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High–resolution pollutant transport in the San Pedro Bay of California

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ABSTRACT

The combined sea port of Los Angeles and Long Beach in California constitutes the second busiest port in the United States by shipping volume. Communities near the ports face environmental justice concerns from a variety of sources including roadway and port related activities. This study examines the transport and diffusion of $PM_{2.5}$ and NO_X in port communities using the high–resolution plume model AERMOD, incorporating surface and aloft observed meteorology and local topography. Pollution impacts of roadway related emissions, direct port activity of cargo handling equipment and commercial shipping vessels are modeled for representative cold and hot months in 2005. Predictions from roadway emissions are compared with the same episode modeled with CALINE4 line dispersion model. Results show high spatial variability as well as increased transport during cold months. In addition, research also shows that while the port activity significantly impacts in–port air pollution, the effects of port activity is limited to within 2–6 km of the ports. Port adjacent communities are most sensitive to roadway related emissions. AERMOD $PM_{2.5}$ and NO_X predictions show a peak correlation coefficient of 43% and 50% compared with observations, respectively.

Keywords:
AERMOD
$PM_{2.5}$
NO_X
Air pollution
Dispersion modeling

Article History:
Received: 13 September 2010
Revised: 14 December 2010
Accepted: 20 December 2010

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doi: 10.5094/APR.2011.030

1. Introduction

The San Pedro Bay of California houses the ports of Los Angeles and Long Beach which serve as the entry point for half of all cargo containers entering the western United States annually (American Association of Port Authorities, 2007). Globalization has caused an increase in sea commerce. Communities near the ports face potential cancer risk levels exceeding 500 in a million from severe air pollution from a wide variety of sources, including port–related activities such as ships and cargo vessels, heavily traveled freeways and surface streets with a high fraction of heavy–duty diesel trucks (Di et al., 2006; Houston et al., 2008). The area has become the focus of intensive studies through several programs of the California Air Resources Board (CARB) (Ault et al., 2009). In order to protect adequately vulnerable populations in this region, it is important to identify pollution hot spots and understand the impacts of emission sources on exposures of populations living in the communities. The area surrounding the San Pedro Bay of California, shown in Figure 1, is the focus of this investigation.

Regional models used to assess the air quality in the South Coast Air Basin of California (SoCAB), like the University of California Irvine–California Institute of Technology (UCI–CIT) three–dimensional atmospheric chemical transport model, use grid size resolutions too large to capture small scale variations caused by plume behavior and local meteorology (Griffin et al., 2004). If this project were to examine the study region shown in Figure 1, the model will only resolve 4 computational cells, making any analysis inadequate and deficient.

Plume models are commonly used to predict local transport and dispersion on a neighborhood scale. The main use of plume models is to examine small–scale impacts of specific sources through a rigorous treatment of diffusion and advection from meteorological conditions and sometimes topography. The United States Environmental Protection Agency (EPA) recommends several different plume models for state implementation plans including CALINE4 (Benson, 1989) and AERMOD (EPA, 2004a; Cimorelli et al., 2005). CALINE4 is a line source dispersion model specifically developed to model traffic–generated pollution, while AERMOD, the most recently developed plume model, is more flexible in emission sources and is widely considered state–of–the–art (Zou et al., 2009).

This project examines the impact of roadway, port and ship related emissions on the local air quality of communities around the San Pedro Bay of California. AERMOD is used to estimate concentrations of nitrogen oxides ($NO_X = NO + NO_2$) and particulate matter smaller than 2.5 µm ($PM_{2.5}$) in port adjacent communities. The two main goals of this project are (1) to use the AERMOD plume dispersion model to estimate pollutant transport on a neighborhood scale due to roadway, ship and port source emissions and (2) to compare the impact of the different emission sources. Local concentration peaks due to each of three sources examined are identified qualitatively as local hot spots.

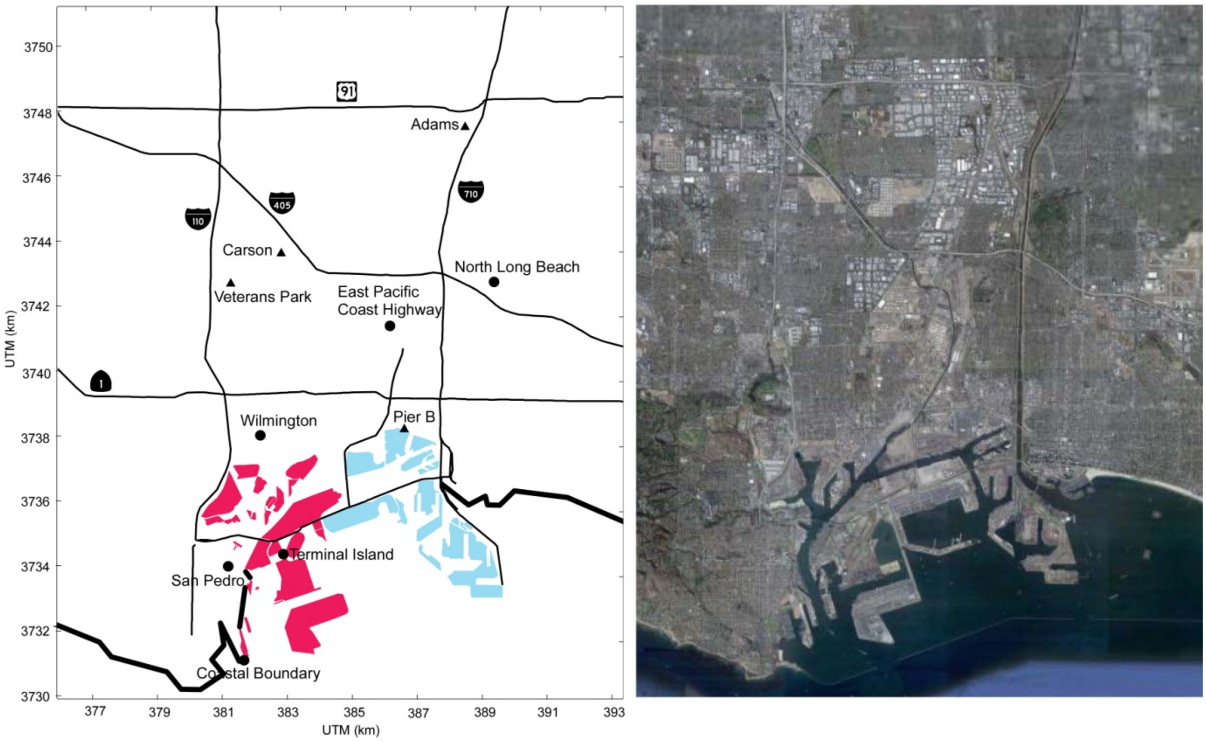

***Figure 1**. Schematic and satellite image of domain in the San Pedro bay of California shown on the left and right, respectively. Los Angeles and Long Beach port activity regions are shown in magenta and teal, respectively. Circles indicate monitoring site locations. Triangles indicate pollution hotspots identified through modeling. A thick black line represents the coast while the other black lines indicate major highways.*

2. Methodology

The overall methodology applied in this study is shown in Figure 2. Modeling plume dispersion requires local scale topographical parameters and both ground and aloft meteorological observations. Three meteorological preprocessors are used to prepare the meteorological data required by AERMOD, as illustrated in Figure 2. The procedure practiced in this study is to use EPA recommend guidelines for AERMOD (EPA, 2005) implementation using publicly available observation data whenever possible. Some new pre and post–processing procedures are presented in order to ensure a complete and thorough output.

Many other short–range transport models are suitable for the modeling conducting in the present study including the Industrial Source Complex Short Term Version 3 (ISCST3) model (EPA, 1995), CALPUFF (Scire et al., 2000), and SCICHEM (Sykes et al., 1994). CALPUFF is the only model to include coastal treatment of the fumigation between land and sea. While CALPUFF has full variability in the horizontal, it does not take into account elevation changes like AERMOD. Hall et al. (2002) showed how AERMOD results are sensitive to changes in height elevation. AERMOD is used for all modeling purposes to be consistent in the treatment of the different sources.

2.1. AERMOD

AERMOD was introduced by The American Meteorological Society/EPA Regulatory Model Improvement Committee to provide a state–of–the–art dispersion model for routine regulatory applications (EPA, 2004a). AERMOD incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain (Cimorelli et al., 2005). It assumes a Gaussian plume distribution in the vertical and horizontal for stable boundary layers, and Gaussian in the horizontal and bi–Gaussian in the vertical for convective boundary layers. AERMOD is a Lagranian, or grid–less, model capable of predicting source impacts from 1 m to 50 km away. AERMOD has been used to model local scale pollution impacts of point and volume sources, including benzene in Philadelphia, PA (Touma et al., 2007), SO_2 in Dayton, OH (Jampana et al., 2004) and Lucas Count, OH (Kumar et al., 2006), hydrogen cyanide in Colorado (Orloff et al., 2006), and PM in Chennia, India (Sivacoumar et al., 2009).

AERMOD is designed to be used in conjunction with several stand–alone programs which preprocess local meteorological and terrain data. The preprocessor programs applied in this study are AERSURFACE (EPA, 2008), AERMET (EPA, 2004b) and AERMAP (EPA, 2004c). AERSURFACE determines the local albedo, surface roughness length, and Bowen ratio using land cover characteristics describing the SoCAB developed by the United States Geological Survey (USGS) (EPA, 2008). The site specific local characteristics determined from AERSURFACE using Southern California USGS data is shown in Table S1 in Supporting Material (SM). AERMAP determines source and receptor heights using terrain elevation data also developed by the United States Geological USGS. Receptor locations mark census centroid block centers contained within the study region.

AERMET organizes and processes meteorological data including wind direction and speed, cloud cover and height, and temperature using surface and upper air measurements. Aloft radiosonde measurements of Vandenberg Air Force Base from the National Oceanic and Atmospheric Administration (NOAA) are used to describe the upper air. Meteorological surface observations of Long Beach Airport obtained from the National Climatic Data Center (NCDC) are used to describe surface conditions. AERMET combines surface and upper air measurements in a 3–phase process that tests for consistency and quality.

There are missing upper air measurements for both January and August which cannot be processed by AERMOD. The missing upper air measurements account for 88 and 6 missing hours in the months January and August, respectively. All of the missing upper

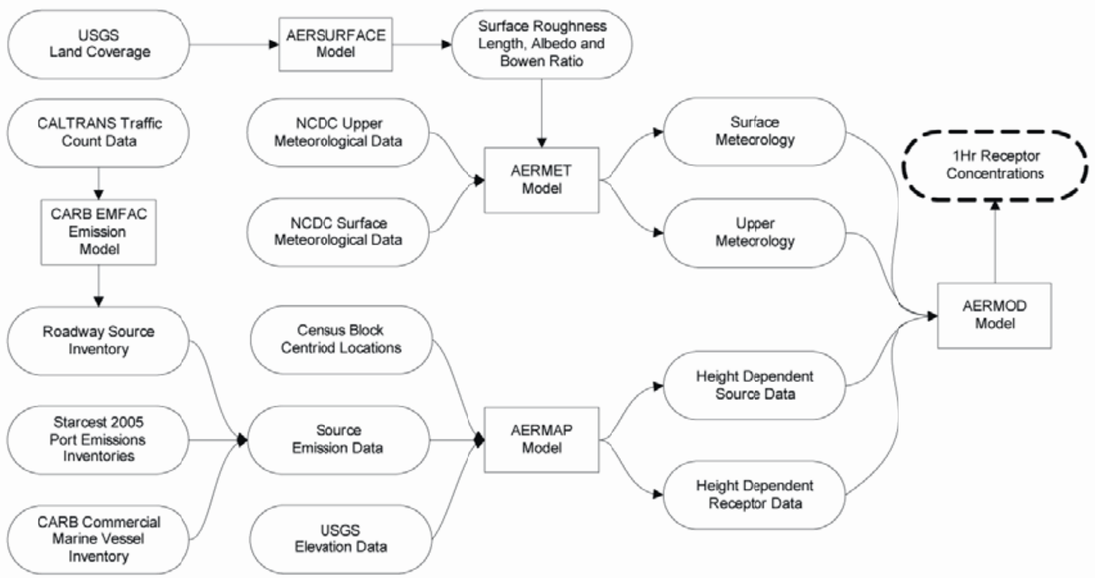

***Figure 2**. Structure of methodology. Computational models are shown with square outlines while data is shown with oval outlines.*

air measurements occur during the night. Twenty four–hour results of January will be lower than if there had been no missing upper air measurements because of higher mixing heights during the day. The missing results are linearly interpolated in time between the last and next AERMOD predictions.

AERMOD, like other plume transport models, cannot process calm winds (zero wind speed) or variable wind directions, which is a well–known issue documented by various studies (Hanna, 1983; Singh et al., 1990; Ontario Ministry of the Environment, 2005; Wu et al., 2009). There are 270 calm wind and 48 variable wind 1–hr instances in January, and 114 calm wind and 17 variable wind 1–hr instances in August out of 744 hours in each month. Calm and variable winds do not satisfy the preconditions of the plume model solution; hence these meteorological conditions can result in partial and incomplete data sets. A typical way to deal with the calm and variable wind problem is to replace these meteorological conditions with tolerable wind velocities and directions that are representative of the physical processes. The wind speed for calm winds is artificially set to a small cutoff value (Singh et al., 1990; Ontario Ministry of the Environment, 2005). In this case, the cutoff value is chosen to be the smallest non–zero velocity handled by AERMET which is 1 knot. Singh et al. (1990) noted that wind direction is equally probable in all directions for calm winds, similar to variable winds. To represent an equally probable wind direction in all directions for calm and variable winds, 12 separate meteorological scenario files are created where each file sets the wind direction for calm and variable winds to a different constant value spanning the unit circle. The results presented are the average of using AERMOD with each of the 12 different meteorological files. The same method was used to treat calm wind conditions in the CALINE4 model simulations (Wu et al., 2009).

AERMOD includes the option to process local building effects with the Plume Rise Model Enhancement (PRIME) (Schulman et al., 2000). Applications of AERMOD–PRIME have been limited so far to modeling a dozen or less sources (Venkatram et al., 2004; Silverman et al., 2007; Faulkner et al., 2008; Barton et al., 2010). The current study used AERMOD to model roadway source emissions as over 100 000 individual sources. The building characteristics for PRIME would need to be evaluated for each source. This would be a plausible extension of the current work, but is beyond the current scope and building characteristics are not considered.

2.2. Emission sources

Three separate emission sources are examined in the investigation of local air quality surrounding the San Pedro Bay of California; roadway, port and ship related emission sources. A comparison of how these sources vary by season can be found in the Figure S1 (see the SM).

Roadway Emissions. Wu et al. (2009) created a 2005 roadway emissions inventory for communities surrounding the Los Angeles and Long Beach ports based on the CARB Emissions Factors model (EMFAC) 2007 vehicle emissions model using an integrated traffic count database that accounts for gasoline and diesel vehicle activity in local highways and streets freeways based on traffic activity data from the California Department of Transportation (CALTRANS) and several other local sources.

Roadway emissions data contains volumetric flow rates of NO_X and $PM_{2.5}$ separated by month, hour and day of week. Roadway segments are divided into adjacent squares with sides lengths equal to the width of the road. These squares are modeled as volume sources with emission rates that vary by hour, month and day of week.

Port Emissions. Starcrest Consulting Group, LLC conducted two separate activity–based emission inventories of the Los Angeles and Long Beach ports in 2005 (Aldrete et al., 2007a; Aldrete et al., 2007b). The emission inventories categorize yearly averages of port related emissions. The inventories include direct port emissions and emissions due to port activity not directly released within the port such as port related emissions from locomotives, ships and heavy duty vehicles. The present study applies the emissions inventory from direct port related activities which is limited to cargo handling equipment. Cargo handling equipment encompasses the aggregated contribution of forklifts, a gantry crane, slide handlers, sweepers, top handlers, yards handlers, bulldozers, dump trucks, excavators, fuel trucks, loaders, main lifts, rail pushers, rollers and other equipment operated within the ports for port related activities. The Starcrest port emissions inventories include detailed maps of the activity regions within the ports where cargo handling equipment is operated.

The port cargo handling equipment activity areas are characterized with polygons using Google Earth to retain the high quality spatial resolution of the cargo handling equipment activity maps. The ports of Los Angeles and Long Beach activity zones are each separately mapped to 25 and 14 individual polygons, respectively, as shown in Figure 1. The polygons are analyzed with a Geographic Information System (GIS) to determine precise vertex coordinates and surface areas. Source emission rates are assumed homogenous within each port's activity area. Port activity areas are modeled by AERMOD as polygon area sources.

Ship Emissions. The approach employed in this study to examine the air pollution impact of ship emissions is the same as other studies (Corbett et al., 2007; Vutukuru and Dabdub, 2008; Matthias et al., 2010) where an atmospheric transport model is used to estimate increased concentrations due to ships. However, past studies have used regional and global transport models to examine the impact of ship emissions while this is the first study to use a local transport model. Although AERMOD assumes a horizontal heterogeneity which does not account for the land–sea micro–environment, it does address the influence of elevation changes due to local topography. Future work should address a modeling protocol to incorporate land–sea interface transport into AERMOD.

The North American ships emission inventory developed by Corbett et al. (2007) is used here to estimate ship related emissions. The inventory characterizes oceangoing cargo traffic in shipping lanes serving U.S. coastlines. The inventory was developed using a bottom–up methodology to obtain a spatially resolved inventory that utilizes historical ship movements, ship attributes and ship emission factors. Vutukuru and Dabdub (2008) successfully applied this ship emissions inventory to a regional photochemical air transport model of SoCAB.

Estimates of total monthly ship emissions of the North American region for the years 2002 and 2010 are interpolated to produce monthly emission rates for January and August 2005. The emission inventory consists of aggregated contributions of many shipping vessels in volume averages intended for use in regional transport models as 4x4 km area sources. Here, these sources are simulated in AERMOD as ground sources with a lateral dimension of 4 km. Because AERMOD is designed to predict short–range transport only (Cimorelli et al., 2005), the global ship emissions inventory is reduced using GIS tools to only include emissions within 30 km of the Los Angeles port. Of the near locations within the emissions data set only 90 locations are over shipping routes and have non–zero emissions. Contour plots of NO_X and $PM_{2.5}$ emissions are presented in the SM (Figure S3).

2.3. Model runs

Two cases surrounding the emissions from roadway, port and ship sources are examined to illustrate the impact of temporal variations within source emissions. The first case refers to the combination of roadway, port and ship emissions as previously described, herein referred to as the steady case. The port emissions consist of yearly averages while the ship emissions consist of monthly averages. The port and ship emission inventories do not provide the temporal resolution to predict diurnal or weekly variations of emissions. The steady case assumes a steady release of emissions from port and ship sources for each modeling period.

A second case has been developed to account for the weekly and daily temporal variations in port and ship sources which are unaccounted in the steady case. Port and ship emissions are parameterized following the methodology proposed by Vutukuru and Dabdub (2008) where 70% of any one day's emissions are between 8 A.M. and 8 P.M. and the remaining 30% of the emissions are between 8 P.M. and 8 A.M. additionally, emissions during the weekend are 50% of the emissions during the week. The total weekly emissions are kept constant and consistent with the steady case. The second parameterized case accounts for both diurnal and weekly variations in port and ship emissions and is hereto referred to as the parameterized case.

2.4. Local meteorology

Two monthly meteorological episodes from 2005 are examined in this study to illustrate the impact of seasonal changes on pollution dispersion. January is examined as a representative cold month with an average and peak temperature 13.3 and 29.4 °C, respectively. August is examined as a representative hot month with an average and peak temperature 20.2 and 35 °C, respectively. Wind roses for January and August are presented in the SM (Figure S2). Winds are predominantly north in January and north–west in August. Each month is analyzed using AERMOD to produce 1–hr average concentrations for all hours of the month.

2.5. Air quality monitoring

CARB maintains and operates numerous air quality monitoring stations across California (data available at http://www.arb.ca.gov/aqd/aqdcd/aqdcddld.htm). The current study compares CARB monitoring site data from East Pacific Coast Highway and North Long Beach with results from AERMOD. The East Pacific Coast Highway monitoring site has data of 24–hr measurements of $PM_{2.5}$ for all days in January 2005 and 27 days in August 2005. The North Long Beach monitoring site has data of 1–hr measurements of NO and NO_2 for 23 hours per day for all the days of January and August 2005. The North Long Beach monitoring data is processed to produce measurements of 24–hr concentrations of NO_X for all the days in January and August 2005. Both the East Pacific Coast Highway and North Long Beach locations are shown in Figure 1.

The Los Angeles Port supplied this investigation with monitoring data of 24–hr $PM_{2.5}$ concentrations at 4 monitoring locations: Wilmington, San Pedro, Coastal Boundary and Terminal Island. Air quality monitoring at these locations began after January 2005 and hence is only compared for the August 2005 episode. Additionally, measurement data is limited to 10 days within August 2005. The locations of the 4 Los Angeles Port monitoring sites are shown in Figure 1.

3. Results and Discussion

The colder climate in January leads to lower mixing heights and increased pollutant concentrations predicted by AERMOD, this is well documented phenomena (He et al., 2006; Wu et al., 2009). Figure 3 shows $PM_{2.5}$ and NO_X monthly average 1–hr concentrations separated by source for January and August from emissions due to roadway, port and ship sources; port and ship results use monthly constant emissions as described in case 1. Port emissions are the same for January and August, while port related $PM_{2.5}$ and NO_X 1–hr monthly average predictions are 2.5 times higher in January than August. Ship emissions are 18% higher in August than January for both $PM_{2.5}$ and NO_X due to seasonal changes in shipping traffic. Still, predictions from ship emissions are 2.1 times higher in January than August for both NO_X and $PM_{2.5}$. January and August $PM_{2.5}$ roadway source emissions are on average 99% similar, while NO_X roadway source emissions are on average 11% lower in August than January. Predicted concentrations from roadway emissions for NO_X and $PM_{2.5}$ are 3.7 and 3.3 times higher in January than August, respectively. Results confirm cold months produce increased dispersion transport compared with warm months due to lower mixing heights and temperatures and weaker sunlight intensity (Zhu et al., 2004; He et al., 2009). Secondary pollutants such as ozone, which are not modeled here, would have increased photochemical production during hot months compared with cold months.

Roadway emission predictions are influenced strongly by highway and roadway locations. Peak concentrations can be seen running through local highways. The East Pacific Coast Highway and North Long beach monitoring locations are both adjacent to major highways and found to be sensitive to roadway emissions. However, the hot spots Pier B, Carson and Adams are adjacent to

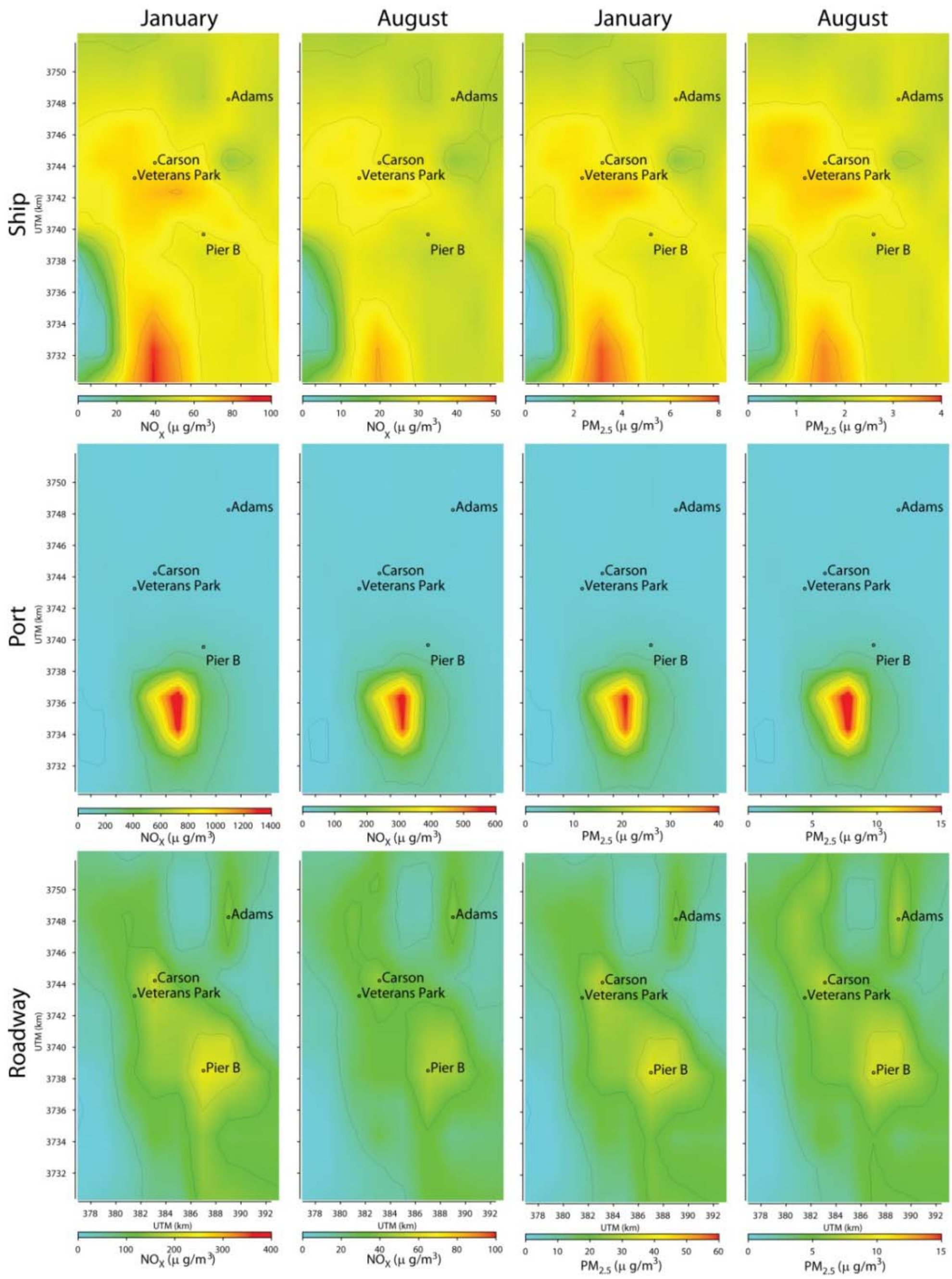

***Figure 3**. AERMOD monthly average predictions ($\mu g/m^3$) of the San Pedro Bay of California from roadway, port and ship emission sources shown in the bottom, middle and top rows, respectively. The first and last two columns show NO_X and $PM_{2.5}$, respectively. The first and third columns show January 2005, while the second and fourth columns show August 2005.*

multiple highways and produce the biggest impact from roadway emissions as shown in Figure 3. Carson is located between highways 110 and 405, and Adams is located between highway 710 and route 91. All the roadway related hot spots are within 2 km of at least 2 major highways.

Port emission predictions show a localized influence where predicted concentrations drops dramatically further than 2–6 km away from the ports compared with the peak concentration. However, Pier B is close enough to the ports to be strongly influenced by their emissions. Port emissions could have a further reaching impact considering photochemical production of secondary pollutants.

Ship emissions cover the largest area of the any of the modeled sources, but are also the most diluted source contributing mainly to background concentrations. Predictions from ship emissions are strongly influenced by local topography. Veterans Park is identified as a local hot spot sensitive to ship emissions because it sits in a valley surrounded by hills.

Figures 4 and 5 show 24–hr $PM_{2.5}$ and NO_X, respectively, for AERMOD modeled results and observations. Estimated concentrations are generally lower than observations, with the exception of the East Pacific Coast Highway during the January 2005 episode. This episode observed a late month peak which was not well characterized by AERMOD and produced on average an over prediction. The steady case produces higher concentrations than the parameterized case due to an over–prediction of nighttime concentrations from AERMOD. Other than a misrepresentation of source emission profiles, results underpredict observations because only local emissions from roadway, port and ship sources are considered. Regional background concentrations and photochemistry are not considered. Current methods to account for chemistry within AERMOD are limited to simple NO oxidation approximations and do not represent the current state of knowledge in numerical atmospheric photochemical mechanisms.

Figure 6 shows an alternate representation of the comparison illustrated in Figures 4 and 5 with a scatter plot of observations and predictions. There is a stronger correlation between measured and predicted concentrations for NO_X than that for $PM_{2.5}$, mainly because there are more anthropogenic and natural sources of PM unaccounted in the model including wave generated aerosols, erosion and secondary organic aerosols. Additionally, the secondary organic aerosol (SOA) component of the PM is mostly likely under represented due to large uncertainties in PM emission inventories regarding polycyclic aromatic hydrocarbons not represented in the model (Kanakidou et al., 2005).

Statistical parameters relating the comparison of predictions and observations are shown in Table 1. The strongest correlated data (R=50%) is from case 2, $PM_{2.5}$ predictions at Terminal Island. Case 1 predictions of $PM_{2.5}$ at Coastal Boundary produce the smallest root mean square error (3.5 $\mu g/m^3$). East Pacific Coast Highway January episode shows the highest mean normalized biases because it over predicts $PM_{2.5}$ on average. $PM_{2.5}$ and NO_X results produce similar correlation coefficients.

The parameterized case, where port and ship emissions are parameterized to account for diurnal and weekly variations, did not produce significantly different results than the steady case. Vutukuru and Dabdub (2008) found a similar result when comparing predictions from constant and parameterized ship emissions. However, it is important to examine this case because it illustrates the variation from diurnal activity. Carbonell et al. (2010) commented on how AERMOD has distinctive night and day time behavior. This distinctive behavior coupled with diurnal variations in emissions has the potential to radically impact results. The parameterized case has higher emission rates during the day where AERMOD predict lower concentrations than at night. This explains why the parameterized case consistently shows lower 24–hr concentrations than the steady case. The steady and parameterized cases relate equally well with observations.

AERMOD predictions of roadway source emissions are compared with a similar modeling study using CALINE4 (Wu et al., 2009). The CALINE4 work aimed to predict the impact of "local" traffic emissions within 3 km of the receptors thus did not consider distant roadway segments which may contribute to the "background" air pollutant concentrations. In other words, the AERMOD model in this study considers both local traffic–generated pollution and a portion of "background" concentrations from distant roadways, which may lead to slightly higher average correlations between estimated concentrations and ambient measurements (both local and background contributions) from AERMOD model. Thus, an absolute comparison with observations would unfairly favor the current model AERMOD. CALINE4 monthly average NO_X predictions for January 2005 are shown in Figure 7, which can be compared with the January average NO_X roadway prediction shown in Figure 3. While CALINE4 does not account for local topography, it does confirm the Adams location to be a primary pollution hot spot due to nearby roadway emissions. The Pier B hot spot is moved 3 km north from where AERMOD predicts a peak. Table 2 compares the correlation coefficient from comparing observations with CALINE4 and AERMOD predictions from roadway source emissions using the four monitoring sites within the Wu et al. (2009) study area which excludes the NO_X monitoring site. A comparison of the bias or root–mean–square–error would unfairly favor AERMOD because more roadway emissions are accounted for than in the CALINE4 study. AERMOD is better correlated than CALINE4 at 2 sites while CALINE4 is better correlated than AERMOD at 2 other sites.

A detailed comparison of CALINE4 and AERMOD is beyond the scope of this paper. Nevertheless, it is observed that CALINE4 treats line sources directly, while AERMOD treats line sources as a series of area sources. AERMOD is a state–of–the–art plume model that requires more meteorological and topographical information than CALINE4. Singh et al. (2006) compared AERMOD and CALINE4 at 2 different receptor sites over 3 days (He et al., 2006). They found that AERMOD over predicted CALINE4 on 2 out 3 days. Silverman et al. (2007) noted that AERMOD's improved handling of ground dispersion leads to greater concentrations near area sources (Singh et al., 2006). On average, AERMOD produces a 5% better correlation with observations than CALINE4.

A 2006 exposure assessment of the ports of Los Angeles and Long Beach conducted by CARB found that direct ship emissions are the largest contributor to local pollution compared with roadway, port and locomotive sources (Di et al., 2006). This study does not contradict the 2006 CARB exposure assessment. The CARB study considers only pollution from port related activity in roadways while our study considers all roadway traffic.

The Los Angeles and Long Beach Clean Truck Program began progressively reducing truck emissions in 2008. By 2012, the program will ban all trucks from the ports which don't meet 2007 emission standards by 2012. The results presented are in favor of the Clean Truck Program effectively reducing local pollution.

The results presented do not account for background concentrations, long range transport or photochemistry. While local topography is considered with AERMOD, it does not consider the built environment such as skyscrapers and local buildings. Additionally, errors inherent in measurement gathering help to explain the discrepancy between modeled and measured concentrations. The result of AERMOD under predicting observations is consistent with literature (Venkatram et al., 2004; Orloff et al., 2006; Kesarkar et al., 2007; Zou et al., 2010).

This study, like most others applying AERMOD, focuses on examining a 24–hr average time scale. Kumar et al. (2006) showed a better correlation between 24–hr AERMOD SO_2 predictions with observations than 1– and 3–hr predictions with observations. Likewise, Zou et al. (2010) found 1– and 3–hr AERMOD predictions performed worse than 24–hr, monthly and annual SO_2 predictions. While a comparison of NO_X 1–hr concentrations at the North Long Beach monitoring site was considered by this investigation, the correlation is poor due to AERMOD's weak diurnal characterization. The difference in AERMOD's treatment of day and night transport produces unrealistic diurnal profiles which do not match emission source profiles. Despite poorly correlated 1–hr concentrations, results show a moderate correlation with 24–hr concentrations. Similar to the peak 47% correlation found by Zou et al. (2010), this study has a 24–hr average peak correlation coefficient of 50%.

4. Conclusions

This study has applied the air dispersion model AERMOD to the San Pedro bay area to examine the impact of NO_X and $PM_{2.5}$ emission sources originating from three sources; roadways, ships and ports. Bottom up activity based and model based emission inventories are used in conjunction with observed meteorology and topography to predict the transport of emissions in a cold and a hot month in 2005. Special care has been taken to preprocess local meteorological conditions, such as replacing calm and variable winds, in order minimize incidents of meteorological conditions which AERMOD will not process.

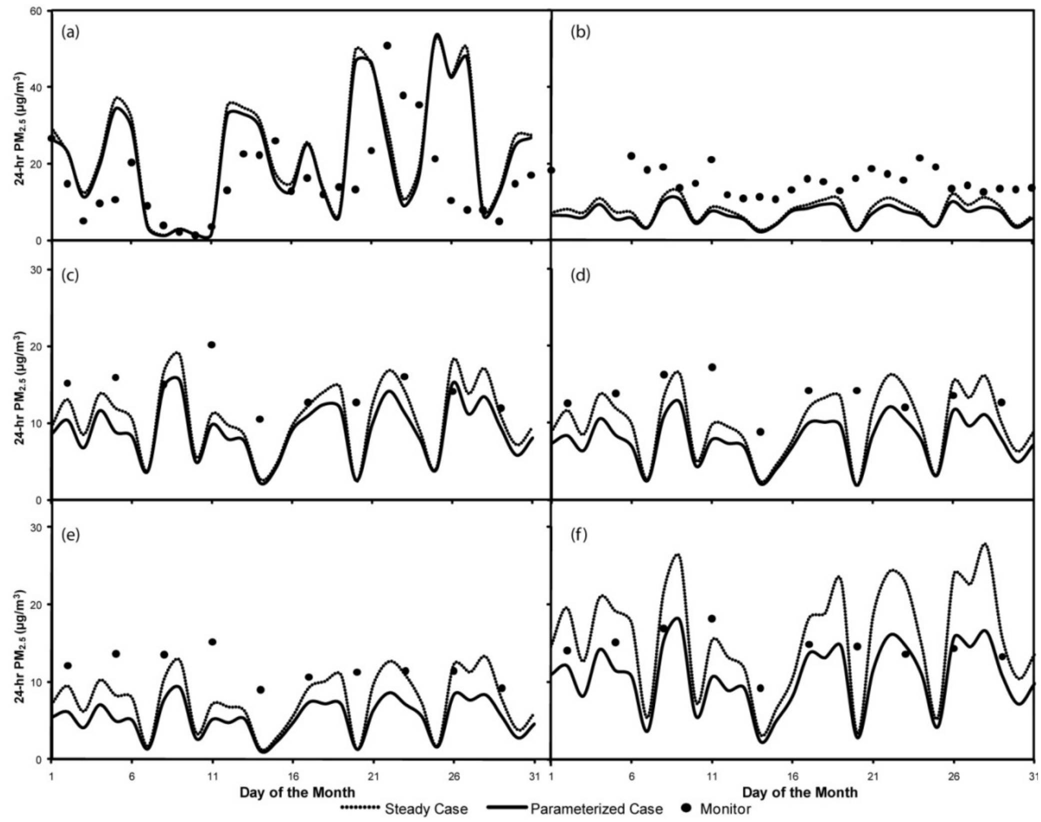

Figure 4. *24-hr $PM_{2.5}$ (µg/m^3) AERMOD predictions vs. monitoring observations:* ***(a)*** *January 2005 at East Pacific Coast Highway,* ***(b)*** *August 2005 at East Pacific Coast Highway,* ***(c)*** *August 2005 at Wilmington,* ***(d)*** *August 2005 at San Pedro,* ***(e)*** *August 2005 at Coast Boundary and* ***(f)*** *August 2005 at Terminal Island. Monitoring data is shown with a black circle. Steady and parameterized cases are shown with dotted and solid lines, respectively.*

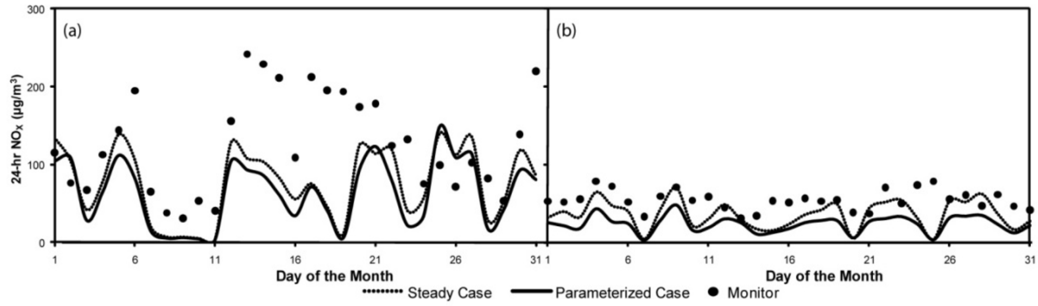

Figure 5. *24-hr NO_X (µg/m^3) AERMOD predictions vs. monitoring observations:* ***(a)*** *January 2005 at North Long Beach and* ***(b)*** *August 2005 at North Long Beach. Monitoring data is shown with a black circle. Steady and parameterized cases are shown with dotted and solid lines, respectively.*

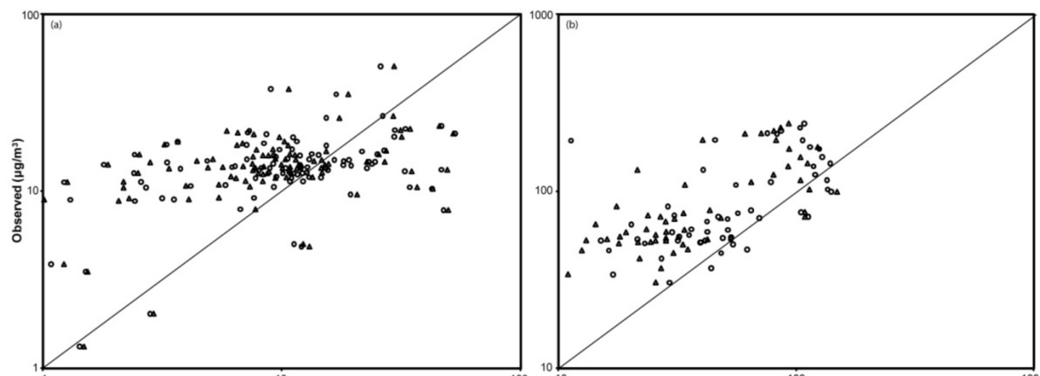

Figure 6. *Scatter plot of 2005 January and August 24-hr (µg/m^3) observations and AERMOD predictions of the San Pedro Bay of California:* ***(a)*** *$PM_{2.5}$ and* ***(b)*** *NO_X are shown on the left and right, respectively. Data from the steady and parameterized cases are shown with a circle and triangle, respectively. Diagonal lines show 1:1 correspondence.*

***Table 1**. Statistical parameters relating predicted AERMOD concentrations vs. observation*

	Location	Species	Month	Correlation Coefficient (%)	Root Mean Square Error ($\mu g/m^3$)	Mean Normalized Bias (%)
Steady Case	East Pacific Coast Highway	$PM_{2.5}$	January	28	13.5	65
	East Pacific Coast Highway	$PM_{2.5}$	August	3	5.0	-49
	Wilmington	$PM_{2.5}$	August	44	4.2	-22
	San Pedro	$PM_{2.5}$	August	33	3.8	-24
	Coastal Boundary	$PM_{2.5}$	August	32	3.5	-34
	Terminal Island	$PM_{2.5}$	August	46	5.3	11
	North Long Beach	NO_X	January	43	60.2	-36
	North Long Beach	NO_X	August	37	17.5	-33
Parameterized Case	East Pacific Coast Highway	$PM_{2.5}$	January	31	13.8	74
	East Pacific Coast Highway	$PM_{2.5}$	August	5	5.3	-56
	Wilmington	$PM_{2.5}$	August	42	4.2	-35
	San Pedro	$PM_{2.5}$	August	40	3.9	-42
	Coastal Boundary	$PM_{2.5}$	August	29	3.8	-54
	Terminal Island	$PM_{2.5}$	August	50	4.0	-25
	North Long Beach	NO_X	January	40	61.9	-47
	North Long Beach	NO_X	August	37	18.9	-55

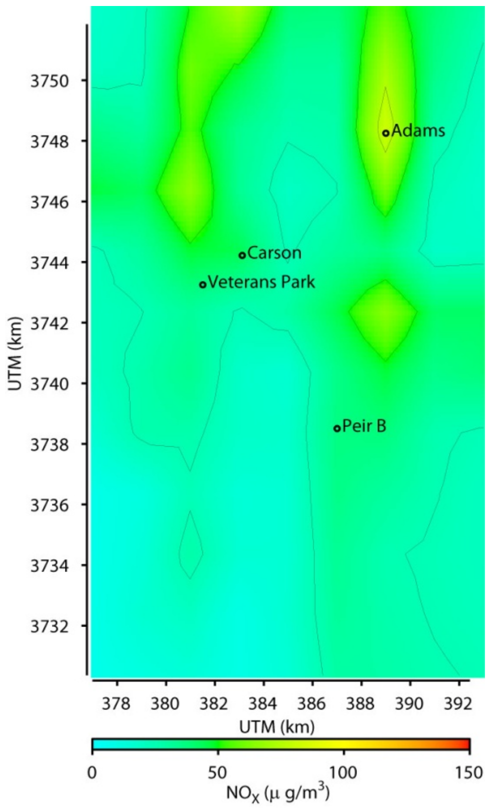

***Figure 7.** CALINE4 monthly average NO_X predictions ($\mu g/m^3$) of the San Pedro Bay of California from roadway source emissions for January, 2005.*

***Table 2**. Correlation coefficients (%) comparing 24-hr $PM_{2.5}$ AERMOD and CALINE4 results from roadway source emissions with observations*

Location	Month	AERMOD	CALINE4
East Pacific Coast Highway	January	26%	35%
East Pacific Coast Highway	August	13%	-13%
Wilmington	August	35%	47%
San Pedro	August	51%	31%
Coastal Boundary	August	25%	25%

Hot months are typically associated with increased pollution levels due to increased photochemical activity and ozone production. However, this study finds higher predicted concentrations during January than August because it only considers local transport and not chemical reactions. Hence, while cold months may have lower secondary pollutant concentrations than hot months, cold months also have increased transport of primary pollutants.

While terrain elevations of the study region are moderate with a 200 m maximum elevation change, this elevation change was significant enough to noticeably impact results. Local topography is responsible for the buildup of pollutants around Veterans Park. The evaluation of transport at different elevations is a unique feature of AERMOD which has provided substantive results.

For the majority of the study region, roadway emission sources are the most significant source of local pollution compared with port and ship emission sources. Based on predicted monthly concentrations, roadways contribute on average 8% more NO_X than ship and port sources, 38% more $PM_{2.5}$ than ship sources and 56% more $PM_{2.5}$ than port sources. However port emissions are the most significant of the three sources near the port, port emissions contribute more pollution than roadway sources within 6 km of the ports. Ship emissions produce the lowest peak concentration of the three sources examined.

Local pollution hot spots from roadway emissions have been found to be most common at the intersection of highways where roadway emissions are highly concentrated. The temporal and spatial variations of the results indicates the need for high–resolution air quality modeling that considers local meteorology and topography in order to understand the influence of local pollution sources.

Acknowledgements

Funding was provided by the UCI Environment Institute: Global Change, Energy, and Sustainable Resources.

Supporting Material Available

Seasonal variability of emissions (Figure S1), wind roses of applied meteorology (Figure S2), monthly ship emissions (Figure S3) and local land characteristics (Table S1). This information is available free of charge via the Internet at http://www.atmospolres.com.

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