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Accounting for plume rise of aircraft emissions and shoreline meteorology enhances AERMOD's description of concentrations measured around Los Angeles airport

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ABSTRACT

The Aviation Environmental Design Tool (AEDT), developed by the FAA, is used to analyze the environmental impact of airport activities on air quality and noise near airports. AEDT incorporates AERMOD to estimate concentrations resulting from aircraft emissions, which possess horizontal momentum as well as buoyancy. The current version (v23132) of AERMOD incorporates plume dynamics associated with such emissions as an ALPHA option. AERMET, AERMOD's meteorological processor does not account for the meteorology of the land-water interface that is likely to be important for airports located on the shorelines of lakes or oceans. An approach to include these effects in AERMOD was previously developed. This study examines the impact of including plume rise and shoreline effects in AERMOD by evaluating model estimates of NO_X and SO_2 with corresponding measurements made during the Los Angeles Airport Air Quality Source Apportionment Study (AQSAS) in the winter and summer of 2012. The performance statistics resulting from this model evaluation suggest that the inclusion of plume rise of aircraft emissions and shoreline effects on meteorological inputs is likely to improve AERMOD's ability to estimate the impact of airport emissions on surrounding air quality.

Implications: Because airport emissions, particularly those from aircraft, affect local air quality, the National Environmental Policy Act (NEPA) requires the use of dispersion models such as AERMOD to assess compliance of air quality regulations when potential expansions of airport activity are planned. The current regulatory version of AERMOD does not include aircraft-specific plume rise and shoreline-related meteorological processes, which affect the dispersion of airport emissions. The preliminary evidences presented in our previous work suggest that the incorporation of these effects will enhance AERMOD's ability to estimate NO_X and SO_2 concentrations associated with airport emissions. These enhancements are beneficial not only for policy-making and regulatory compliance but also for promoting sustainable development near airports and protecting public health.

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Introduction and objectives

Airports play a crucial role in facilitating the movement of people and goods, promoting regional, national, and global commerce and serving as the intersection point between various transportation modes (Arunachalam et al. 2017). Emissions from airports have characteristics that differ from stationary sources because the significant fraction that originates from moving aircraft is associated with horizontal momentum in addition to buoyancy. Several studies have examined the impact of aircraft emissions during landing and takeoff (LTO) operations (Arunachalam et al. 2011) as well as during full flight (Barrett, Britter, and Waitz 2010; Vennam et al. 2017). However, the grid-based models used in these studies did not have the spatial resolution to examine the impact of plume behavior in the immediate vicinity of airports. The analysis of data collected during the Project for the Sustainable Development of Heathrow (PSDH), conducted at Heathrow Airport, suggested that the behavior of jet plumes had noticeable effects on ground-level concentrations of NO_X measured at monitors within and in the vicinity of the airport (Carslaw et al. 2006, 2008). Such studies have motivated the development of plume-rise algorithms for dispersion models. The ADMS-Airport model (Carruthers et al. 2011; CERC, 2020) includes a plume-rise algorithm that accounts for the

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momentum and buoyancy of jet emissions in a reference frame attached to aircraft. The LASPORT model (Janicke, Fleuti, and Fuller 2007), applied in several European countries, estimates the impact of airport emissions using a Lagrangian approach to track particles from sources. This approach considers only horizontal momentum in simulating jet emissions. Barrett, Britter, and Waitz (2013) developed a three-dimensional model for aircraft plume rise based on equations governing the evolution of the mass, the momentum, and the buoyancy of aircraft engine emissions. This numerical model has not been included in any dispersion model.

The results from the previous studies on plume rise have guided the formulation of a plume-rise model that we have incorporated into AERMOD (v23132) (Cimorelli et al. 2005), which is a component of the Aviation Environmental Design Tool (AEDT) (FAA, 2023). In AERMOD, most of the airport sources, including aircraft, are currently treated as area or volume sources. In the earlier version of AERMOD (v22112) for regulatory applications, plume rise is treated by prescribing the initial plume height and width of the volume source associated with jet emissions. These dimensions, based on LIDAR observations made by Wayson et al. (2008), do not explicitly account for the evolution of the plume governed by momentum and buoyancy dynamics. Recently, USEPA released a new version (v23132) with an ALPHA option referred to as "ARCFTOPT" that accounts for plume rise of aircraft emissions with an algorithm described in Pandey, Venkatram, and Arunachalam (2023).

In this paper, we compare the results from AERMOD (v23132) with measurements when airport sources are modeled as area sources, with and without the new plume-rise algorithm, in describing the dispersion of jet plumes. The data utilized in the evaluation are NO_X and SO_2 concentration measurements obtained during the 2012 winter and summer campaigns of the LAX Air Quality Source Apportionment Study (AQSAS) at the Los Angeles International (LAX) airport in California.

Description of the LAWA field study

Los Angeles International Airport (LAX), the main airport serving the Greater Los Angeles Area, was the eighth busiest airport in the world and fourth in the United States in 2023, with approximately 75 million passengers. This represents a growth of over 1 million passengers per year since 2012, when the passenger volume was approximately 63.7 million (LAWA 2024). Concern over the impact of LAX emissions on surrounding air quality motivated the LAX Air Quality Source Apportionment study (LAX AQSAS). This study was carried out by Los Angeles World Airports (LAWA) authority in three stages to assess the impact of air pollutants from LAX activities in and around the airport during two different six-week field measurement campaigns: the "winter monitoring season" from 1/31/12 to 3/13/12 and the "summer monitoring season" from 7/18/12 to 8/28/12 (Tetra Tech, Inc 2013). The primary objective of the LAX AQSAS was to assess the potential impacts of airport-related emissions on ambient air quality of communities located next to the airport. In the winter and summer monitoring seasons, chemical species such as NO_X, SO_2, $PM_{2.5}$, CO, and BC (Black Carbon) were measured at three different types of measurement sites: four "core" sites, named Air Quality (AQ), Community North (CN), Community South (CS), and Community East (CE), and four "satellite" and nine "gradient" sites at different time scales (Figure 1).

The LAX airport has two main airfields, South Airfield and North Airfield, each with two runways (Figure 1). Extensive air quality observations were measured at the four core sites, AQ, CN, CS, and CE. The AQ site was located at the South Coast Air Quality Management District (SCAQMD), Hastings site, which was northwest of the airport in Playa del Rey. The CN was located at Westchester, about 1.5 km east of the North Airfield. The CS 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 located at Lennox, approximately one-half km east of the I-405 Freeway and about 1.5 km east of the South Airfield (Figure 1) (Tetra Tech, Inc 2013; Arunachalam et al. 2017, ACRP Report 179).

In this study, model estimates were compared with 1-hour averaged SO_2 and NO_X concentrations measurements made at the four core monitoring sites—AQ, CN, CS, and CE—for 42 days during each of the winter (02/01/2012–03/13/2012) and summer (07/18/2012– 08/28/2012)) seasons at the LAX Airport. Before describing the measurement–model comparisons, we provide a summary of the wind flow patterns that affected the concentrations at the four monitors.

Summary of observed data

Observed plume behavior at core sites

Bivariate polar plots are useful in identifying the sources of pollutants measured at sites (Carslaw et al. 2006). Figures 3 and 4 show the variation of SO_2 and NO_X concentrations with wind speed and wind direction at the four core sites—AQ, CN, CS, and CE— during the winter and summer studies. These plots are best interpreted by examining the wind roses generated with data

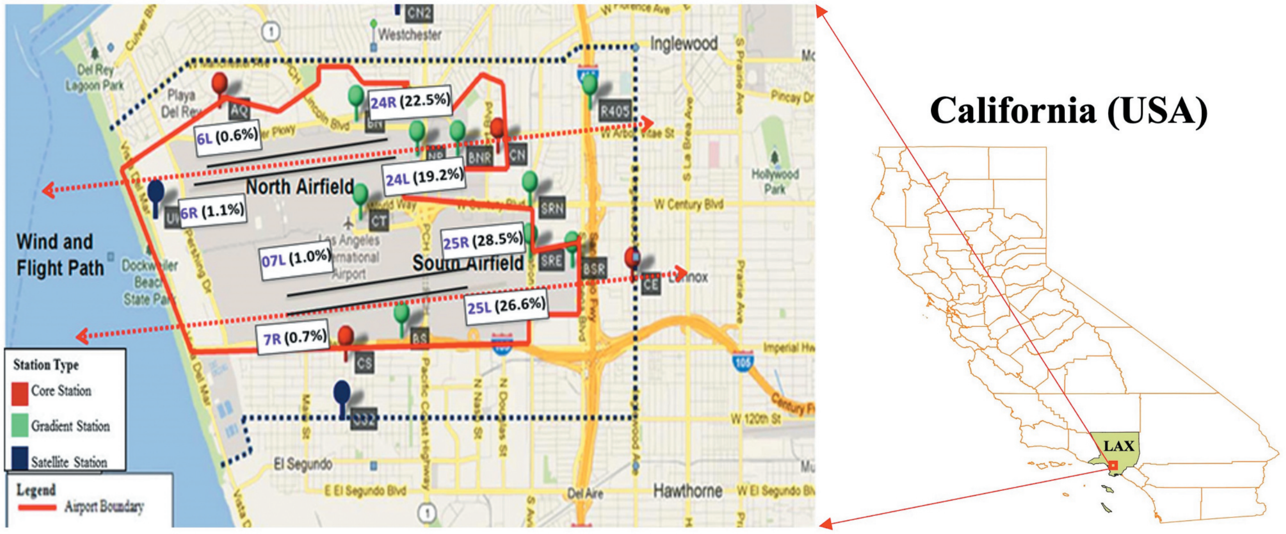

Figure 1. Locations of core, gradient, and satellite monitoring sites at LAX during AQSAS Phase III (adapted from (Pandey, Venkatram, and Arunachalam 2022; Arunachalam et al. 2017, ACRP report 179). (The green polygon on the right is the Los Angeles County, within which the LAX airport is located.).

from AERMET (USEPA, 2023), the meteorological preprocessor of AERMOD. In winter, the winds originate from the northeast during the late night and early morning hours, maintaining this direction until approximately hour 8. The winds are westerly during the remaining hours; the speeds are higher during this time compared to those during the nighttime hours. During summer, the winds blow from the west about 90% of the time. The winds are relatively calm during the period from 1 to 8 hours (Figure 2).

At AQ, the highest mean SO_2 concentrations occur when the wind is blowing from the southeast at around 5 m/s (Figure 3). At CN, the highest mean measured SO_2 concentrations occur when the wind is coming from the west, southwest, and south directions when the wind speed is between 4 m/s and 8 m/s (Figure 3). This behavior of concentrations at CN is consistent with the fact that aircraft-related operations occur upwind of CN for these wind directions during daytime in winter and most of the time during summer (Figure 1). Site CS, located south of the south airfield, is impacted by tall buildings of downtown Los Angeles city when the winds are southeasterly and southwesterly (Figure 1). The peak measured SO_2 mean concentration occurs when winds are from the northeast direction at a wind speed of around 10 m/s during the winter season. This suggests that the impact of emissions during takeoff from the end of the south airfield (Figure 3a). In summer, the observed SO_2 mean concentration is lower because the prevailing westerly winds do not transport emissions to the site (Figure 3b). Site CE is largely impacted by roadway sources, and it has lower SO_2 concentrations because this site is located next to the major highways where SO_2 emissions from vehicles are negligible compared to those from aircraft. The mean SO_2 concentrations reach 0.5 ppb when the westerly and southwesterly winds transport emissions from the airport to the site. In both winter and summer, westerly winds result in higher contributions from on-airport sources especially at the CN and CE monitoring sites.

At AQ, the highest mean NO_X concentrations occur when the wind blows from the southeast or east at 5 m/s. (Figure 4). This observed behavior is attributed to the contribution of aircraft-related operations to this site; AQ is north of the north airfield end (Figure 1). At CN and CS sites, during the winter study, the highest mean NOx concentrations occur when the wind blows from the northeast; this does not happen during the summer study (Figures 4). The behavior during winter is attributed to NOx emissions during landing and takeoff operations in the south airfield (Figure 1). At site CE, the highest mean NO_X concentrations occur when the wind blows from the northeast or east (Figure 2); this is likely due to contributions from roadway sources to site CE, which is next to major highways (Figure 1). Overall, during winter, the mean NO_X concentrations are approximately twice those measured during summer at all four core sites. The mean NO_X concentrations reach 15–20 ppb when westerly winds transport emissions from aircraft-related operations to the sites.

A detailed analysis of observed SO_2 and NO_X concentrations and explanation of the potential contribution from aircraft activity during LTO operations is given in the supplementary information/material of this paper.

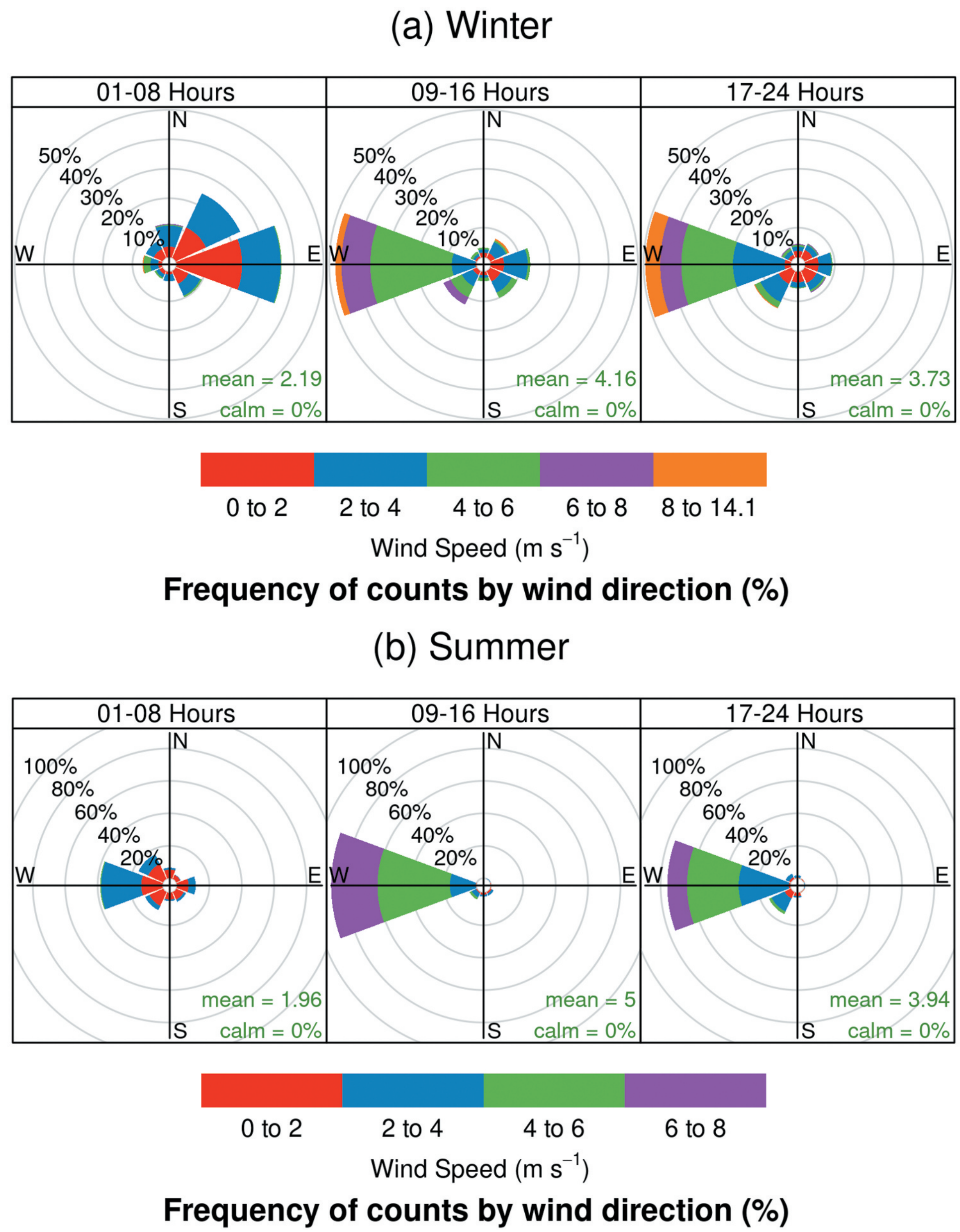

Figure 2. Wind rose plots in (a) winter and (b) summer seasons of 2012, showing frequency of counts by wind direction as a percentage of the total from all directions.

Description of Model

Aircraft plume-rise methodology within AERMOD

AERMOD (version 23132, https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models) is currently used to address the majority of airport sources, including aircraft, which account for a substantial fraction of airport emissions. Aircraft emissions during landing and takeoff (LTO) cycles are transient and buoyant and occur at various altitudes above the ground. AERMOD accounts for emissions at different altitudes and the latest version accounts for the plume rise of jet emissions using the approach described in Pandey, Venkatram, and Arunachalam (2023).

We incorporate the plume-rise algorithm in the area source framework of AERMOD (Pandey, Venkatram, and Arunachalam 2023) by assuming that the different types of aircraft contributing to emissions in any one of the area sources can be represented by a “typical” aircraft whose characteristics are computed through a weighted average of the characteristics of aircraft that pass through the area source. Emissions from an aircraft are treated as line thermals that have horizontal momentum and buoyancy; the plume is first governed by horizontal momentum, which induces vertical growth of the plume while the velocity in the plume decreases with distance from the aircraft. Buoyancy

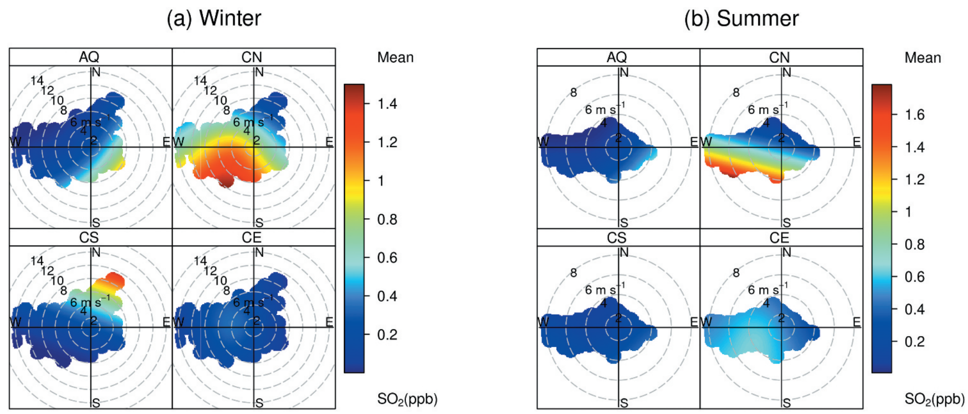

Figure 3. Bivariate polar plots of measured SO_2 concentrations at all four core (AQ, CN, CS, and CE) sites during the (a) winter and (b) summer seasons of 2012 at LAX.

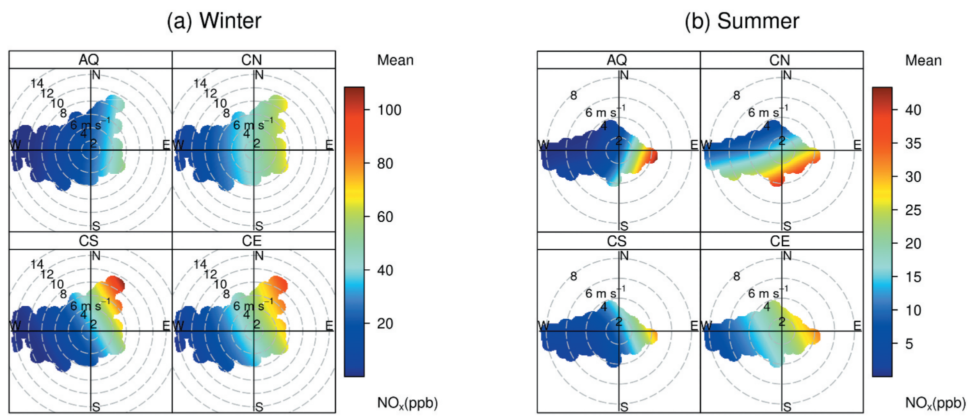

Figure 4. Bivariate polar plots of observed NO_X concentrations at all four core (AQ, CN, CS, and CE) sites during the (a) winter and (b) summer seasons of 2012 at LAX.

takes over once the horizontal velocity in the plume is comparable to the mean ambient velocity. Buoyancy results in plume rise and growth of plume dimensions; as in common plume rise treatments, plume rise is terminated either when the plume becomes negatively buoyant in stable conditions or when the rate of plume rise becomes comparable to the standard deviation of turbulent velocity fluctuations outside the plume. The horizontal momentum and the buoyancy of the line thermal associated with jet aircraft emissions are related to aircraft engine characteristics: thrust, fuel burn rate, aircraft velocity, air-fuel ratio, rated power, and engine bypass ratio. Details of the formulation are provided in Pandey, Venkatram, and Arunachalam (2023). These engine parameters were generated using the Aviation Environmental Design Tool (AEDT) (FAA, 2023) and transformed into AERMOD-ready input files (e.g., INP and HRE files) by the Federal Aviation Administration's (FAA) contractor, the Volpe center, for LAX airport during both seasons.

AERMOD's model performance is governed by two primary inputs: meteorological information and emission data, which are described next.

Model inputs

Emissions

FAA's AEDT (version 3e) is used to model aircraft SO_2 and NO_X emissions on the surface (during landing and takeoff) as a series of $20m \times 20m(length \times width)$ area sources; taxi surface sources are modeled as area sources having the actual geometrical dimensions of each taxi segment and airborne emissions are modeled as a series of $200m \times 200m(length \times width)$ area source segments with initial vertical spreads (σ_{z_o}) of 4.1 m. Sources next to gates (during idle) are modeled as area polygons (Pandey, Venkatram, and Arunachalam, 2024). Non-aircraft SO_2 and NO_X emissions estimates are based on the EDMS (Emissions and Dispersion Modeling System) emission inventory of LAX, which accounts for all the aircraft and non-aircraft sources for winter (02/01/2012–03/13/2012) and summer (07/18/2012– 08/28/2012) seasons of 2012 (Tetra Tech, Inc 2013).

The hourly averaged total SO_2 and NO_X emissions (aircraft and non-aircraft) for each of the 42-day study period of winter and summer monitoring seasons are shown in Figure 5. These emissions include the Chevron refinery (located south of the airport), other stationary sources within the airport, on-road traffic sources, and other marine sources. The Chevron refinery and other stationary sources are assigned 10.92 g/s and 0.05 g/s of SO_2 and 18.66 g/s and 2.20 g/s of NO_X emissions in the two seasons; these emissions are fixed throughout the study period in the absence of more-specific information (Arunachalam et al. 2017, ACRP Report 179; Tetra Tech, Inc, 2013). The Chevron refinery is situated south of the south airfield. Marine sources are situated within the coastal waters west of the airport. Although the marine sources represent significant contributions to the study area emissions (i.e., approximately 31% of total SO_2 emissions and 40% of total NO_X emissions), their contribution to concentration impacts within the study area is not significant compared with those of airport sources (Tetra Tech, Inc, 2013) because of their effective distances from the airport. A detailed description of emission distribution among each source group is given in the supplementary information/material of this paper.

Non-aircraft SO_2 and NO_X emissions vary little between the winter and summer studies. Aircraft SO_2 and NOx emissions are close to 50% of non-aircraft emissions in both seasons during the 7–19 daytime hours. The relative contributions of aircraft are larger in the evening hours when non-aircraft emissions decrease. The diurnal profiles of SO_2 and NO_X aircraft emissions show that aircraft activity decreases during the morning and late-night hours (Figure 5).

Non-airport sources can contribute to the concentrations at the four core sites when the wind blows toward the monitoring station from these sources. The Chevron refinery is likely to affect CS when the wind blows from the southwest (Figure 1).

The differences between AEDT LAX winter and summer SO_2 and NO_X emissions arise because the LAX winter study was originally set up in EDMS and was imported into AEDT by the FAA. The aircraft operations are based on profiles that distribute the annual operations to quarter-hourly resolution. This study setup, however, results in

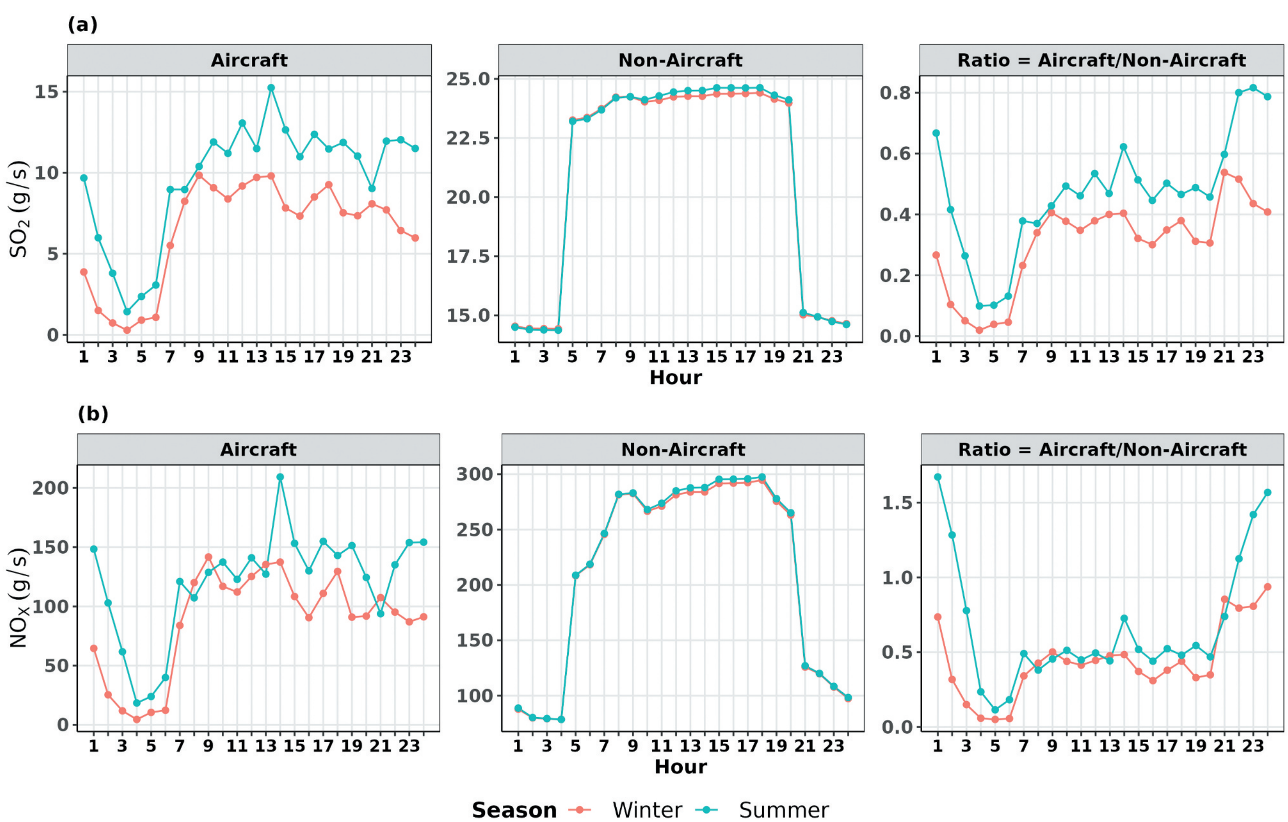

Figure 5. Comparison of hourly averaged aircraft and non-aircraft (a) SO_2 and (b) NO_X emissions during the winter and summer field studies.

differences in the hourly distribution of flights compared to the actual operations and does not distinguish one aircraft type from another. Therefore, the winter study does not capture differences in modeled emissions attributable to differences in operations and differences in aircraft types. On the other hand, the AEDT LAX summer study is built on more realistic assumptions and higher-fidelity databases. The information on aircraft operations in the summer study comes from the Performance Data Analysis and Reporting System (PDARS) (FAA, 2015), which provides detailed flight track information and enables AEDT to model actual flight operations on an hourly basis. Furthermore, in the summer study, the taxi emissions are modeled accurately by adjusting the taxi speeds to match the actual taxi times.

Meteorology

The meteorological inputs for the winter and summer seasons of 2012 were generated using KLAX (Los Angeles Airport) surface observations (WBAN 722950), KNKX (San Diego Marine Corps Air Station) upper air soundings (WBAN 722930), and 1-minute ASOS (Automated Surface/Weather Observing Systems) data from KLAX (Arunachalam et al. 2017, ACRP Report 179). The meteorological inputs were generated using AERMET (v14134) and AERMINUTE (v14337) using the surface, upper air, and ASOS 1-minute data. In ACRP Report 179, Arunachalam et al. (2017) identified 12 hours with missing data during the winter study period and 1 hour with missing data in the summer study period. These gaps in both seasons were filled by running AERMET using observations from nearby airports including Hawthorne Municipal Airport (KHHR), Santa Monica Municipal Airport (KSMO), Long Beach Airport (KLGB), and John Wayne-Orange County Airport (KSNA), located at distances of 8.1, 8.7, 29.1, and 58.9 km from LAX airport (KLAX), respectively (Arunachalam et al. 2017, ACRP Report 179). Note that the field studies did not install instrumentation such as sonic anemometers or radar profilers who could have provided the meteorological inputs required to run AERMOD. So, it was necessary to rely on AERMET to process routine meteorological measurements to provide the inputs. This introduces uncertainty into model results; discussed next.

Modifications in AERMET meteorology

The meteorological conditions at LAX airport can be influenced by processes that are not fully taken into consideration by the AERMET model (Pandey, Venkatram, and Arunachalam 2022). One of these factors pertains to LAX's coastal location. When the wind blows from the west, it passes over cold water before reaching the warmer land of the airport. This results in an upward heat flux that creates an internal boundary layer directly above the airport. Consequently, the stable boundary layer predicted by AERMET may not reflect the actual atmospheric conditions that facilitate the dispersion of airport emissions. We account for this possibility by using an internal boundary layer model (IBL) (Venkatram 1977) to simulate the meteorology over LAX under stable conditions when the winds are westerly. We estimate the height of the internal boundary layer using a temperature difference of 2^0C between land and water; this value, which is uncertain, is based on data presented in Hsu (1984). The heat flux in the IBL results in positive values of the convective velocity scale w_*.

We allow for an alternative treatment of shoreline meteorology based on observations of Rahn and Mitchell (2016), which indicate that onshore flows at LAX are associated with foggy conditions and a neutral boundary layer whose height is about 400 m. To simulate these conditions, we take the Monin-Obukhov length to be 1,000 m, recalculate the friction velocity, and take the convective velocity scale to be zero; these micrometeorological variables govern the vertical and horizontal plume spreads in AERMOD.

The default input file produced by AERMET had a maximum roughness length of 0.2 m. We increase this value to 0.3 m when the wind blows from the northeast and southeast quadrants to account for the impact of tall buildings in downtown Los Angeles during these winds. This value of 0.3 m, which is uncertain, allows us to explore the possibility that model performance can improve if the original AERMET file were to account accurately for the effects of downtown buildings.

In the next section, we summarize the results from the evaluation of AERMOD after implementing plume rise and modifying AERMET outputs.

Model results

To focus on the impact of aircraft-related emissions on the four core sites, the concentrations are grouped to reflect the time of day and wind-flow patterns described by the wind roses. The hours 1 to 8 describe nighttime, hours 9 to 16 are daytime, and hours 17 to 24 correspond to evening. In addition to this, the concentrations are also grouped in 45 degrees wind-direction bins/sectors: (0–45], (45–90], (90–135], (135–180], (180–225], (225–270], (270–315], and (315–360] to examine the impact of aircraft operations at a particular receptor.

The impact of the modifications in AERMOD model is evaluated at the four core sites during winter and summer using (a) mean concentrations averaged over the hourly and wind-direction bins/sectors and (b) overall concentration distribution using percentile line plots. We also evaluated model performance using commonly used statistical measures of model performance (Cox and Tikvart 1990): fractional bias based on the 26 robust highest concentrations (FB) and fraction of the model estimates with a factor of two of the corresponding observations (FAC2) (Chang and Hanna 2004). The U.S. EPA recommends these metrics to measure the performance of dispersion models that are used in regulatory applications.

Model performance statistics are presented for four different cases:

(1) *Default*: The meteorological inputs are baseline AERMET outputs, and plume rise of jet emissions is not modeled. This corresponds to the way AERMOD would be normally applied to estimate the air-quality impact of airport emissions.
(2) *Plume Rise*: Same as Case 1, except that plume rise is modeled using the ALPHA option "ARCFTOPT" of AERMOD (v23132), the approach described in Pandey, Venkatram, and Arunachalam (2023).
(3) *Shoreline*: Same as Case 2 except that the meteorological inputs are modified to account for shoreline and urban effects described in Pandey, Venkatram, and Arunachalam (2022). Shoreline effects are modeled only when AERMET predicts stable conditions during onshore flows.
(4) *Neutral*: Same as Case 3 except that during both daytime and nighttime, meteorology is treated as neutral, rather than unstable to account for the possibility of foggy conditions in LAX during onshore flows.

Concentrations averaged over hourly bins

The mean concentration variation of the model estimated SO_2 and NO_X concentrations averaged over each hourly bin at the four core sites (AQ, CN, CS, and CE) for the two seasons are compared with corresponding mean observations in Figures 6 and 7.

SO_2 concentrations

Figure 6 compares the performance of the four model scenarios through the ratio of the modeled to the measured SO_2 concentrations averaged over the time bins described earlier. The lines above and below unity on the y-axis correspond to a factor-of-two interval.

We see that the *Default* version overestimates the concentrations during the early morning and late evening hours at the AQ and CS sites, which are at the far ends of the runways. *Plume Rise* and meteorological modifications reduce this overestimation. However, these modifications reduce the concentrations below the factor-of-two line during the daytime. At the CN site, the modeled concentrations are generally lower than the measured concentrations. The modification to neutral conditions reduces this underestimation during the daytime. At CE, all the modifications to the *Default* version improve model performance to bring the ratios of the modeled to the measured concentrations closer to the one-to-one line. Assuming neutral meteorology appears to make the most noticeable improvements during both daytime and nighttime hours.

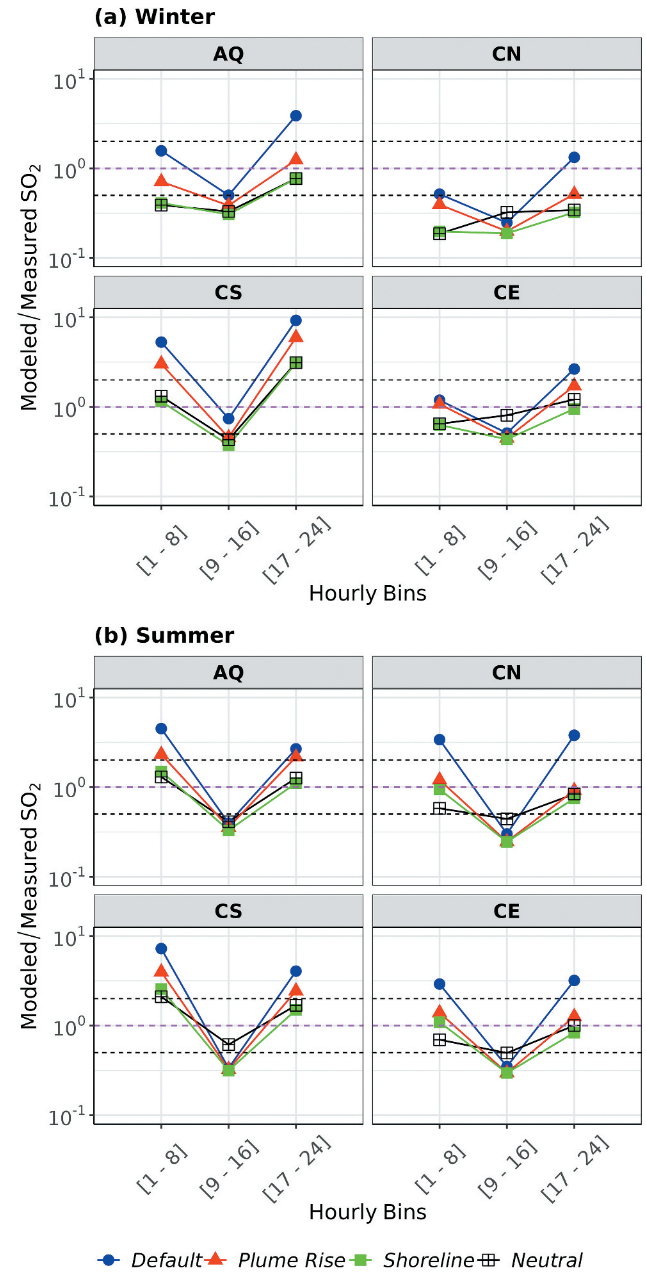

Figure 6. Ratio of modeled to measured SO_2 concentrations averaged over hourly bins at the four sites (AQ, CN, CS, and CE) during the (a) winter and (b) summer studies.

Figure 6, depicting results corresponding to the summer study, shows the *Default* version of the model overestimating SO_2 concentrations during the early morning and late evening hours at all four sites. The overestimation is reduced substantially with the introduction of plume rise, which does not appear to make much difference during the daytime hours, presumably because daytime turbulence overcomes the effects of plume rise. Except for the *Neutral* version, all the scenarios underestimate concentrations during the daytime hours. It is also clear that modifying the AERMET-modeled daytime convective conditions to neutral and, thus, reducing turbulent dispersion leads to improvement in daytime model performance. In addition to this, the change in stable/nighttime onshore flows to neutral further reduces the concentrations at all sites during the early morning hours; whereas, in late night hours it enhances the concentrations.

NO_X concentrations

Figure 7 indicates that during the winter season, all four scenarios of AERMOD underestimate the measured NO_X concentrations at the four sites—AQ, CN, CS, and CE—during the daytime hours. During the early morning and late evening hours, the estimates from the *Default* and the *Plume Rise* scenarios are generally within a factor of two of the model estimates at the CS site primarily because the *Default* version tends to overestimate the impact of emissions as indicated in the modeling of SO_2 concentrations.

All three alternate model scenarios show a substantial improvement in performance compared to *Default* during the summer field study. As in the case of SO_2, the modifications to the model result in reductions in the overestimation of concentrations during the early morning and late evening hours when plume rise and conversion to unstable conditions reduce ground-level concentrations. It should also be noted that both during the winter and summer field studies, conversion of the daytime unstable conditions and nighttime stable conditions to less dispersive neutral conditions lead to an increase in ground-level concentrations, bringing them closer to the one-to-one line.

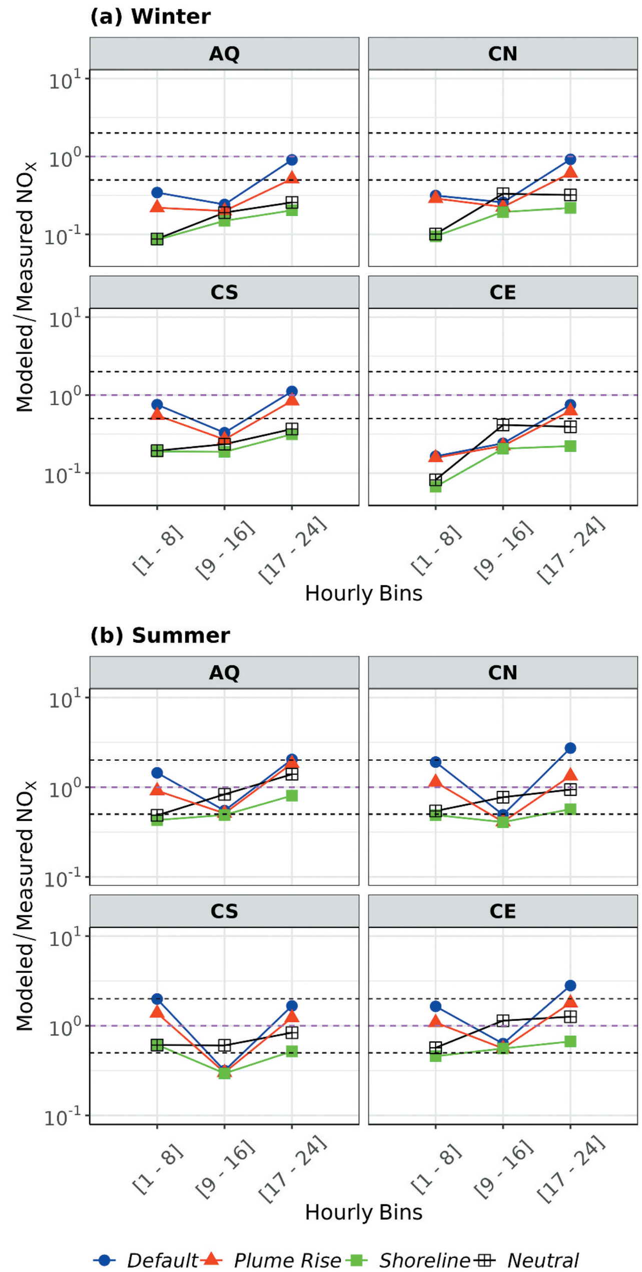

Figure 7. Ratio of modeled to measured NO_X concentrations averaged over hourly bins at the four sites (AQ, CN, CS, and CE) during the (a) winter and (b) summer studies.

Concentrations averaged over wind-direction bins/sectors

The mean concentration variation of the model estimated SO_2 and NO_X concentrations averaged over each wind-direction bin/sector at the four core sites—AQ, CN, CS, and CE—for the two seasons are compared with corresponding mean observations in Figures 8 and 9. At the AQ site, we expect aircraft operations to be evident when the wind blows from the [90–180] sector, CN from the [135–315] sector, CS from the [270–90] sector, and CE from the [225–315] sector.

SO_2 concentrations

Figure 8 compares the performance of the four model scenarios through the ratio of the modeled to the measured SO_2 concentrations averaged over the eight wind-direction bins/sectors of 45 degrees described earlier. The lines above and below unity on the y-axis correspond to a factor-of-two interval.

We see that the *Default* version overestimates the concentrations specific to the airport-related contributions based on the wind direction for each site based on its location described earlier, on these wind-direction

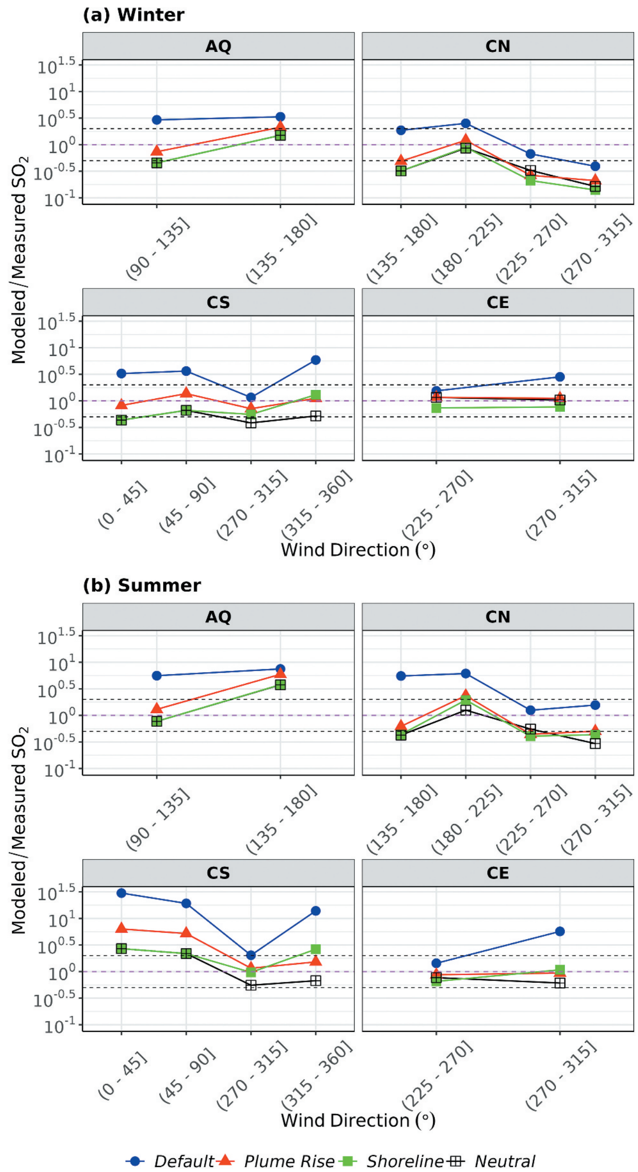

Figure 8. Ratio of modeled to measured SO_2 concentrations averaged over wind-direction bins at the four sites (AQ, CN, CS, and CE) during the (a) winter and (b) summer studies.

bins/sectors. *Plume Rise* reduces the concentrations and brings the ratios of modeled to measured concentrations closer to one-to-one line in both seasons. Further, the *Shoreline* modifications (combined with urban roughness change) in the meteorological input parameters reduce the concentrations at all sites. On the other hand, with the *Neutral* modifications, the concentrations are further reduced at some bins at all sites in both seasons. However, concentrations also increase slightly at some bins at all sites due to the reduction of turbulence in neutral conditions. Overall, the overestimations are reduced substantially in all three scenarios (*Plume Rise*, *Shoreline*, and *Neutral*) when aircraft-related emissions affect the specific site.

NO_X concentrations

Figure 9 indicates that during the winter season, all four AERMOD scenarios underestimate the measured NO_X concentrations at the four sites—AQ, CN, CS, and CE—in most of the wind-direction bins/sectors. In the 0–225 degree bin at CS and the 135–360 degree bin at CE, the estimates from the *Default* and the *Plume Rise* scenarios are generally within a factor of two of the model estimates.

All three alternate model scenarios show a substantial improvement in performance compared to *Default* during the summer field study. This is particularly noticeable at the CN site during summer, wherein the modeled to the measured ratios of the *Plume Rise*

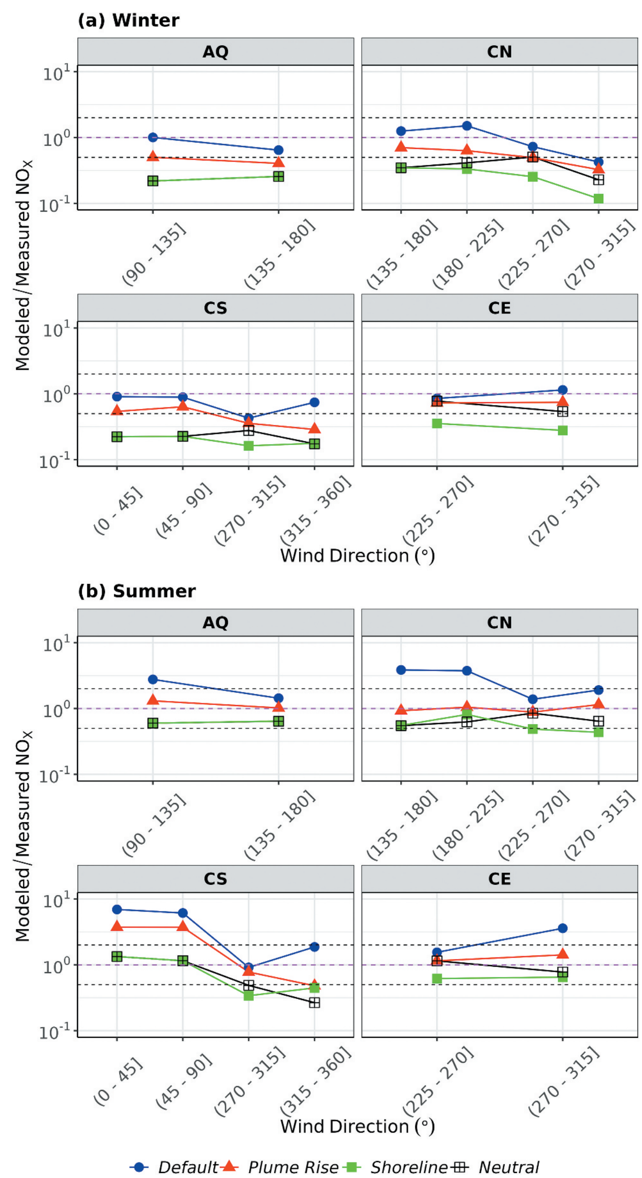

Figure 9. Ratio of modeled to measured NO_X concentrations averaged over wind-direction bins at the four sites (AQ, CN, CS, and CE) during the (a) winter and (b) summer studies.

scenario lie close to the one-to-one line for all the wind-direction bins. At CE, the improvement is clear during onshore westerly winds.

A comparison of observed to modeled plume behavior using bivariate polar plots at each of the four core sites—AQ, CN, CS, and CE—is provided in the supplementary information/material of this paper.

Overall concentration distributions

The performance of the four model scenarios in describing the observed concentrations is depicted in Figure 10, which plots the observed 5th, 50th (median), and 95th percentiles of the measured distributions against the corresponding modeled values. The overall QQ distribution plots and percentile plots at each site and each hourly time bin and wind-direction bin for SO_2 and NO_X concentrations are given in the supplementary information of this paper.

We see that plume rise reduces and, thus, improves the 95th percentile concentrations modeled by *Default* in winter and summer leaving the other percentiles essentially unchanged. The median values are within the factor-of-two lines for all four model scenarios. The 5th percentile values are underestimated by all model scenarios. The modeled concentration distribution is closer to the measured distributions in the summer than in the winter study.

The measured concentrations of NO_X (Figure 11) are underestimated in the four modeled scenarios during the winter study. Note that plume rise has a relatively small effect on the *Default* 95th percentile value; the other modifications lead to underestimation below the factor-of-two line. However, during the summer study, the plume-rise modification brings the 95th percentile value close to the one-to-one line; the rest of the percentile values are within the factor-of-two interval for this modification. The modifications to the meteorology do not lead to further model improvements.

Regulatory application of model

Because regulatory applications of AERMOD focus on the values at the upper end of the modeled concentration distributions, it is useful to examine the performance of the modified versions of the model in terms of statistics based on the 26 highest values of the modeled and measured concentrations (Cox and Tikvart 1990) as recommended by the U.S. EPA. These statistics are presented in Table 1.

The fractional bias (FB) is defined by

$$FB = 2\frac{(Measured - Modeled)}{(Measured + Modeled)} \tag{1}$$

FAC2 refers to the fraction of modeled values within a factor of two of the corresponding measured values. The ratio of the robust highest concentrations, RHC (Ratio_RHC), is the ratio of the modeled RHC to that of the measured, where the RHC of each set is computed using the 26 highest values.

We introduce a new metric "Performance Distance (PD)" based on a 3-D coordinate system in which each statistical measure of model performance is measured along each of the three axes. Then a set of three statistics represent a point in this 3-D space. Then PD is the Eulerian distance of each of these points from the ideal set, (0,1,0):

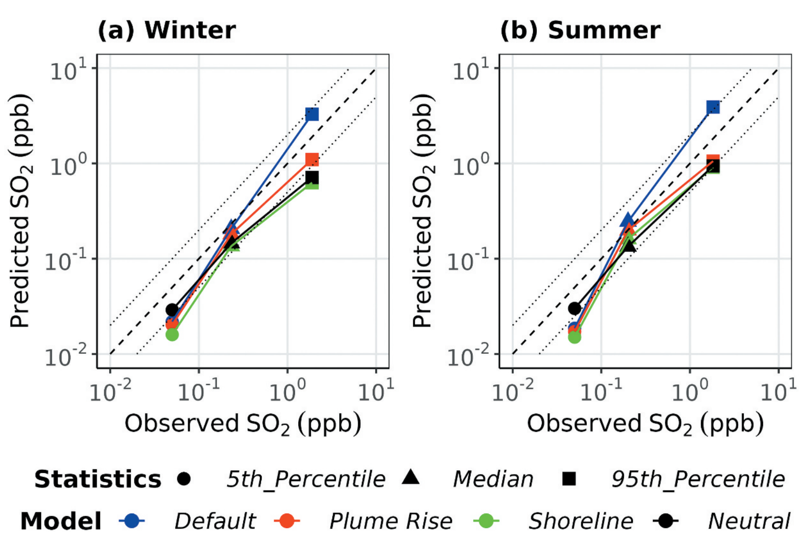

Figure 10. Distributions of measured SO_2 concentration distributions compared with modeled values. Concentrations correspond to values combined from all four sites.

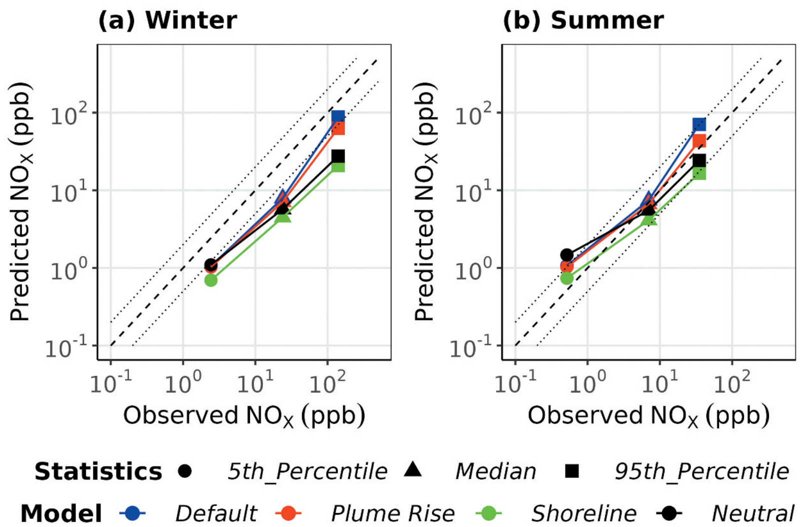

Figure 11. Distributions of measured NO_X concentration distributions compared with modeled values. Concentrations correspond to values combined from all four sites.

Table 1. Fractional bias (FB) based on the top 26 highest concentrations, FAC2 (factor of two) and the ratio of robust highest concentrations (Ratio_RHC) for winter and summer seasons of 2012.

			Statistical Measures of Model Performance			
Pollutant	Season	Model	FB	FAC2 (%)	Ratio_RHC	Performance Distance (PD)
SO_2	Winter	*Default*	−1.55	89	7.92	7.09
		Plume Rise	−1.53	97	7.51	6.69
		Shoreline	−0.83	52	2.43	1.72
		Neutral	−1.00	63	3.02	2.28
	Summer	*Default*	−1.36	87	5.27	4.48
		Plume Rise	−1.26	91	4.40	3.63
		Shoreline	−0.63	68	1.92	1.16
		Neutral	−0.75	99	2.20	1.42
NO_X	Winter	*Default*	−0.37	16	1.46	1.03
		Plume Rise	0	9	1	0.91
		Shoreline	1.01	3	0.33	1.55
		Neutral	1	9	0.33	1.51
	Summer	*Default*	−1.29	79	4.62	3.85
		Plume Rise	−0.63	89	1.91	1.11
		Shoreline	−0.05	85	1.05	0.17
		Neutral	0.19	86	0.83	0.29

$$PD = \sqrt{FB^2 + \left(1 - \frac{FAC2}{100}\right)^2 + (Ratio\_RHC - 1)^2} \quad (2)$$

Improvement in the model is indicated by approach of PD to its ideal value of zero. We note that PD as defined here, is only one possible way of combining the three performance indices.

The positive FB and the values of the Ratio_RHC relative to unity suggest the underestimation of the highest concentrations of SO_2 and NO_X during the winter and summer field studies.

For SO_2, the overall FAC2 improves from *Default* to *Plume Rise* model scenarios in both seasons. Additionally, in the summer study, it also improves in the *Neutral* model scenario. On the other hand, for NO_X, all model scenarios in the summer season show improvements in FAC2 relative to *Default*. However, during the winter season, FAC2 is low compared to the summer season due to the differences in the emissions and observations as discussed in “Emissions” and “Observed plume behavior at core sites” respectively (Table 1).

The PD metrics indicate that the introduction of plume rise and modifications to the input meteorology leads to improvement in the description of SO_2 concentrations in the winter and summer field studies. As Figure 12 indicates, the introduction of shoreline meteorology makes the biggest change to model performance expressed in terms of PD. The change to neutral conditions from convective conditions during onshore flows makes a smaller change.

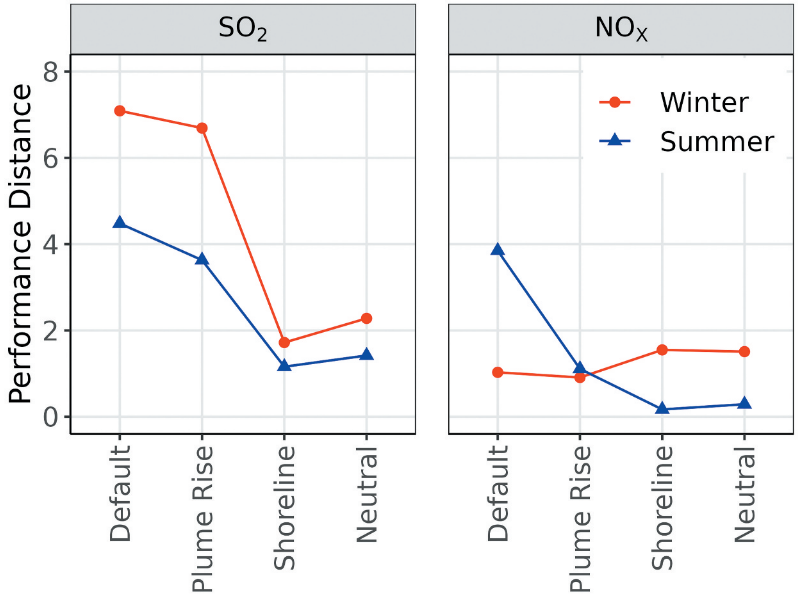

Figure 12. Change in performance distance with model modification.

For NO_X concentrations, the introduction of plume rise makes a slight improvement to performance of the *Default* version during the winter study. The modifications to meteorological inputs seem to increase the PD during the winter. On the other hand, during the summer study, the incorporation of plume rise makes the largest improvement to model performance. Modifications to shoreline meteorology and conversion to neutral conditions make smaller contributions to improving the performance of the *Default* version of the model.

Sensitivity analysis during winter

Based on emissions and mixing height

The results presented in the previous sections indicate that AERMOD underpredicts the NO_X observed concentrations at all four sites for all three time bins during the winter study. In addition, we also see that the model underestimates the observed SO_2 concentrations at the CN and CE sites, especially during the winter study. To examine the reasons for this behavior, we performed a sensitivity analysis by limiting the mixing height to 200 m and replacing the winter emissions with the summer emissions (as overall aircraft SO_2 and NO_X emissions are approximately 50% and 37% higher during summer; non-aircraft emissions are approximately 0.4% and 0.8% higher during summer study as compared to winter) in the *Default* and *Plume Rise* model scenarios during winter. We name these new model scenarios as *Default (New)* and *Plume Rise (New)*, respectively. Figure 13 compares the performance of the four model scenarios (*Default*, *Default (New)*, *Plume Rise*, *Plume Rise (New)*) through the ratio of the modeled to the measured SO_2 and NO_X concentrations averaged over the time bins described earlier. The lines above and below unity on the y-axis correspond to a factor-of-two interval.

We see that the *Default (New)* and *Plume Rise (New)* versions increase the SO_2 and NO_X concentrations during daytime. The increase in the modeled NO_X concentrations is not significant even with the higher summer emissions. This is because, as seen in the bivariate polar plots (Figures 3 and 4), westerly winds that bring aircraft emissions to the receptors are 40% less frequent in winter than in summer. This analysis demonstrates that even with a reduced mixing height and the use of higher summer aircraft emissions in winter, the model continues to underpredict observed NO_X concentrations, especially during the early morning and the daytime hours. Additionally, Non-Parametric Trajectory Analysis (NTA) from AQSAS study also shows increased northeasterly and southeasterly winds pointing to background/non-airport sources being more significant during winter than during summer. At the CN site, on-airport sources contributed 24% in winter compared with 76% in summer. Overall, NO_X at all the monitoring sites were most likely dominated by non-airport sources during winter (Tetra Tech, Inc, 2013). To corroborate this, we performed a study described in the next section.

Using observed background NO_X concentrations

During the winter season, more than 45% of the winds originate from the northeast and the southeast

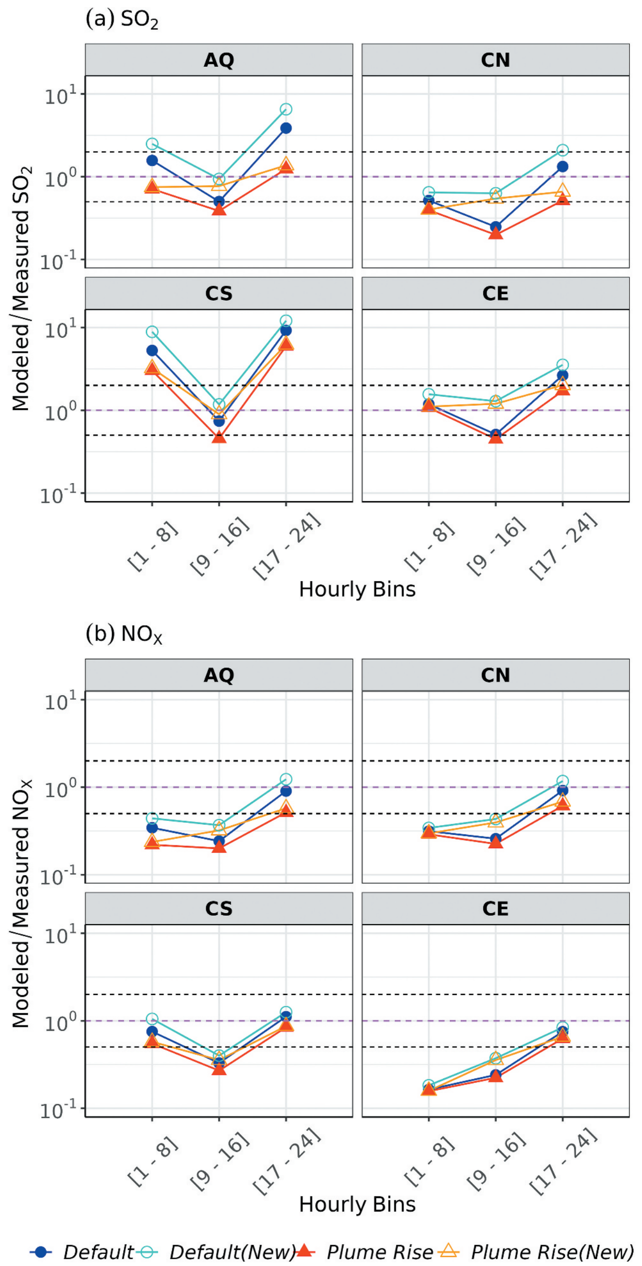

Figure 13. Ratio of modeled to measured SO_2 and NO_X concentrations averaged over hourly bins at the four sites (AQ, CN, CS, and CE) during the winter study.

directions (Figure 2). This suggests that the core sites CN and CE are impacted by emissions from Los Angeles city core, especially during the late night and the early morning hours. This led to a sensitivity analysis in which modeled estimates from non-airport contributions were replaced with observed concentrations of NO_X measured at Air Quality Station (AQS) ID: 06-037-1103 of the California Air Resources Board (CARB) situated in the center part of the Los Angeles city), which is approximately 13 miles from the Los Angeles International Airport This allowed us to avoid the impact of possible limitations in the non-airport emissions inventory on the performance of AERMOD at the core sites. In addition to this, as discussed earlier, we used summer emissions in winter and limited the mixing height to 200 m. We name these new model scenarios *Default (New_Bg)* and *Plume Rise (New_Bg)*, respectively.

Figure 14 compares the performance of the four model scenarios (*Default*, *Default (New_Bg)*, *Plume Rise*, *Plume Rise (New_Bg)*) through the ratio of the modeled to the measured NO_X concentrations averaged over the time bins described earlier. The lines above and below unity on the y-axis correspond to a factor-of-two interval. We see that the *Default (New_Bg)* and *Plume Rise (New_Bg)* versions increase the NO_X concentrations and are close to one-to-one line, especially at the CN and CE sites. The increase in the modeled NO_X concentrations is significant throughout the day. This is because, as seen in the bivariate polar plots (Figures 3 and 4), easterly winds that bring non-airport emissions to the receptors are 45% more frequent in winter than in summer.

Conclusion

The paper examines the effects on model performance of two modifications in the formulation of AERMOD/AERMET, with a focus on modeling aircraft emissions at airports. The *Plume Rise* version treats plume rise of jet exhaust emissions. *Shoreline* incorporates meteorology associated with the internal boundary layer that develops when cold stable air flows from a large water body onto a warmer land surface. The *Neutral* version converts the meteorology during daytime unstable and nighttime stable conditions to neutral conditions to simulate the moderating influence of the water body in the vicinity of the Los Angeles International (LAX) airport.

The results of the model evaluation based on observations from the LAX AQSAS during two different seasons presented in this paper show that the suggested modifications improve AERMOD's performance, relative to the default release version, in estimating ground-level concentrations associated with aircraft emissions from LAX. These evaluation results are presented in terms of the ratio of the mean modeled and the measured concentrations corresponding to specified hourly time and wind-direction bins and overall concentration distributions. The incorporation of plume-rise processes for treating jet exhaust emissions into AERMOD generally decreases the mean concentration ratios that are much larger than unity during the early morning and late evening hours by as much as 50%,

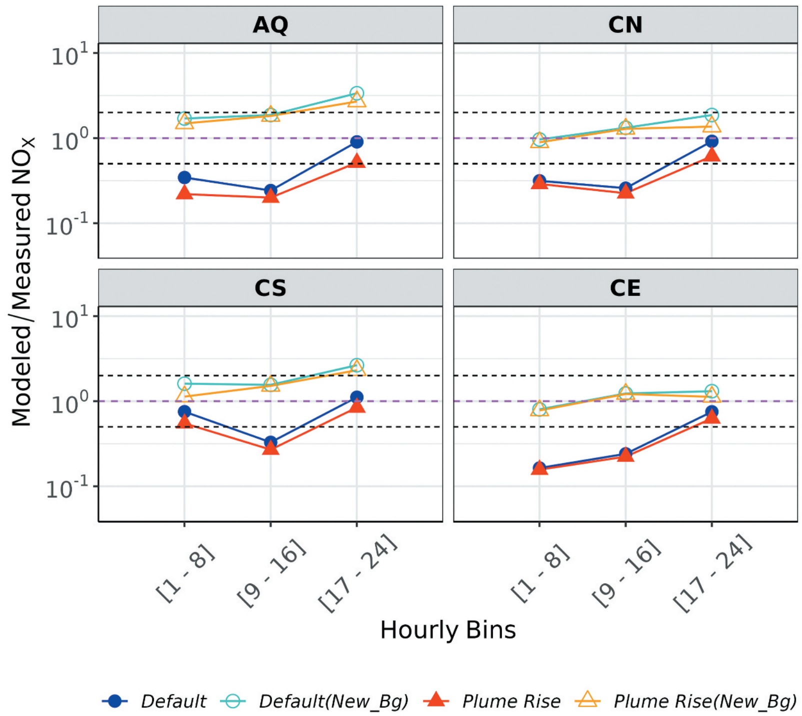

Figure 14. Ratio of modeled to measured NO_X concentrations averaged over hourly bins at the four sites (AQ, CN, CS, and CE) during the winter study.

when atmospheric turbulence does not overwhelm the effects of elevated and vertically dispersed plumes. Accounting for shoreline meteorology also brings down the overestimated concentrations during these hours through the conversion of stable conditions to more-dispersive unstable conditions. The underestimated values during the daytime are brought closer to unity when daytime unstable conditions are converted to less dispersive neutral conditions. Additionally, the analysis based on grouping concentrations using wind-direction bins shows improved model performance, especially, in the *Plume Rise* scenario at each site based on its location in the airport.

The results indicate that different versions of the model perform better during the summer study than in the winter study. This suggests that emissions estimates and meteorological inputs could be more uncertain in winter than in summer as described earlier. The accuracy of the emissions estimates could be improved during the winter study if the emissions are generated by AEDT using detailed flight trajectories and operations data on an hourly basis as in the summer study. Additionally, as in the summer study, taxi emissions can be modeled more accurately by adjusting taxi speeds to match actual taxi times.

We find that the underestimation of NO_X during the winter study is reduced significantly when concentrations of NO_X measured at the CARB Central Los Angeles monitor replace modeled non-airport contributions based on emissions from the LAWA study. This analysis suggests that AERMOD provides an adequate estimate of the air quality impact of airport emissions when it incorporates plume rise of jet exhaust and modifications to account for shoreline effects. While the LAWA study provided a relatively complete picture of pollutant concentrations associated with airport activities, it did not collect the meteorological information required to construct the meteorological inputs, such as surface heat flux, boundary layer height, and surface friction velocity that are used to model dispersion in AERMOD. This paper offers insight into the impact of these gaps in characterizing meteorological inputs on model results. These results suggest that future field studies designed to collect data required to model the impact of airport emissions will need to pay attention to meteorological information gathered with instrumentation such as sonic anemometers to provide surface momentum and heat fluxes and sodars to provide information on vertical profiles of wind speed and turbulence. In addition, as previously stated in the study that described the formulation of the plume-rise algorithm (Pandey, Venkatram, and Arunachalam 2023), observations of the behavior of aircraft plumes are limited. There are no direct measurements of the behavior of the aircraft plume when buoyancy becomes the major force in the vertical rise and dispersion of the exhaust plume especially close to the runway during takeoff and landing. This emphasizes that along with fixed-site measurements, there is also a need for detailed field LIDAR measurements that capture the behavior of jet exhaust.

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Disclosure statement

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Data availability statement

The data used in this study are available from the corresponding author, S. A., upon reasonable request.

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16. Abstract

The Aviation Environmental Design Tool (AEDT), developed by the FAA, is used to analyze the environmental impact of airport activities on air quality and noise near airports. AEDT incorporates AERMOD to estimate concentrations resulting from aircraft emissions, which possess horizontal momentum as well as buoyancy. The current version (v23132) of AERMOD incorporates plume dynamics associated with such emissions as an ALPHA option. AERMET, AERMOD's meteorological processor does not account for the meteorology of the land-water interface that is likely to be important for airports located on the shorelines of lakes or oceans. An approach to include these effects in AERMOD was previously developed. This study examines the impact of including plume rise and shoreline effects in AERMOD by evaluating model estimates of NOX and SO2 with corresponding measurements made during the Los Angeles Airport Air Quality Source Apportionment Study (AQSAS) in the winter and summer of 2012. The performance statistics resulting from this model evaluation suggest that the inclusion of plume rise of aircraft emissions and shoreline effects on meteorological inputs is likely to improve AERMOD's ability to estimate the impact of airport emissions on surrounding air quality.
Implications: Because airport emissions, particularly those from aircraft, affect local air quality, the National Environmental Policy Act (NEPA) requires the use of dispersion models such as AERMOD to assess compliance of air quality regulations when potential expansions of airport activity are planned. The current regulatory version of AERMOD does not include aircraft-specific plume rise and shoreline-related meteorological processes, which affect the dispersion of airport emissions. The preliminary evidences presented in our previous work suggest that the incorporation of these effects will enhance AERMOD's ability to estimate NOX and SO2 concentrations associated with airport emissions. These enhancements are beneficial not only for policy-making and regulatory compliance but also for promoting sustainable development near airports and protecting public health.

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