LAX on the shoreline. Winds from the west pass over water before they encounter warmer land. The resulting upward heat flux creates an internal boundary layer over the airport, which suggests that the stable boundary layer predicted by AERMET might not occur in reality. This is supported by Wei et al. (2018) who demonstrate the significant role of the thermal internal boundary layer in determining $PM_{2.5}$ and PM_{10} concentrations measured in a coastal city in China. AERMET does not also account for the roughness associated with the tall buildings in downtown Los Angeles, which the winds flowing from the east into LAX encounter.

We account for these two effects by modifying the output from AERMET by 1) using an internal boundary layer model to simulate the meteorology over LAX when the winds are westerly and AERMET output corresponds to stable conditions, and 2) increasing the roughness length when the wind blows from downtown Los Angeles in the east.

3.2. *Accounting for the internal boundary layer and roughness change*

The modification in meteorology when the wind blows from the ocean to warmer land is based on a simple internal boundary layer (IBL) model. Fig. 3 provides the physical picture used to derive the model. In this examination of the role of the IBL in the meteorology of a coastal airport, we will adopt the simple model that the height, z_i of the IBL at a distance, *x*, from the shoreline is given by (Venkatram, 1977),

$$z_i = \frac{(\theta_m - \theta_w)}{\gamma} \tag{1}$$

where θ_m is the potential temperature of the well-mixed IBL, θ_w is the temperature obtained by extrapolating the potential temperature above the water to the water surface, and γ is the gradient of the potential temperature above the water surface. If we assume that the convective IBL is created by an average upward kinematic heat flux, H_0, we can show that

$$z_i^2 = 2\frac{H_0}{\gamma}\frac{x}{u_m} \tag{2}$$

where u_m is the mixed layer wind speed. This equation does not account for the variation of u_m and H_0 with the distance from the shoreline, *x*, and provides realistic estimates of the IBL at coastlines where relevant data are available (Hsu, 1986 Stunder and Sethuraman, 1985).In applying the model to modify the output from AERMET, we take $u_m = u_{10}$, $\gamma = 0.01^0C/m$, and $\theta_m - \theta_w = 2^0C$, values that are consistent with those used in the study by (Hsu, 1986). With an estimate of z_i from Equation (1), Equation (2) provides an estimate of the heat flux from

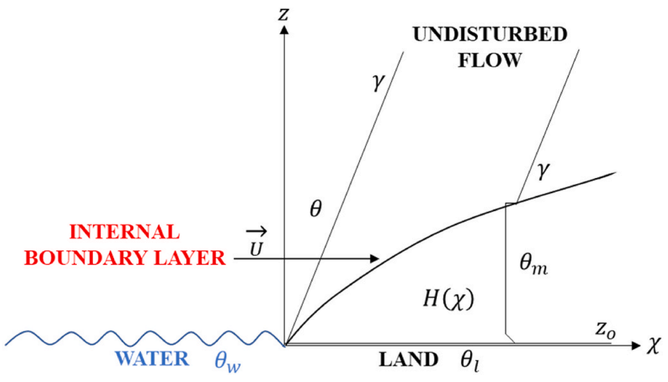

Fig. 3. Development of internal boundary layer over land.

$$H_0 = \frac{\gamma u_{10} z_i^2}{2x} \tag{3}$$

Then, the friction velocity, u_*, the convective velocity scale, w_*, the Monin-Obukhov length, *L*, are recalculated with values of u_{10}, z_0, z_i and H_0 solving the surface similarity equations iteratively. The modified heat flux, H_{0m}, is used to compute the modified friction velocity, u_{*m}, from original friction velocity, u_* using M-O similarity as follows

$$u_{*m} = u_* \frac{\varphi_m\left(\frac{z_r}{L}, \frac{z_0}{L}\right)}{\varphi_m\left(\frac{z_r}{L_m}, \frac{z_{0m}}{L_m}\right)} \tag{4}$$

where φ_m is the M-O profile function for the wind speed, z_r is the height at which the wind speed is measured, and the subscript, *m*, denotes modified values. We take $z_{0m} = z_0$, when the impact of the IBL is estimated. Equation (4) requires an iterative calculation because L_m on the right-hand side of the equation depends on u_{*m}.

We change the roughness length to account for the effect of the Los Angeles urban area on flow from the east. The surface variables are modified assuming that the upward heat flux is not affected by the roughness change. Then, u_{*m}, is computed from Equation (4).

Fig. 4 shows the effects of the modifications on the diurnal variation of the friction velocity, u_*, which is one of the key variables that control surface dispersion. We see that the friction velocity in MM is larger than that of the OM during the early morning and late evening hours when 1) the stable periods predicted by AERMET become unstable during onshore flow, or 2) flows from Los Angeles are modified by the increased roughness length. The impact of these changes in surface variables on model performance is discussed next.

4. Model performance

The performance of the AERMOD model is evaluated at the four core sites using data from the winter and summer campaigns through a set of statistics that were used to estimate the improvement in AERMOD's performance in describing measured concentrations relative to that of the Industrial Source Complex (ISC) model (Perry et al., 2005). We compare the distributions of modeled values and corresponding observations using Quantile-Quantile (Q-Q) plots in which modeled concentrations, sorted from high to low, are plotted against similarly sorted observations. In addition, we use the statistical measures, ratio of robust highest modeled value to measured value and Factor of Two (FAC2) (Chang and Hanna, 2004). The robust highest concentration (RHC) uses the top 26 highest concentrations using the procedure described in (Cox and Tikvart, 1990). FAC2 refers to the fraction of the model estimates that is within a factor of two of the corresponding measurements. An ideal model would yield values of RHC ratio = 1, and FAC2 = 100%.

Table 1 shows the effect of modifying the meteorology on AERMOD's performance in estimating 1-h (1-hr Avg), 3-h (3-hr Avg), and 24-h (24-hr Avg) averages during the winter and summer periods. We see that most of the performance statistics improve with MM replacing OM. This improvement in model performance is also seen in Figs. 5 and 6, showing the Q-Q plots for the concentrations combined from the four sites. The vertical dotted line in the Q-Q plots represents the lower detection limit of the observations made during LAX AQSAS 2012 study. Table 1 shows that the CN site is an outlier with most of the performance statistics deteriorating. We are not able to provide good reasons for this result and is an area of future work. However, AERMOD using MM estimates the high concentrations at this site, which is important for air

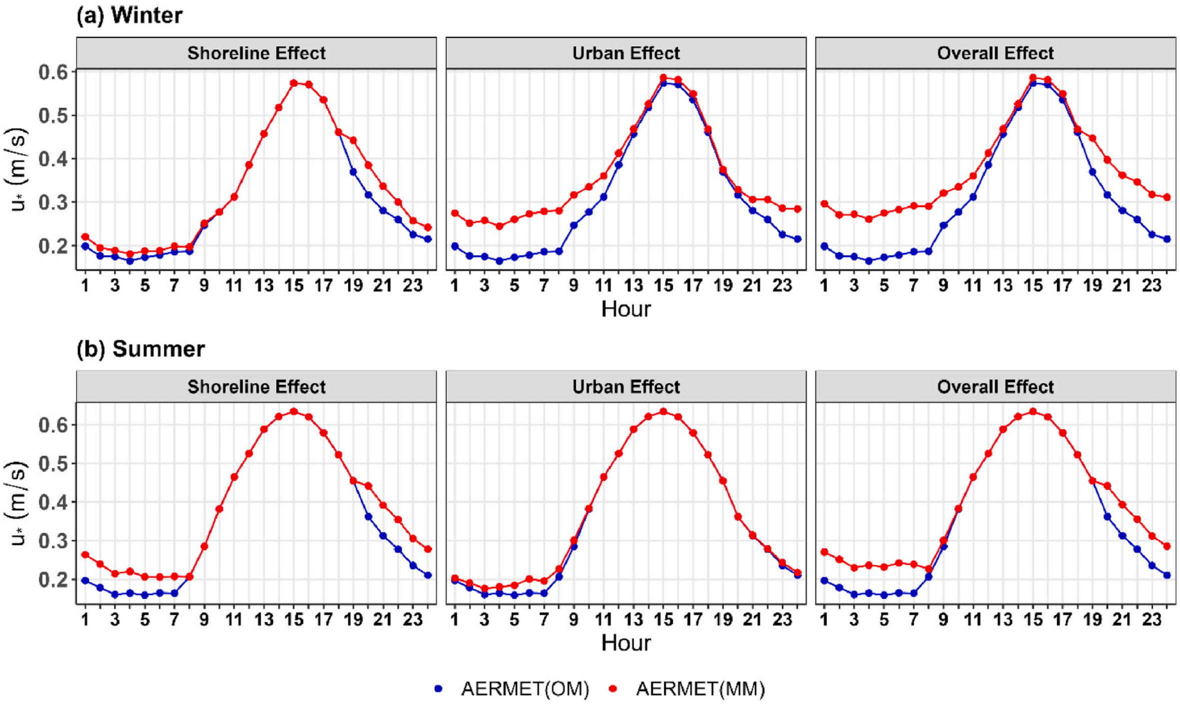

Fig. 4. Diurnal variation of u_* (surface frictional velocity) with and without modification in AERMET input files.

Table 1
Comparison of Model Performance Statistics from AERMOD using Original (OM) and Modified Meteorological (MM) Inputs. Bold cells show where MM has better performance statistics.

Winter	Site	1-hr Avg		3-hr Avg		24-hr Avg	
Statistics		OM	MM	OM	MM	OM	MM
Ratio of RHC	AQ	6.67	**1.96**	4.22	**1.52**	1.73	**0.69**
	CN	2.60	**0.92**	2.23	**0.67**	0.80	0.31
	CS	12.19	**4.08**	7.53	**2.84**	3.63	**1.50**
	CE	3.51	**1.21**	2.29	**0.72**	1.05	**0.47**
	All	7.72	**2.53**	5.30	**1.76**	1.63	**0.70**
FAC2 (%)	AQ	78	61	77	74	76	**100**
	CN	25	4	25	3	95	0
	CS	34	**84**	31	**56**	0	**29**
	CE	64	**79**	65	**84**	62	**81**
	All	86	74	90	**95**	61	**93**
Summer	Site	1-hr Avg		3-hr Avg		24-hr Avg	
Statistics		OM	MM	OM	MM	OM	MM
Ratio of RHC	AQ	6.37	**2.93**	3.31	**1.57**	2.66	**1.36**
	CN	2.42	**1.09**	1.97	**0.73**	0.95	0.39
	CS	12.67	**5.18**	8.55	**3.59**	4.46	**2.17**
	CE	2.94	**1.63**	2.13	**0.91**	1.37	**0.57**
	All	4.92	**1.94**	3.13	**1.27**	1.37	**0.61**
FAC2 (%)	AQ	49	**49**	55	**60**	62	**95**
	CN	99	50	100	53	100	50
	CS	62	46	57	50	60	**95**
	CE	95	86	99	**100**	100	**100**
	All	90	78	92	89	93	**99**

quality assessment in regulatory applications.

The key effect of modifying the meteorology on model predictions is the reduction of the overestimates resulting from the use of OM in AERMOD. This is qualitatively illustrated in the diurnal plot of Fig. 7. The high concentration peaks seen in the early morning and late evening hours are associated with stable hours (small positive M-O lengths) when vertical dispersion is suppressed. The surface layer becomes less stable during these hours when the meteorological inputs are modified. This leads to major reductions in the peaks, which do not appear in the observed concentrations. The underestimation of concentrations during the daytime might be related to the fact that the AERMOD area source algorithm used to model aircraft emissions does not account for the effects of low and variable wind conditions. AERMOD does include low wind meander for point and volume sources, but does not incorporate this feature in the area source algorithm. Penn et al. (2015) obtained similar results when they compared EDMS-AERMOD estimates with corresponding measurements of NO_X at one receptor and BC (Black Carbon) concentrations at three different receptors at LAX airport during a field study conducted over 42 days during the summer of 2008. They found that AERMOD underestimated the NO_X concentrations approximately by 40–50% whereas BC concentrations are underestimated by up to 80% during daytime. The underestimation of SO_2 concentrations might also be related to the treatment of moving aircraft-related sources as area sources in AERMOD, and which could be an area of future work.

5. Conclusions

We evaluate the performance of AERMOD (and AERMET) in estimating SO_2 concentrations measured at four sites (AQ, CN, CE, and CS) in and around the Los Angeles airport during the LAX Air Quality Source Apportionment Study (AQSAS) for 42 days each during the winter and summer seasons of 2012. The results indicate that AERMOD overestimates 1-h SO_2 concentrations at these sites during the early morning and late evening hours. Our analysis indicates that this overestimate is related to the meteorological inputs generated by AERMET, which does not account for meteorological features unique to the Los-Angeles: proximity to the ocean as well as to downtown Los Angeles.

We modify AERMET outputs using a simple model that accounts for the meteorological characteristics of the convective internal boundary layer that forms when stable air from the ocean flows onto warmer land. We account for the influence of the buildings in downtown Los Angeles by increasing the roughness when the flow is easterly. These two effects enhance the friction velocity, which governs dispersion in the surface layer, during the early morning and late evening hours when the original meteorology from AERMET yields overestimates of concentrations during these periods.

The modified meteorological inputs result in improvements in model

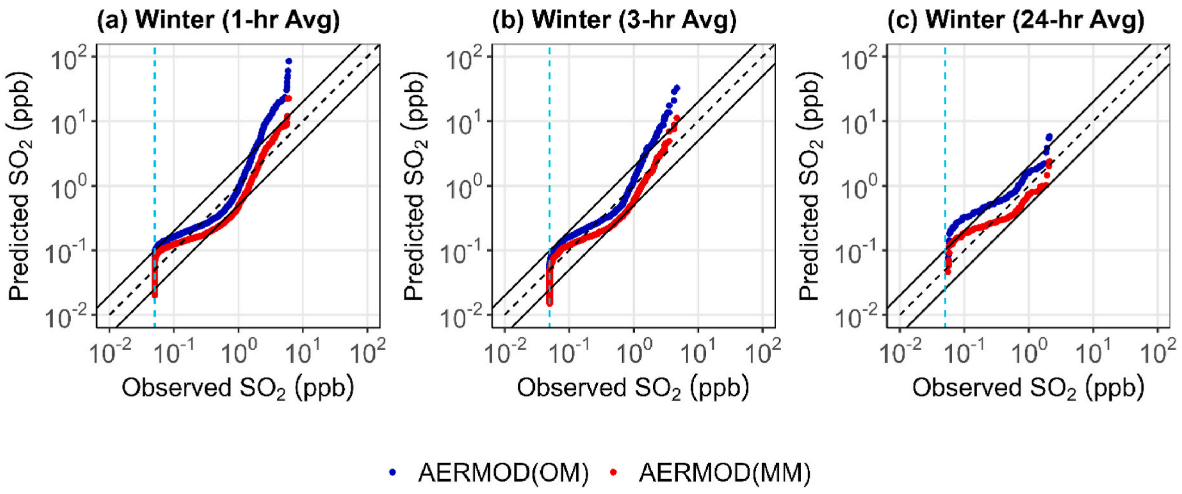

Fig. 5. Q-Q plots showing the effect of modifying the meteorology inputs for the winter experimental period. Concentrations refer to composites from all four sites.

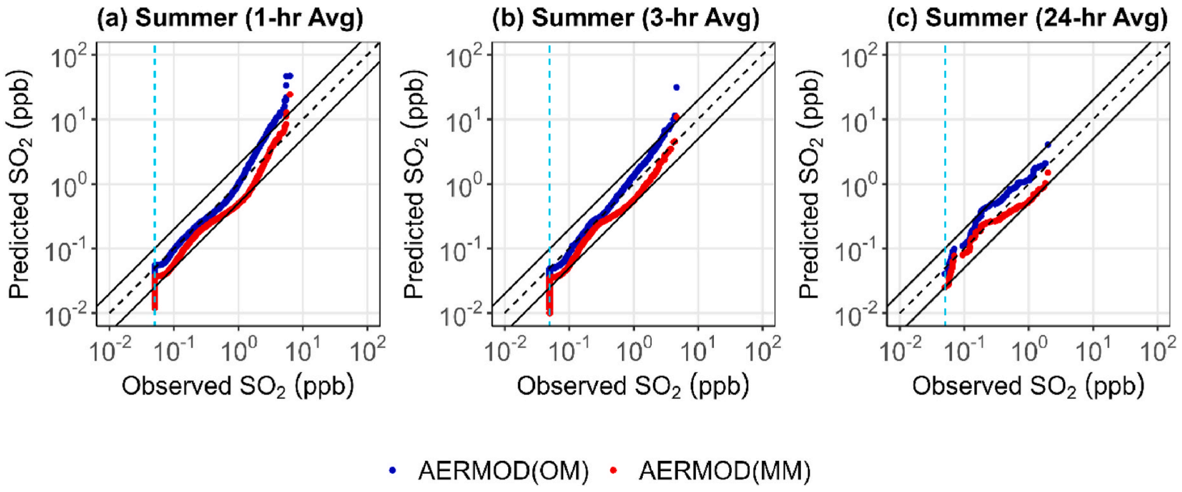

Fig. 6. Q-Q plots showing the effect of modifying meteorological inputs for the summer experimental period. Concentrations refer to composites from all four sites.

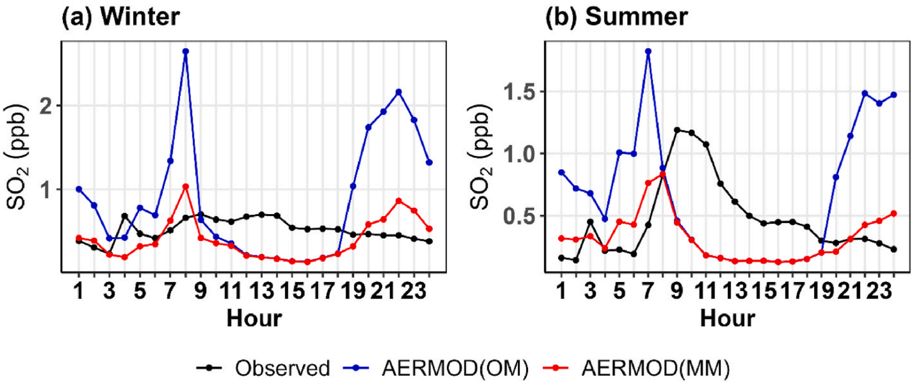

Fig. 7. Diurnal variation of SO_2 concentrations averaged over the four sites and experimental periods.

performance statistics relative to those with the original meteorological inputs. Table 1 indicates that MM yields robust highest concentrations that are within a factor of 2 of the corresponding measurements for the 3-hr avg and 24-hr avg concentrations during the winter campaign as well as for the 1-hr avg, 3-hr avg, and 24-hr avg concentrations during the summer campaign. On the other hand, the original meteorology from AERMET results in modeled concentrations that meet this criterion only for the 24-hr avg concentrations for the winter and summer campaigns.

The results presented in this study indicate that improvements in meteorological inputs that reflect unique features of the airport location are likely to improve the performance of AERMOD in estimating the air quality impacts of the airport emissions. There are other aspects of aircraft and airport operations that might require better treatment to improve model performance. This is likely to be best accomplished by a change in the AERMOD modeling framework to allow better characterization of aircraft sources during LTO cycles, and to account for the effects of variable low winds in the airport.

CRediT authorship contribution statement

Gavendra Pandey: Methodology, Software, Data curation, Formal analysis, Writing – original draft. **Akula Venkatram:** Conceptualization, Methodology, Validation, Writing – review & editing. **Saravanan Arunachalam:** Methodology, Project administration, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research work was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 19 through FAA Award Number 13-C-AJFE-UNC under the supervision of Jeetendra Upadhyay. ASCENT (Aviation Sustainability Center) (http://ascent.aero) is a US DOT-sponsored Center of Excellence. The authors wish to gratefully acknowledge the Los Angeles World Authority (LAWA) for providing datasets from the LAX AQSAS Study. The authors also thank the two reviewers for their valuable comments.

References

Arunachalam, S., Valencia, A., Woody, M.C., Snyder, M.G., Huang, J., Weil, J., Soucacos, P., Webb, S., Airport Cooperative Research Program (ACRP) Research Report 179, Transportation Research Board, National Academies of Sciences, Engineering, and Medicine, 2017. Dispersion Modeling Guidance for Airports Addressing Local Air Quality Health Concerns. Transportation Research Board, Washington, D.C. https://doi.org/10.17226/24881.

Barrett, S.R.H., Britter, R.E., 2008. Development of algorithms and approximations for rapid operational air quality modelling. Atmos. Environ. 42, 8105–8111. https://doi.org/10.1016/j.atmosenv.2008.06.020.

Carr, E., Lee, M., Marin, K., Holder, C., Hoyer, M., Pedde, M., Cook, R., Touma, J., 2011. Development and evaluation of an air quality modeling approach to assess near-field impacts of lead emissions from piston-engine aircraft operating on leaded aviation gasoline. Atmos. Environ. 45, 5795–5804. https://doi.org/10.1016/j.atmosenv.2011.07.017.

Chang, J.C., Hanna, S.R., 2004. Air quality model performance evaluation. Meteorol. Atmos. Phys. 87 https://doi.org/10.1007/s00703-003-0070-7.

Cimorelli, A.J., Perry, S.G., Venkatram, A., Weil, J.C., Paine, R.J., Wilson, R.B., Lee, R.F., Peters, W.D., Brode, R.W., 2005. AERMOD: a dispersion model for industrial source applications. Part I: general model formulation and boundary layer characterization. J. Appl. Meteorol. 44, 682–693. https://doi.org/10.1175/JAM2227.1.

Cohen, M.A., Ryan, P.B., 1989. Observations less than the analytical limit of detection: a new approach. JAPCA 39, 328–329. https://doi.org/10.1080/08940630.1989.10466534.

Cox, W.M., Tikvart, J.A., 1990. A statistical procedure for determining the best performing air quality simulation model. Atmos. Environ., Part A 24, 2387–2395. https://doi.org/10.1016/0960-1686(90)90331-G.

Doird, 2015. Western Sydney Airport EIS-Local Air Quality and Greenhouse Gas Assessment (No. AQU-NSW_001_9417B). Western Sydney Airport–Environmental Impact Statement.

EPA, 2005. Federal Register :: Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions (2060-AK60 No. 05–21627). EPA-AH-FRL-7990-9.

FAA, 2014. Aviation Environmental Design Tool (AEDT) [WWW Document]. https://aedt.faa.gov/. https://aedt.faa.gov/, 7.31.22.

Feinberg, S.N., Turner, J.R., 2013. Dispersion modeling of lead emissions from piston engine aircraft at general aviation facilities. Transport. Res. Rec. 2325, 34–42. https://doi.org/10.3141/2325-04.

Groma, V.O., Ferenczi, Z., Osán, J., Török, S., Steib, R., 2018. Verification of the EDMS model adapted to Budapest Liszt Ferenc airport. Int. J. E Polit. 63, 137. https://doi.org/10.1504/IJEP.2018.097308.

Hsu, S.A., 1986. A note on estimating the height of the convective internal boundary layer near shore. Boundary-Layer Meteorol. 35, 311–316. https://doi.org/10.1007/BF00118561.

Kim, B., Rachami, J., Robinson, D., Robinette, B., Wyle, K.N., Arunachalam, S., Davis, N., Baek, B.H., Shankar, U., Talgo, K., Yang, D., Hanna, A.F., Wayson, R.L., Noel, G., Gliff, S.S., Zhao, Y., Hopke, P.K., Kumar, P., Airport Cooperative Research Program, Transportation Research Board, National Academies of Sciences, Engineering, and Medicine, 2012. Guidance for Quantifying the Contribution of Airport Emissions to Local Air Quality. Transportation Research Board, Washington, D.C. https://doi.org/10.17226/22757.

Kuzu, S.L., 2017. Estimation and dispersion modeling of landing and take-off (LTO) cycle emissions from Atatürk International Airport. Air Qual. Atmos. Health 11, 1–9. https://doi.org/10.1007/s11869-017-0525-5.

Makridis, M., Lazaridis, M., 2019. Dispersion modeling of gaseous and particulate matter emissions from aircraft activity at Chania Airport, Greece. Air Qual. Atmos. Health 12, 933–943. https://doi.org/10.1007/s11869-019-00710-y.

Martin, A., 2006. Verification of FAA's Emissions and Dispersion Modeling System Verification of FAA's Emissions and Dispersion Modeling System (EDMS) (Master Thesis). University of Central Florida, Orlando, FL. Available at: http://stars.library.ucf. edu/etd/1044.

Penn, S.L., Arunachalam, S., Tripodis, Y., Heiger-Bernays, W., Levy, J.I., 2015. A comparison between monitoring and dispersion modeling approaches to assess the impact of aviation on concentrations of black carbon and nitrogen oxides at Los Angeles International Airport. Sci. Total Environ. 527–528, 47–55. https://doi.org/10.1016/j.scitotenv.2015.03.147.

Perry, S.G., Cimorelli, A.J., Paine, R.J., Brode, R.W., Weil, J.C., Venkatram, A., Wilson, R.B., Lee, R.F., Peters, W.D., 2005. AERMOD: a dispersion model for industrial source applications. Part II: model performance against 17 field study databases. J. Appl. Meteorol. 44, 694–708. https://doi.org/10.1175/JAM2228.1.

Sabatino, S.D., Solazzo, E., Britter, R., 2011. The sustainable development of Heathrow Airport: model inter-comparison study. Int. J. E Polit. 44, 351. https://doi.org/10.1504/IJEP.2011.038436.

Simonetti, I., Maltagliati, S., Manfrida, G., 2015. Air quality impact of a middle size airport within an urban context through EDMS simulation. Transport. Res. Transport Environ. 40, 144–154. https://doi.org/10.1016/j.trd.2015.07.008.

Steib, R., Ferenczi, Z., Labancz, K., 2007. Airport (Ferihegy-Hungary) air quality analysis using the EDMS modeling system. In: Proc. 11th International Conference Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes. Presented at the HARMO, HARMO, pp. 407–411.

Steib, R., Labancz, K., Ferenczi, Z., Alföldy, B., 2008. Airport (Budapest Ferihegy-Hungary) air quality analysis using the EDMS modeling system. Part I. Model development and testing. Q. J.Hungar.Meteorol.Serv. 112, 99–112.

Stunder, M., Sethuraman, S., 1985. A comparative evaluation of the coastal internal boundary-layer height equations. Boundary-Layer Meteorol. 32, 177–204. https://doi.org/10.1007/BF00120934.

Tetra Tech, Inc., 2013. LAX air quality and source apportionment study. Los Angeles World airports. Available at: http://www.lawa.org/airQualityStudy.aspx?id=7716.

Tian, Y., Huang, W., Ye, B., Yang, M., 2019. A new air quality prediction framework for airports developed with a hybrid supervised learning method. Discrete Dynam Nat. Soc. 2019, 1–13. https://doi.org/10.1155/2019/1562537.

Venkatram, A., 1977. Internal boundary layer development and fumigation. Atmos. Environ. 1967 (11), 479–482. https://doi.org/10.1016/0004-6981(77)90011-7.

Wayson, R.L., Brian, K.Y., Hall, C., Thrasher, T., Colligan, B., Draper, J., 2003. Integration of AERMOD into EDMS (No. 355) rosap (https://rosap.ntl.bts.gov/view/dot/10031.

Wei, J., Tang, G., Zhu, X., Wang, L., Liu, Z., Cheng, M., Münkel, C., Li, X., Wang, Y., 2018. Thermal internal boundary layer and its effects on air pollutants during summer in a coastal city in North China. J. Environ. Sci. (China) 70, 37–44. https://doi.org/10.1016/j.jes.2017.11.006.

Zhou, Y., Levy, J.I., 2009. Between-airport heterogeneity in air toxics emissions associated with individual cancer risk thresholds and population risks. Environ. Health 8, 22. https://doi.org/10.1186/1476-069X-8-22.