



# Modeling the air quality impact of aircraft emissions: is area or volume the appropriate source characterization in AERMOD?

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## Abstract

Modeling dispersion of aircraft emissions is challenging because aircraft are mobile sources with varying emissions rates at different elevations depending on the operating mode. Aircraft emissions during landing and take-off cycle (LTO) influence air quality in and around the airport, and depending on the number of aircraft operations and location of the airport, this influence may be significant. AERMOD (v22112) incorporates a variety of conventional source types to characterize the intended emissions source, leaving the question of which conventional source type(s) best characterizes aircraft activities across the four modes of LTO cycle, unanswered. Currently, the publicly released version of FAA's Aviation Environmental Design Tool (version 3e) models aircraft emissions as a set of AREA sources for all flight segments. A research version of AEDT allows users to model aircraft sources—both fixed wing and rotorcraft—as a series of VOLUME sources in AERMOD. However, both source treatments do not account for plume rise of aircraft jet exhaust. This paper compares AERMOD's performance in describing SO<sub>2</sub> concentrations associated with airport sources by comparing model results from the two source options during the summer campaign of the Air Quality Source Apportionment study conducted at the Los Angeles International Airport. We conclude that both VOLUME source and AREA treatments overestimate the highest observed SO<sub>2</sub> concentrations despite not accounting for background sources. The VOLUME source option reduces this overestimation by using a higher initial plume spread than the AREA option does, and through the inclusion of meander. Our results suggest the need to include the plume rise of jet exhaust when using AERMOD for airport air quality studies.

**Keywords** AERMOD · Aircraft · Air quality · Meander · Plume rise · Source characterization

## Introduction

Airports affect air quality in their vicinity because of emissions from aircraft and their supporting systems (Arunachalam et al. 2011, 2017; Kim et al. 2012). This impact is likely to grow over the next few decades as air travel within the United States (U.S.) is projected to increase yearly at the rate of 1 to 2% (FAA 2018). To account for this growth, over half of the 35 busiest airports within the U.S. have increased the capacities of their runways and terminals (Ryerson and Woodburn 2014). These developments are likely to lead to increases in pollutant emissions from aircraft and vehicles

associated with airport operations (Arunachalam et al. 2019; Hudda et al. 2020). There is thus a need for a dispersion model which can demonstrate that the increase in emissions due to this growth results in local air quality that is still in compliance with Federal and local regulations (USEPA 2005).

In 2005, the United States Environmental Protection Agency (USEPA) adopted AERMOD (Cimorelli et al. 2005), the most recent version of short-range steady-state atmospheric dispersion model for air quality regulatory applications. AERMOD (v04300) was incorporated into EDMS (Emissions and Dispersion Modeling System) (Martin 2006) by the U.S. EPA in 2006 despite the fact that AERMOD was not designed to model elevated mobile sources. In May 2015, EDMS was replaced by the FAA's (Federal Aviation Administration) AEDT (Aviation Environmental Design Tool (FAA 2023)), which includes AERMOD as the air quality model. The representation of mobile sources, such as motor vehicles and aircraft sources during the LTO

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cycles, is traditionally represented as AREA or VOLUME sources placed at various heights AERMOD (v22112) recently included an option to model on-road mobile sources as LINE segments.

Several studies have treated airport-related emissions with AREA sources (using EDMS or AEDT) in applying AERMOD (Makridis and Lazaridis (2019); Tian et al. (2019); Groma et al. (2018); Kuzu (2017); Arunachalam et al. (2017); Doird (2015); Penn et al. (2015); Simonetti et al. (2015); Feinberg and Turner (2013); Tetra Tech Inc (2013); Kim et al. (2012); Sabatino et al. (2011); Zhou and Levy (2009) and Barrett and Britter (2008); Steib et al. (2007); Martin (2006) and Wayson et al. (2003)). To our knowledge, there is only one study in the open literature in which these emissions are characterized (using EDMS) as VOLUME sources (Carr et al. 2011). However, both the source types do not account for plume rise of jet exhaust. Furthermore, the current AREA source treatment does not account for plume meander, which is important in low and variable wind conditions. Currently, AERMOD is the only regulatory tool that can be utilized to demonstrate regulatory compliance in the U.S.; AERMOD allows the user to represent emissions as POINT, AREA, AREAPOLY, LINE, or VOLUME sources. Although the choice of representation is clear in most cases, it is not for atypical sources such as aircraft, which move over the airport and whose exhausts have both horizontal momentum and buoyancy.

In this paper, we compare the results from AERMOD when airport sources are represented as either AREA or VOLUME sources. The data used in the comparison were collected during the summer campaign of the Los Angeles International Airport (LAX) Air Quality Source Apportionment study (AQSAS) conducted at the LAX in California during the period July 18–August 28, 2012. Measured SO<sub>2</sub> concentrations were used in this exercise because the majority of sources close to LAX emit little SO<sub>2</sub> compared to aircraft. These emissions can be readily quantified because they depend on the sulfur content of aircraft fuel.

## Methodology

### Aviation Environmental Design Tool

FAA has developed and maintained the AEDT to perform dispersion modeling for airport-related emission sources to support the analysis required by the National Environmental Policy Act (NEPA) and the Clean Air Act, among other regulatory requirements and requests within the U.S. (FAA 2023). AEDT can be used to support the development of a geospatial and temporal distribution of emissions (referred to throughout as “emissions inventory”) for aviation sources including aircraft (e.g., elevated, ground

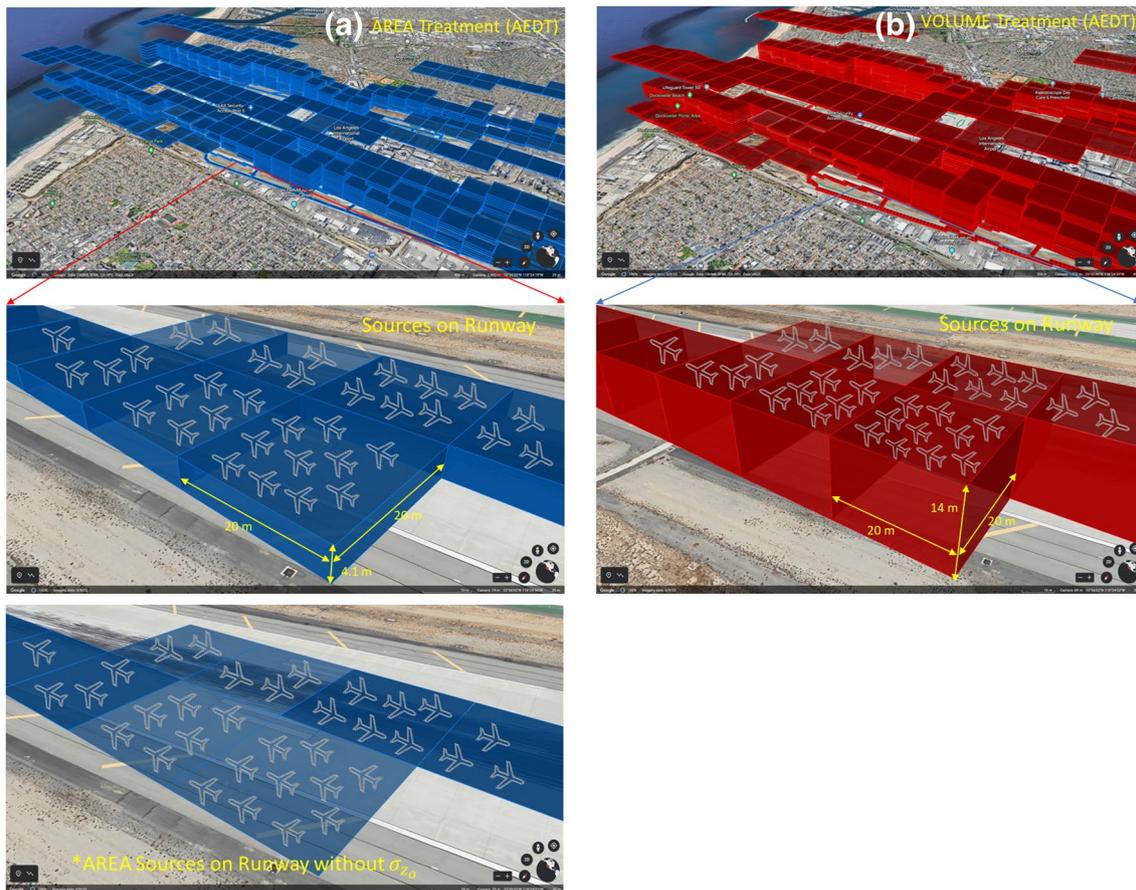
roll, and taxi segments) and other airport activities such as ground support equipment (GSE), ground access vehicles (GAVs), auxiliary power units (APUs), and stationary sources (FAA 2023). AEDT has two embedded models for dispersion modeling. These models, developed and maintained by the U.S. EPA, include the American Meteorological Society (AMS) and U.S. EPA Regulatory Model (AERMOD) and its preprocessor for meteorological data (referred to throughout as “met data”), AERMET.

AERMOD uses the AEDT emissions inventory and two sets of meteorological data (surface and upper air), generated by AERMET, to model dispersion of airport emissions. AERMET processes raw met data from observations from sources such as the National Weather Stations (NWS) to create micrometeorological inputs required by AERMOD. AERMOD yields concentrations at selected receptors.

AEDT uses existing internal databases of physical airport layouts (here LAX) and aircraft source characteristics, together with user inputs of aircraft operations schedules, weather data, and runway use patterns to develop AERMOD-ready emission files for pollutants of interest with a time resolution of 1 h (FAA 2023). In the publicly available version of FAA’s AEDT, all segments of an aircraft operation (e.g., elevated, ground roll, and taxi segments) are modeled as one or more AREA sources that default to an aspect ratio of 10:1, which is an AERMOD requirement. AEDT utilizes a 3-dimensional voxel grid to represent aircraft emissions, mainly designed to collect emissions from airborne segments. However, while voxel grids satisfy the 10:1 requirement of AERMOD, they do not necessarily fix the aspect ratio to 10:1, with taxi segments being the exception. The height of the entire voxel grid for an airport study is limited to a mixing height of 3000 ft (914.4 m). The emissions can be characterized as AREA or VOLUME sources; the latter (implemented in AEDT version 3e) is not available to the public yet as this feature is hidden behind a hash key (FAA 2023), but is likely to be released in the near future.

In AERMOD, emissions from distributed sources are described as AREA sources over a defined area with a specified vertical spread; the emissions are assumed to be uniformly distributed over the specified area (Fig. 1a). On the other hand, the VOLUME representation treats these sources as a set of three-dimensional sources with a defined volume, and emissions are assumed to be released vertically from a specific height (Fig. 1b) (USEPA 2022).

In Fig. 1, we illustrate how AEDT treats the emissions at each surface source irrespective of the source characterization; AEDT assigns these emissions to each cuboid by adding the emissions from the aircraft as they travel through each cuboid in a particular hour. As required by AERMOD, it yields emissions as gram/second per square meter for AREA sources and gram/second for VOLUME sources.



**Fig. 1** Schematic of AERMOD standard (a) AREA and (b) VOLUME sources. (Note: Number of aircraft in each cuboid is arbitrary and for illustration purpose only)

Airborne sources are treated in a similar manner. In AEDT, cuboids located less than 300 m above ground have a default vertical spacing of 20 m. For cuboids above 300 m, the spacing extends from 300 m to mixing height (~914.4 m, it is fixed for emission dispersion within AEDT); there is only one cuboid that extends from 300 to ~914.4 m, and it is situated at ~619.2 m. In other words, all aircraft emissions above 300 m are assigned at 619.2 m in a single bin as an AREA or VOLUME source in AEDT. In addition, the horizontal spacing for aircraft AREA or VOLUME airborne sources is set to 200 m. The orientation angle of aircraft AREA sources is zero. The release height of aircraft surface AREA or VOLUME sources is equal to the average vertical distance between sources plus 12 m from ground level. The options above can be changed based on selected modeling preferences within AEDT. Aircraft AREA sources have an initial vertical dimension/dispersion parameter ( $\sigma_{z_0}$ ) of 4.1 m whereas VOLUME sources use 14 m based on LIDAR measurements made at the Los Angeles airport by Wayson et al. (2004). This cannot be changed by the user. However, in this study, to perform the sensitivity analysis,

we changed it manually after generating AERMOD input files from AEDT.

The differences in model results resulting from the two source treatments are best illustrated by applying AERMOD to the Los Angeles International Airport, where the necessary model inputs, emissions, and meteorology were developed to analyze data from field studies conducted in 2012. We next provide brief descriptions of the airport and the field studies.

### Brief description of LAX AQSAS

For a community near any airport, the impact of airport operations on air quality is a potentially major public health problem. LAX is one of the busiest airports in the U.S. and is situated close to the Los Angeles downtown. To determine the extent of the LAX airport's effects on the neighborhood, the Los Angeles World Authority (LAWA) carried out the Los Angeles Source Apportionment Study (LAX AQSAS Phase III) in 2012 over the course of two separate 6-week field monitoring

campaigns: the “winter observation period” from January 31 to March 13, 2012, and the “summer observation period” from July 18 to August 28, 2012 (Tetra Tech Inc 2013).

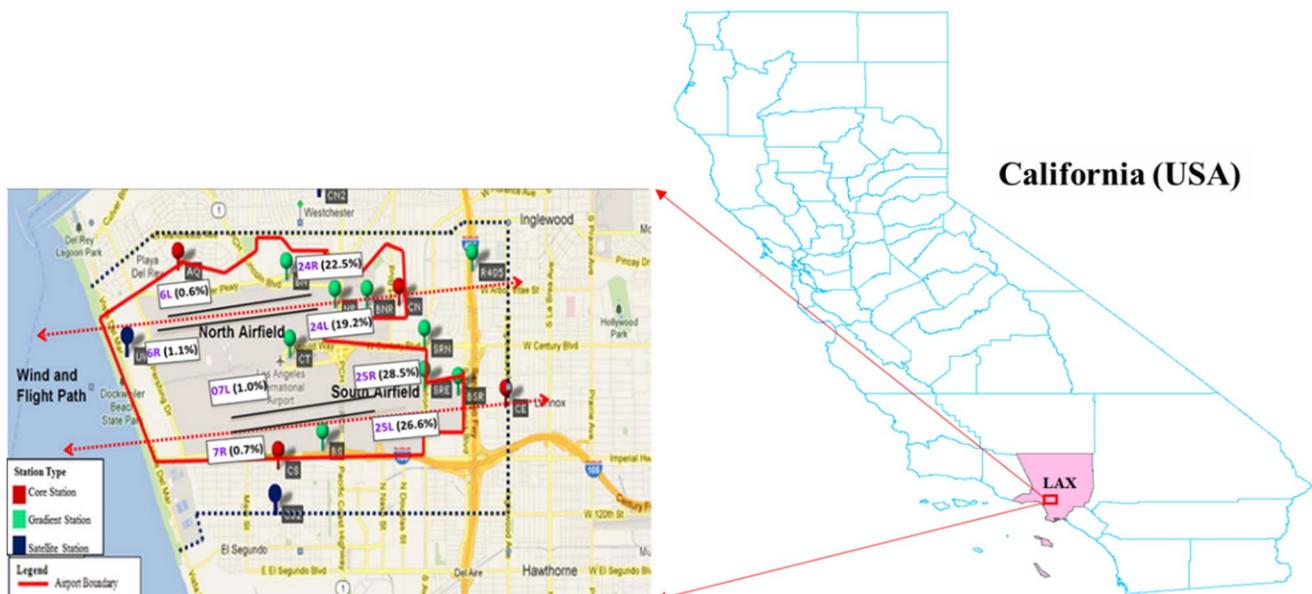
Three different types of measurement sites (four “core,” four “satellite,” and nine “gradient”) with various time scales were used to measure NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, CO, and BC (black carbon) in both the winter and summer seasons (Fig. 2). The LAX airport has two main airfields, South Airfield, and North Airfield, each with two runways. Numerous air quality measurements were made at four key sites: the “Air Quality (AQ) site,” the “Community North (CN) site,” the “Community South (CS) site,” and the “Community East (CE) site” (Tetra Tech Inc 2013; Arunachalam et al. 2017, ACRP Report 179).

AERMET was used to create the hourly meteorological inputs for this study period utilizing surface data from KLAX (Los Angeles Airport) (WBAN 722950) and upper air soundings from KNKX (San Diego Marine Corps Air Station) (WBAN 722930), situated 89 miles from LAX.

Figure 3 shows the distribution of SO<sub>2</sub> concentrations measured at these sites during the LAX field study. We see that the highest concentrations occur around 9 AM and do not exceed 6.3 ppb. The bottom panel of the figure (Fig. 3b) indicates that these concentrations are associated with friction velocities ( $u_{*s}$ ) between 0.15 and 0.3 m/s rather than values close to 0.1 m/s, which is not expected if all the major sources are close to the ground. We examine whether the magnitude of the highest concentrations and the behavior of observed concentrations are reflected by model estimates from the AREA and VOLUME treatments of aircraft sources.

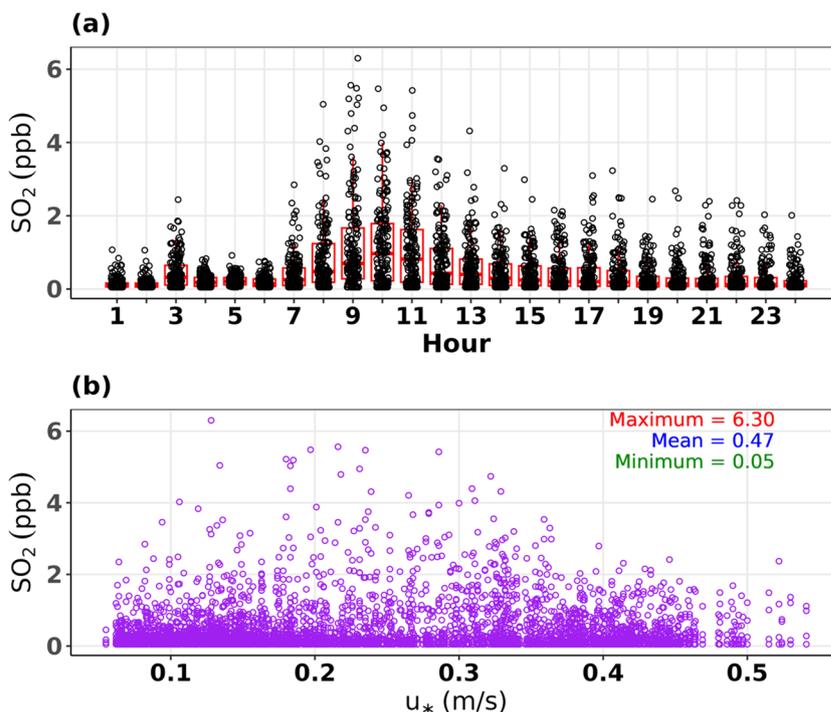
## Modeling study design

In applying AERMOD to the LAX, FAA’s AEDT (version 3e) was used to model surface aircraft emissions as a series of 20 m × 20 m (length × width) AREA sources and airborne emissions as a series of 200 m × 200 m (length × width). AREA source segments had initial vertical spreads ( $\sigma_{z_0}$ ) of 4.1 m (Table 1). Figure 1 represents the visualization of standard AERMOD AREA and VOLUME sources. As stated earlier, FAA recently added a new feature that is hidden behind a hash key (not publicly available) in AEDT 3e (FAA 2023) that allows users to model aircraft sources—both fixed wing and rotorcraft—as VOLUME sources with a fixed initial lateral ( $\sigma_{y_0}$ ) and vertical dispersion ( $\sigma_{z_0}$ ) parameters based on each aircraft type, and whose values are fixed irrespective of the aircraft category (Table 1). The initial plume dimension,  $\sigma_{z_0}$ , for an AREA source is used as 4.1 m (fixed value, however input of  $\sigma_{z_0}$  is optional for AREA sources within AERMOD framework) while  $\sigma_{z_0}$  for VOLUME source is fixed at 14 m based on LIDAR measurements made at the Los Angeles airport by Wayson et al. (2004).  $\sigma_{y_0}$  for a VOLUME source is the length of the side/4.3 (USEPA 2022). We used this feature to model aircraft as VOLUME source as an alternative to the traditional AREA source approach segments. However, GATE sources are modeled as AREAPOLY (AREA–Polygon) in both types of aircraft AEDT source treatments. Based on the height and LTO cycle, we divided all the AERMOD sources into the following five source categories:



**Fig. 2** Locations of core, gradient, and satellite monitoring stations at LAX during AQSAS Phase III (adapted from Arunachalam et al. (2017), ACRP Report 179; Pandey et al. (2022)). Pink polygon on the right is the Los Angeles County, within which the LAX airport is located

**Fig. 3** Overall observed SO<sub>2</sub> concentration distribution (a) at each hour, and (b) with friction velocity ( $u_*$ ) during the 42 days in the summer season of 2012 at LAX



**Table 1** AERMOD source input parameters for the source treatments

Source group		Release height (m)	Source treatment					
			AREA			VOLUME		
			Length (m)	Width (m)	Angle (degree)	$\sigma_{z_0}$ (m)	$\sigma_{y_0}$ (m)	$\sigma_{z_0}$ (m)
Airborne	AIRG300M	619.2	200	200	0	4.1	46.51	14
	AIRL300M	22 to 302	200	200	0	4.1	46.51	14
Surface	Runway	12	20	20	0	4.1	4.65	14
	Taxi	12	Variable	Variable	Variable	4.1	4.65	14

- AIRG300M—all airborne sources greater than 302 m height (generally, AEDT places all these sources at 619.2 m height),
- AIRL300M—all airborne sources up to 302 m height,
- GATE at height 1.5 m,
- RUNWAY at a height 12 m along runways, and
- TAXI at height 12 m.

The source characterization/number of GATE sources are similar in both AREA and VOLUME studies as AREAPOLY.

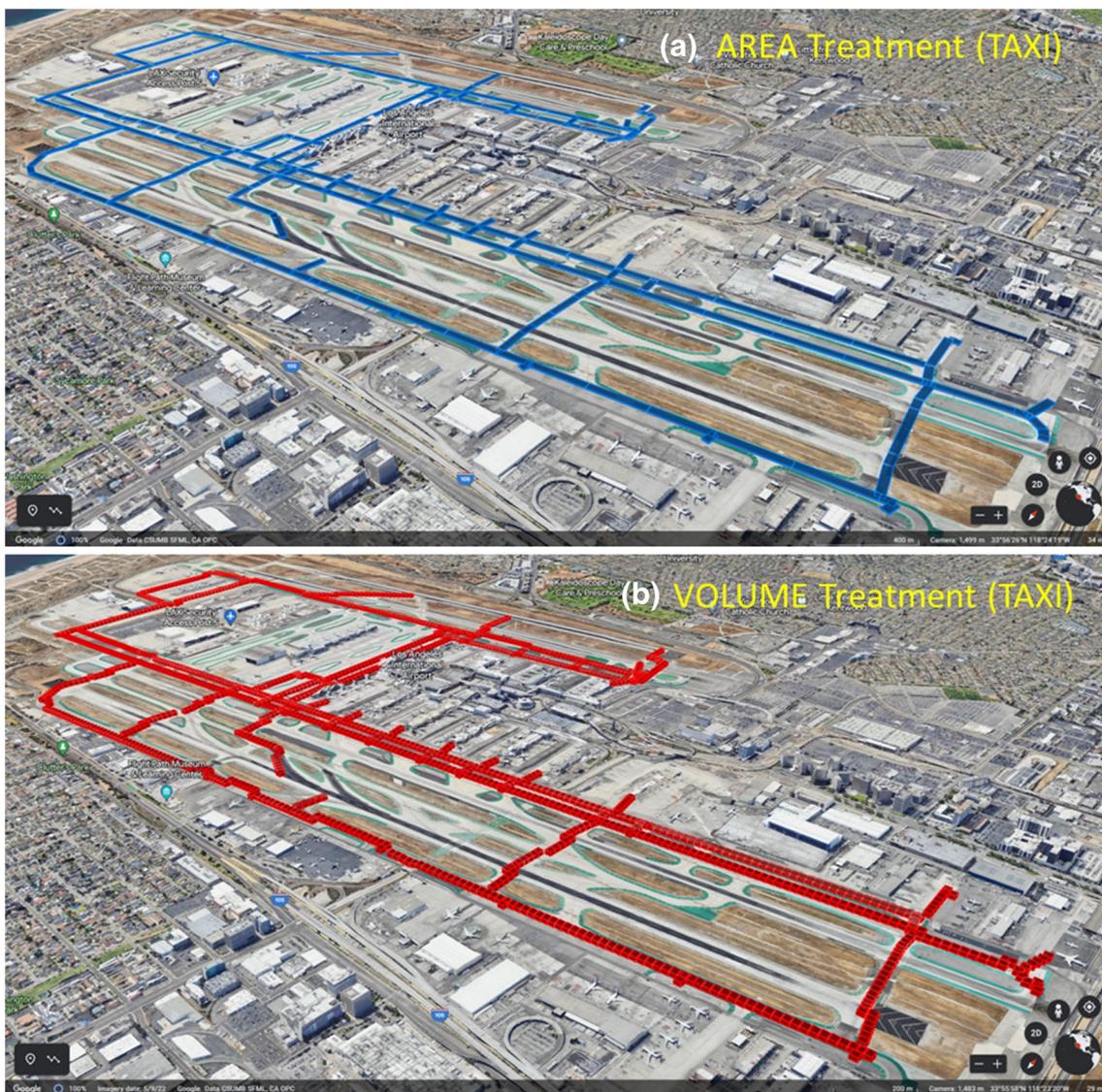
In AERMOD, the width, length, and angle define the shape and orientation of the AREA source. These variables allow users to specify the dimensions and orientation of the emission source in the horizontal plane. In this study, the group length, width, and angle parameters are varied from 20 to 22.86 m, 0 to 227.92 m, and  $-180^\circ$  to  $180^\circ$  respectively, to describe the orientations and shapes of the taxiways at the Los Angeles Airport.

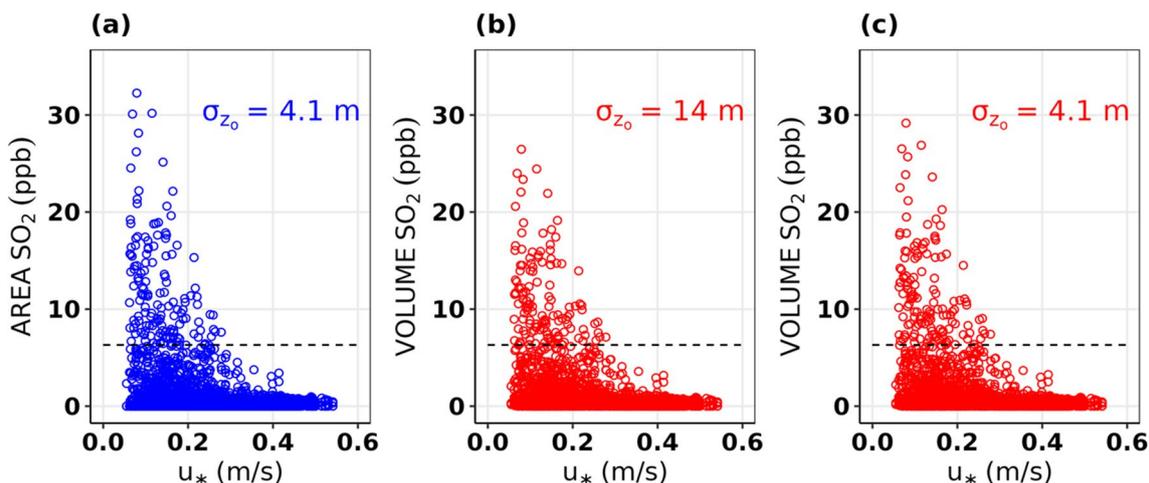
### AEDT source placement and emissions in LAX study

We compared the number of sources in AEDT-generated AERMOD-ready input files for AREA and VOLUME representations of sources. The number of VOLUME sources to describe TAXI sources is about 14 times the number of AREAs (Table 2). The reason for this is that each TAXI link is modeled as a single AREA source corresponding to the true length and width of the taxi paths (as a rectangle) (Fig. 4a). In the VOLUME description, each TAXI link is divided into 20 m  $\times$  20 m squares housing a VOLUME with a fixed aspect ratio of 1:1 (Fig. 4b). The number of RUNWAY and AIRBORNE sources are 38% and 45% higher in the VOLUME treatment compared to the AREA treatment (Table 2). Note that in the VOLUME treatment, each aircraft type (e.g., turbojet, turbofan, turboprop, turboshaft, and helicopter) is separated as a separate source for each cuboid. The total SO<sub>2</sub> emissions are distributed among the VOLUMES and AREAs. A detailed description of emissions comparison is provided in the supplementary information of this paper.

**Table 2** Quantitative comparison of number of sources and emissions in AREA and VOLUME treatments

Source group		Number of sources in each treatment		Increase (%) in VOLUME		SO <sub>2</sub> emissions (ton/period) in each treatment	
		AREA	VOLUME			AREA	VOLUME
Airborne	AIRG300M	19,013	26,296	38.3	44.7	11.91	11.91
	AIRL300M	4729	7142	51.0		5.81	5.81
Surface	RUNWAY	2593	3569	37.6		6.00	6.00
	TAXI	248	3320	1238.7		14.01	14.01
	GATE	21	21	0		1.19	1.19
Total		26,604	40,348	51.7		38.92	38.92

**Fig. 4** Taxi source placements at LAX in (a) AREA, and (b) VOLUME treatments



**Fig. 5** Variation of AERMOD estimates with the friction velocity for (a) AREA, and (b and c) VOLUME source treatments with differing  $\sigma_{z_0}$ . The black dashed line represents the overall maximum observed  $\text{SO}_2$  concentration at LAX

**Model results**

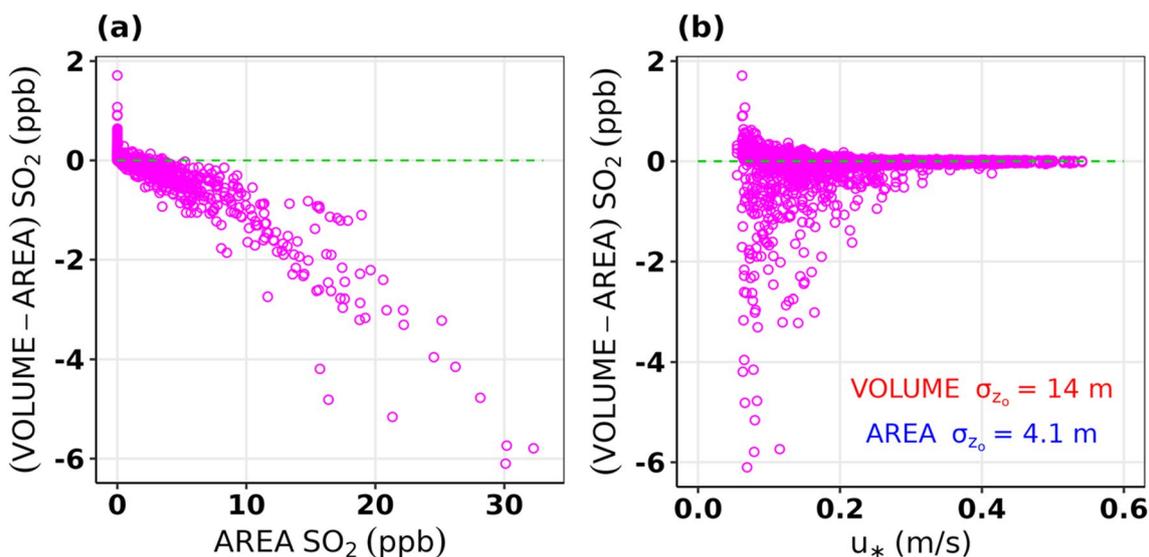
**Dispersion comparison from the source treatments**

Here, we compare AERMOD estimates of  $\text{SO}_2$  from the two source treatments at the four core sites. For this comparison, we use the same number of sources in both treatments by manually converting all the VOLUME sources into AREA sources and fixing the  $\sigma_{z_0}$  as 4.1 m. The detailed description based on these conversions (sensitivity case) is included in the supplementary information of this paper.

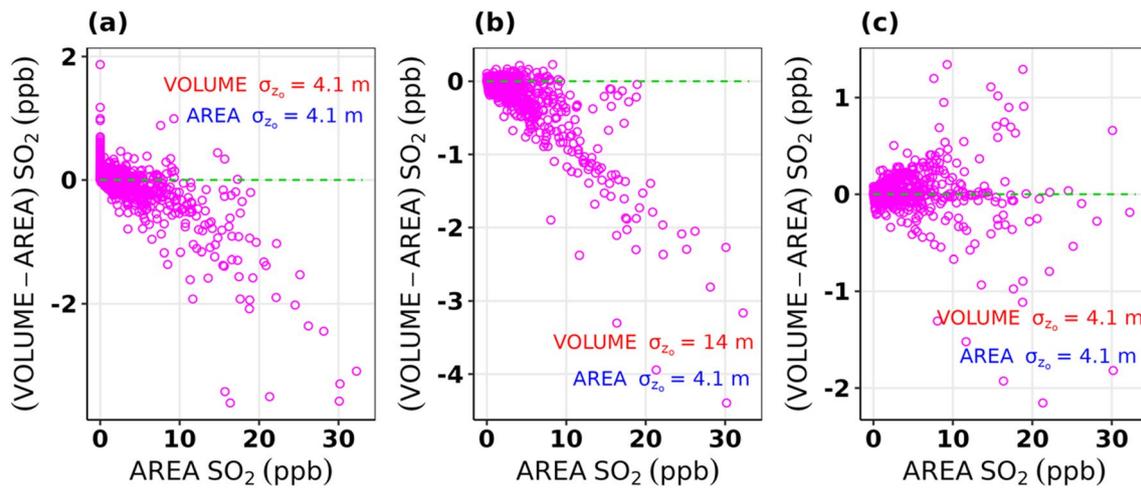
Figure 5 compares the variation of AERMOD estimated  $\text{SO}_2$  concentrations with the friction velocity,  $u_*$ , for the

two source treatments. It shows that both model estimates do not reflect the behavior of the observed  $\text{SO}_2$  concentrations: the concentrations decrease with  $u_*$  with the highest values occurring close to the lowest values of  $u_*$ , while the observed maxima occur between  $u_* = 0.15$  to  $0.3$  m/s. Furthermore, the maximum concentrations are above 20 ppb, a value that is well above the observed 6.3 ppb. We expect the model estimates to be lower than the observed high values because they do not include background sources.

The VOLUME treatment provides lower estimates at the high end of the concentration distribution as seen in Fig. 6. The VOLUME treatment is consistently lower than the AREA description with the discrepancy increasing with



**Fig. 6** Differences between model estimates from the two source treatments. (a) Comparison against AREA source treatment, and (b) comparison against  $u_*$



**Fig. 7** Impact of  $\sigma_{z_0}$  and meander on VOLUME estimates. (a) Left panel uses the same  $\sigma_{z_0}$  for the two source treatments, the (b) middle and (c) right panels remove meander

the AREA estimate. These differences are most evident at the lowest values of the friction velocity ( $u_*$ ). The largest difference is about 6 ppb when the AREA model estimate is about 30 ppb.

The lower values of  $\text{SO}_2$  from the VOLUME treatment are associated with higher initial  $\sigma_{z_0} = 14$  m (AREA  $\sigma_{z_0} = 4.1$  m) and the inclusion of meander. Figure 7 shows that using the same values of  $\sigma_{z_0} = 4.1$  m does not remove the trend in the VOLUME estimates: they are still lower, but the values are higher than those in the default VOLUME description. The middle panel of Fig. 7 indicates that the larger  $\sigma_{z_0} = 14$  m in the VOLUME treatment contributes more than the removal of meander to the values in the high end of the VOLUME estimates relative to the corresponding AREA estimates. Figure 7 c shows that results from VOLUME are within 1 ppb of the AREA description when  $\sigma_{z_0}$  values from the two descriptions are set to the same value of 4.1 m and meander is switched off.

In addition, the detailed description of each sensitivity based on the number of sources,  $\sigma_{z_0}$ , and meander component and the findings from the sensitivity are provided in the supplementary information of this paper.

## Conclusions

Pollutant emissions from airports have significant impacts on surrounding air quality. Estimating this impact using a dispersion model poses a difficult problem because most of the emissions originate from moving sources, the aircraft. These sources move over large areas of the airport during taxiing, taking off, and landing. Most dispersion models, such as AERMOD, are not designed to handle such moving sources. AERMOD can estimate the impact of vehicular

emissions only because the density of vehicles on a highway is usually large enough to assume that the vehicles are embedded in a stationary line source of emissions. This assumption might hold for emissions originating from aircraft lining up to take their turn for take-off. This situation might occur in busy airports during peak hours but is unlikely in most airports. So, it becomes necessary to represent the emissions from moving aircraft as originating from stationary areas over which the aircraft traverse before takeoff and after landing. These areas can be at elevated locations that the aircraft occupy in the atmospheric boundary layer.

These areas of emissions can be treated in one of two ways, as AREA sources or VOLUME sources in AERMOD. The analysis results presented in this paper show both treatments of airport sources do not yield AERMOD model estimates that are consistent with the magnitudes and the trends of the observed  $\text{SO}_2$  concentrations. The VOLUME description yields lower concentrations than those from the AREA description, but the magnitude of the highest concentrations is about five times larger than the observed values even when background sources are not included.

These results suggest that the inclusion of a plume rise algorithm for aircraft jet exhaust is likely to yield model estimates that are more consistent with observations than those from the current version of AERMOD for both source treatments. Carslaw et al. (2006) show, through an analysis of data collected at Heathrow Airport, that plume rise of jet exhaust gives rise to the observed behavior of concentrations varying with friction velocity. Pandey et al. (2023) provide an approach to modeling plume rise for aircraft sources in AERMOD. The magnitudes of the plume rise estimated by the model are an order of magnitude higher than the 14 m specified in VOLUME. Also, adding plume rise would avoid

arbitrary assumptions about the initial vertical spread of the plume in AERMOD. In addition to plume rise, the inclusion of meander in AREA source treatment will enhance the low concentrations and potentially reduce the magnitude of the high concentrations.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s11869-024-01517-2>.

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**Author contribution** Gavendra Pandey: conceptualization, methodology, software, data curation, formal analysis, writing—original draft. Akula Venkatram: methodology, validation, writing—review and editing. Saravanan Arunachalam: conceptualization, methodology, project administration, supervision, funding acquisition, writing—review and editing.

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**Data availability** Data will be made available on request.

## Declarations

**Ethics approval** Not applicable.

**Consent for publication** All the authors gave their consent for the publication of this manuscript.

**Competing interests** The authors declare no competing interests.

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