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Particulate matter levels and children's lung function in a rural cohort near a drying saline lake

Fangqi Guo[a], Elizabeth M. Kamai[b], Sandrah P. Eckel[a], Dayane Duenas Barahona[b], Luis Olmedo[c], Esther Bejarano[c], Christian Torres[c], Christopher Zuidema[d], Edmund Seto[d], Shohreh F. Farzan[a], Jill E. Johnston[a,b]

Introduction: The drying Salton Sea in California is a growing source of wind-blown dust, raising particulate matter (PM) levels in surrounding areas. The impacts of these exposures on children's lung function remain poorly understood. We examined the relationship between PM levels and lung function in children near the Salton Sea.

Methods: We enrolled 491 children (mean age: 10.2 years), who were followed over ~1.5 years, contributing 1,269 lung function assessments. Forced expiratory volume in the first second of exhalation (FEV_1) and forced vital capacity (FVC) were measured using a commercial spirometer. Average PM concentrations were estimated for 3 and 12 months preceding each spirometry assessment, using 12 stationary monitors operated by the California Air Resources Board. Analyses were performed using mixed effects linear models adjusting for demographics and underlying health conditions.

Measurements and Results: Each 1 μg/m³ increase in average $PM_{2.5}$ exposure over 12 months before assessment was associated with a 31.5 ml lower FVC (95% confidence interval [CI] = −57.2, −5.9) and a 32.7 ml lower FEV_1 (95% CI = −56.4, −8.9). A 10-μg/m³ increase in average PM_{10} exposure over 12 months was associated with a 146.6 ml reduction in FVC (95% CI = −230.4, −62.9) and a 122.0 ml reduction in FEV_1 (95% CI = −197.8, −46.2). Associations within a 3-month exposure window showed similar results. PM exposure was associated with impaired lung function in both asthmatic and non-asthmatic children, with a slightly greater impact observed in those with asthma.

Conclusion: PM exposure near the Salton Sea is related to reduced lung function of pediatric residents.

Keywords: Lung function; Children; Salton Sea; Drying lake; Particulate matter PM2.5 PM10; Spirometry, FVC, FEV1

[a]Department of Population and Public Health Sciences, Keck School of Medicine, University of Southern California, Los Angeles, California; [b]Department of Environmental & Occupational Health, University of California, Irvine, California; [c]Comite Civico del Valle, Brawley, California; [d]Department of Environmental & Occupational Health Sciences, University of Washington, Seattle, Washington

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Investigators seeking access to the data should submit a study protocol and contact the PIs, Dr. Shohreh Farzan (sffarzan@usc.edu) and Dr. Jill Johnston (Jillj1@uci.edu).

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**Corresponding Author. Address: Department of Environmental & Occupational Health, University of California, 856 Health Sciences Road, Irvine, CA 92617. E-mail: Jillj1@uci.edu (J.E. Johnston).*

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Introduction

Wind-blown dust has emerged as an important source of particulate matter (PM) and has become a growing public health concern.[1] In the southwestern United States, limited water resources, combined with increasing periods of extreme heat and droughts, are intensifying the production of wind-blown dust and dust storms.[1,2] In California, these conditions are accelerating the rapid decline of the Salton Sea, a 350-square-mile terminal lake located in a highly productive agricultural area in the southeastern border region of the state.[3,4] This shallow terminal lake was created inadvertently when the Colorado River was diverted, filling a dry salt bed. The Salton Sea has persisted in this arid desert climate, largely supplied by irrigation runoff from adjacent agricultural lands.[5] Over the past two decades, climate change, coupled with human activities such as water transfers and conservation measures, has contributed to a significant decline in the Sea's water levels.[6,7] This has exposed approximately 16,000 new acres of dry lakebed,[8] exacerbating local air pollution and increasing PM levels.[6,7] Mobilized dust

What this study adds

The Salton Sea is a drying saline lake in one of the driest regions of Southern California. Its exposed lakebed is a major contributor to PM in the region, but the impact of this dust on children's lung function remains largely unknown. Using longitudinal data from the Children's AIRE cohort near the Salton Sea, we evaluated the relationship between PM exposure and children's lung function. Higher $PM_{2.5}$ and PM_{10} levels were consistently associated with lower FEV_1 and FVC. The observed effect sizes were larger than those reported in urban cohorts, highlighting environmental justice concerns for children near the lake.

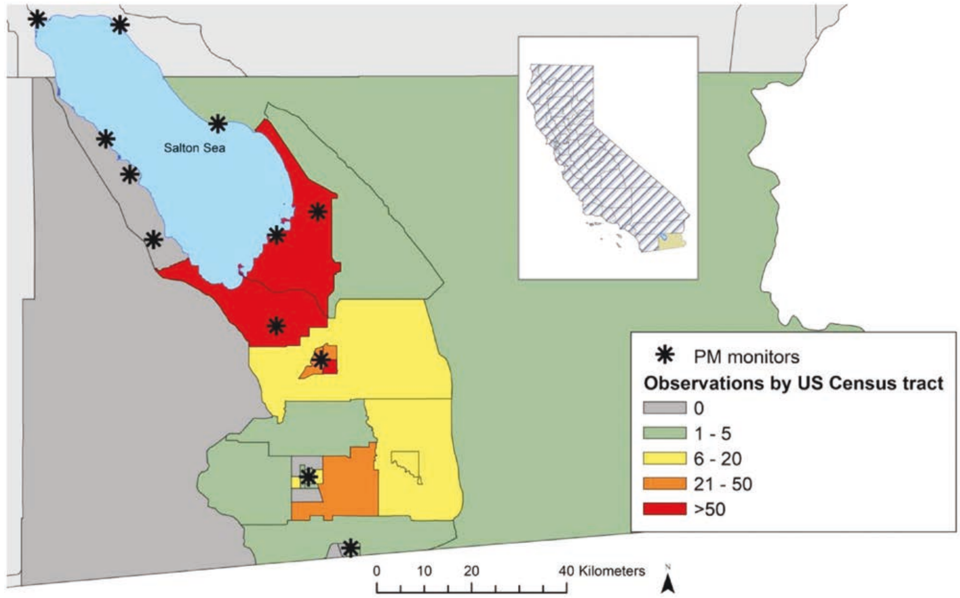

Figure 1. PM monitors and count of observations of AIRE cohort participants (2017–2019) by census tract. This figure is adapted with permission from Johnston, J. E., et al. (2024). Environmental Research, 263, 120070. Copyright © 2024 Elsevier.

from such saline playa or lakebeds is related to a high proportion of PM_{10} that can carry numerous contaminants, including adsorbed sulfate, chloride, pesticides, and toxic metals.[5] Over the next decade, an estimated 40% of the Salton Sea will be exposed to wind erosion, increasing PM_{10} emissions locally by about 11%.[9]

Across the globe, drying inland lakes, such as Owens Lake and the Great Salt Lake in the western United States, the Aral Sea in central Asia, Lake Urmia in the Middle East, and Lake Chad in western Africa, have resulted in a dramatic increase in dust emissions and local air pollution levels.[10–14] Although research has examined the relationship between drying lakes and air pollution, as well as general health impacts, there is a lack of specific studies investigating the direct health implications of dust from exposed lakebeds of shrinking lakes.[5] The unique environmental conditions of the Salton Sea may create a significant health threat, specifically for respiratory health and for vulnerable populations, such as children.[15] Children's natural defenses are less developed compared with adults, which might make them especially susceptible to the harmful effects of the airborne dust.[16,17]

The Children's **A**ssessing **I**mperial Valley **R**espiratory Health and the **E**nvironment (AIRE) Study is a prospective community-based cohort study designed to investigate environmental influences on children's respiratory health, with a specific focus on the potential health effects of the drying Salton Sea.[3] Our recent publication showed that more hours of dust event exposure from the Salton Sea were associated with lower lung function in this cohort of children.[18] Still, little is known about the associations between other Salton Sea–related environmental exposures (e.g., ambient PM concentrations) and lung function.

The current study aimed to use data from the AIRE cohort to investigate (1) the impacts of $PM_{2.5}$ and PM_{10} levels on children's lung function, and (2) whether observed associations vary by children's asthma status.

Methods

Study population

The Children's AIRE cohort[3] was designed in partnership with Comite Civico del Valle, a local community-based organization dedicated to civic engagement and health-based initiatives in Imperial Valley, in response to community environmental health concerns.[5] The region is known to experience poor air quality, with elevated levels of coarse particulate matter (PM_{10}).[5] In addition to the multiple environmental burdens, the majority of the Hispanic population (>80%) in this region also faces significant socioeconomic challenges, including high rates of unemployment (over 20%) and poverty (nearly one-third of children).[3]

At baseline (2017–2019), a cohort of 731 children in first through third grade and their parents were enrolled (Figure 1). From 2019 to 2022, 499 participants consented to continue biannual lung function assessments, along with physical examinations and health questionnaires. Bilingual questionnaires, adapted from the validated International Study of Asthma and Allergies in Childhood toolbox,[19] and questionnaires used as part of the Southern California Children's Health Study (CHS),[20] collected data on demographics, lifestyle, home characteristics, medical history, respiratory and asthma symptoms and diagnoses, and medication use.

All parent participants provided their written informed consent before their child's participation. Children also provided assent for their involvement in the study. The University of Southern California Institutional Review Board reviewed and approved all study protocols (HS-17-00204; HS-17-00823).

Assessment of lung function

Beginning when children reached the fourth grade and were approximately 9–10 years of age, children underwent lung function assessments using a commercially available ndd Easy-On PC (Andover, MA) spirometer. Trained study staff administered maximal-effort spirometry tests, following American Thoracic Society guidelines. Each child performed 3–7 maneuvers to obtain reliable measurements.[21] Reliable measurements were defined according to American Thoracic Society criteria, requiring at least three acceptable maneuvers with the two highest spirometry values within 150 ml of each other. The ndd Easy-On PC spirometer automatically selected the highest forced expiratory volume in the first second of exhalation (FEV_1) and forced vital capacity (FVC) values from the acceptable maneuvers and provided real-time quality control feedback, which was reviewed by trained staff to confirm test reliability. The ndd software

Table 1.

Characteristics of the study sample (n=491)

	Mean ± SD or n (%)
Baseline age (years)	10.2 ± 0.6
Lung function measures per participant	2.6 ± 1.3
Sex	
Female	267 (54.4%)
Male	224 (45.6%)
Ethnicity	
Non-Hispanic	31 (6.3%)
Hispanic	421 (85.7%)
Not reported	39 (7.9%)
Parent preferred language	
English	316 (64.4%)
Spanish	175 (35.6%)
Baseline height (cm)	141.4 ± 7.7
Baseline BMI (kg/m^2)	21.5 ± 5.4
Health insurance type	
None	36 (7.3%)
Private	129 (28.7%)
Public	284 (63.3%)
Not reported	42 (8.6%)
Baseline asthma	
No	368 (75.0%)
Yes	123 (25.0%)
Baseline recent respiratory disease symptoms[a]	
No	404 (82.3%)
Yes	87 (17.7%)
Baseline lung function	
FVC (ml)	2267.7 ± 587.7
FEV_1 (ml)	1926.1 ± 412
Air-flow obstruction (FEV_1/FVC ratio <0.7)	35 (7.1%)

[a]Yes, if a child had wheeze, dry cough at night, frequent cough, bronchitis, or congestion during the past 3 months.

collected and logged multiple spirometry measures, including FEV_1, FVC, and maximal mid-expiratory flow. Our analysis focused on FEV_1 and FVC, as both measures are established as strong and independent predictors of respiratory disease, cardiovascular mortality, and all-cause mortality.[22] Additionally, each participant's height (measured to the nearest 0.1 cm) and weight (measured to the nearest 0.1 kg) were recorded.

Particulate matter exposure assessment

A nearest-monitor approach was used to estimate participant PM exposure.[23,24] Ambient air quality data for $PM_{2.5}$ and PM_{10} were sourced from the 12 monitors (Figure 1) within the California Air Resources Board Air Resources Board's Air Quality Monitoring Information System.[25] Participants' caregivers provided residential addresses for the child at baseline and at each follow-up visit. If residential addresses were unavailable (4.7% of observations), the address of the participant's school was used instead. Distances between participants' addresses and the nearest PM monitor ranged from <100 m to 19 km, and the median distance was 2.2 km. Overall, 97% of the cohort lived within 11 km of a monitor site. For each participant, we identified the nearest California Air Resources Board monitor with valid PM measurements during the past 12- and 3- month periods preceding each lung function assessment.[15]

Covariates

Primary covariates included age, sex, height, height square, body mass index, body mass index squared, spirometry staff, health insurance type (public or private) as a proxy for social–economic status, asthma status (baseline or incident cases), presence of respiratory disease symptoms during the past 3 months, and study wave. These variables were a priori selected based on prior literature[26,27] and evaluations in our model (Table S1, https://links.lww.com/EE/A399). In addition to these primary covariates, we additionally adjusted for the following variables in sensitivity analyses: parents' preferred language (Spanish or English), presence of secondhand smoking in home, prenatal maternal smoking, allergies during the past 3 months, and respiratory disease treatment during the past 3 months. Respiratory disease symptoms were identified if the child had one of the following symptoms in the past 3 months: wheezing/whistling in the chest, dry cough at night, frequent cough, bronchitis, and congestion in the chest. Allergies in the past 3 months were identified as positive if a parent reported their child had any allergy symptoms, such as watery eyes, runny nose, and sneezing. Respiratory disease treatment was considered positive if a parent reported their child had treatment by a doctor or other health professional for pneumonia, bronchiolitis, bronchitis, or asthma. Most covariates (e.g., demographics and health status) were collected at enrollment and in annual follow-up assessments using self-administered questionnaires completed by the caregivers.

Statistical methods

Of the 731 participants who were enrolled in the AIRE study, 499 completed at least one spirometry measure. We then excluded eight participants due to missing core covariates (birthdate and weight/height), which resulted in a final sample size of 491 participants, with a total of 1,269 measurements over the follow-up period.

We investigated the distribution of each variable of interest and reported n(%) for categorical variables, and mean ± standard deviation for continuous variables (Table 1). We examined each variable of interest's raw association with spirometry measures, and results were included in the supplementary files; https://links.lww.com/EE/A399. Given the multilevel structure of the data, with participants nested within schools, and the longitudinal design of the study, we employed mixed-effects models to account for both within-school and within-participant variability. We used single-predictor mixed-effects linear models to investigate associations of annual PM exposures with spirometry measures, adjusting for the primary covariates mentioned previously. We also presented results of the association between spirometry measures and 3-month exposures as an additional analysis. Sensitivity analyses were subsequently conducted to adjust for additional covariates, as described earlier.

In addition to the main model described earlier, we also used the same modeling strategy to conduct stratified analysis based on participants' baseline asthma status. An interaction term (air pollutant × asthma status) was added to the main model to investigate if asthma status changed the air pollution–lung function association. To improve the precision of parameter estimates, all confidence intervals presented were calculated from robust standard errors. All analyses were conducted using STATA SE 17.0.

Results

As displayed in Table 1, of the 491 study participants, the baseline age (mean ± standard deviation) was 10.2 ± 0.6. During a mean follow-up of 1.5 years, participants contributed 1,269 lung function measurements. Our study sample had slightly more females than males (54.4% vs. 45.6%), and the majority of them identified as Hispanic/Latino (86%). Nearly two-thirds (63.3%) relied on public insurance, and 7.3% were uninsured, suggesting that most participants came from low-income families. Asthma was present in 25% of participants at enrollment. The distribution of baseline spirometry tests indicated that 35 (7.1%) participants had an FEV_1/

FVC ratio lower than 0.7, indicating some extent of airflow obstruction (Table 1).

In the study communities near the Salton Sea, the 12-month average concentrations of $PM_{2.5}$ and PM_{10} were 7.8 and 41.1 μg/m³, respectively (Table 2). The previous 3-month average levels were slightly higher, at 8.1 and 43.6 μg/m³ for $PM_{2.5}$ and PM_{10}.

Results of mixed effect linear models (Figure 2 and Table S2, https://links.lww.com/EE/A399) suggested that per μg/m³ increase in average $PM_{2.5}$ exposure over the 12 months before lung function assessment was associated with a 31.5 ml reduction in FVC (95% CI = −57.2, −5.9) and a 32.7 ml lower FEV_1 (95% CI = −56.4, −8.9). An additional 10-μg/m³ increase in average PM_{10} exposure over the previous 12 months was associated with a 146.6 ml reduction in FVC (95% CI = −230.4, −62.9) and a 122.0 ml lower FEV_1 (95% CI = −197.8, −46.2). Three-month PM levels were highly correlated with 12-month levels (Corrs ~0.75; Table 2), and overall, associations of 3-month PM levels with spirometry measures were similar to findings with the 12-month exposures (Figure 2 and Table S2, https://links.lww.com/EE/A399). Sensitivity analyses that accounted for additional covariates produced similar findings (Table S3, https://links.lww.com/EE/A399).

The modifying effects of asthma status are shown in Figure 3 and Table S4, https://links.lww.com/EE/A399. In general, both asthmatic and non-asthmatic children's lung functions were affected by the adverse impact of PM, with children with baseline asthma more susceptible than children without asthma. For example, for children without baseline asthma, each 1 μg/m³ increase in previous 12-month $PM_{2.5}$ exposure levels was associated with a 25.6 ml decrease in FEV_1 (95% CI = −46.8, −4.4). This effect estimate was doubled for children with baseline asthma (β = −52.3; 95% CI = −80.9, −23.8; *P* for interaction <0.001). Similar trends were observed for PM_{10}.

Discussion

In our study of children living near the Salton Sea, a drying saline lake in a rural region with PM_{10} annual levels over twice the California standard,[28] we found that higher $PM_{2.5}$ and PM_{10} levels were linked to poorer lung function, as measured by FVC and FEV_1. Our previous investigation found that 3-month exposure to dust event hours was associated with reduced lung function.[18] The present study extends this understanding by showing that, in addition to dust events, $PM_{2.5}$ and PM_{10} concentrations also adversely affect children's lung function in communities surrounding a drying saline lake.

The drying lakebed of the Salton Sea can be a significant source of PM air pollution.[8,9] Higher levels of PM exposure have been linked to higher prevalence of asthma, wheezing, and other respiratory symptoms.[15,29] Across the globe, numerous inland lakes have been or are currently drying up, leaving behind exposed lakebed and posing a growing threat to public health.[10,11,30–32] In the United States, water diversion in 1920 led to the complete desiccation of Owens Lake; as a result, it became a major source of PM in the Western United States for decades.[12] More recently, the Great Salt Lake in Utah has been rapidly shrinking and has lost nearly 60% of its pre-diversion surface area with corresponding increases in arsenic-laden playa.[33] Given that wind-blown dust from drying lakebeds is typically associated with a high proportion of PM_{10} with sulfate, chloride, pesticides, and heavy metals,[32] exposure to these PM sources may lead to more severe health consequences.

In addition to the environmental health risks associated with exposures near the Salton Sea, our study participants, who are predominantly a rural, marginalized population residing near the United States–Mexico border, face significant socioeconomic challenges. In this unique cohort, we observed a negative association between exposure to PM and lung function. This finding is consistent with previous research, particularly studies conducted in urban areas, such as the CHS, a longitudinal cohort that focuses on urban children in Southern California.[34–38] CHS studies demonstrated that exposure to ambient air pollutants, including PM, was associated with deficits in lung function and reduced lung-function growth in children.[26,27] However, the effect size identified in our cohort is greater than that reported in this urban cohort. For example, a CHS study that has a similar study design reported that a 1-μg/m³ increase in averaged $PM_{2.5}$ exposure over 6 years was associated with a small decrease in lung function, specifically a 0.22% decrease in FEV_1 (equivalent to 5.3 ml) and a 0.17% decrease in FVC (equivalent to 4.7 ml).[38] While our study of a rural population found a much larger effect, with a 1-μg/m³ increase in averaged $PM_{2.5}$ exposure over 12 months associated with a 34.2 ml decrease in FVC and a 32.5 ml decrease in FEV_1. Similarly, the effect size of PM_{10} was also stronger in our rural border cohort compared to the CHS urban cohorts.[38] We found that a 10-μg/m³ increase in PM_{10} exposure during the previous 12 months was associated with over a 100-ml decrease in both FVC and FEV_1, which is a meaningful decline in lung function. Such reductions have been linked to reduced exercise capacity and a higher risk of premature mortality, indicating important long-term health consequences.[39] The larger effect size observed in our study suggests that the environmental hazards near the Salton Sea may be particularly harmful to respiratory health, and these sources warrant further investigation.

Field studies of dust emissions from the Salton Sea have found that the playa-like surfaces are a significant source of year-round dust emissions.[40] A 10-minute sustained wind could generate approximately 30 pounds of dust per acre per hour,[41] posing a significant threat to regional air quality.[8,9] While communities around the Salton Sea are experiencing significant increases in wind-blown dust, the impact of this drying lake-induced dust on children's lung function has been largely unexplored.[5] Nevertheless, in a similar scenario, dust from other sources (e.g., deserts) has been strongly linked to impaired lung function in children.[42–47]

Similar to other studies focusing on United States–Mexico border pediatric populations,[48,49] our cohort has a high prevalence of asthma, with one in four participants having the

Table 2.

Distribution of particulate matter exposures estimated from child's residential address (n observations = 1,268)

Exposure	Unit	Mean	Std.	Min	Max	Corr[a]
$PM_{2.5}$						
3-month average	μg/m³	8.1	2.7	2.4	13.3	0.75
12-month average	μg/m³	7.8	1.8	3.8	10.9	
PM_{10}						
3-month average	μg/m³	43.6	18.1	4.8	78.0	0.73
12-month average	μg/m³	41.1	7.6	15.3	62.5	

[a]Correlation between the 3-month and 13-month averages for the same pollutant

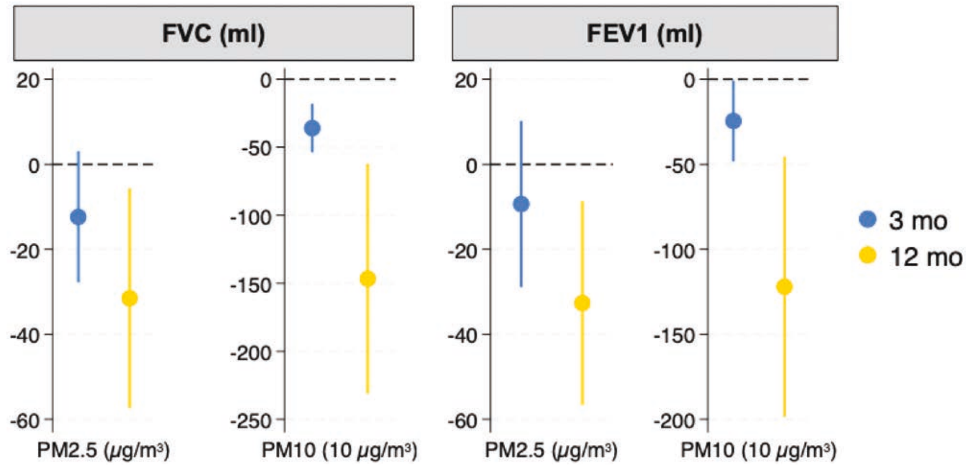

Figure 2. Exposure to short-term (3-month) and long-term (12-month) average particulate matter and spirometry measures. Beta with 95% CI. Results were obtained from single-exposure multilevel mixed effects linear models that accounted for individual-level and school-level random intercepts. Every model adjusted for age, sex, height, height squared, BMI, BMI squared, spirometry staff, insurance type, baseline or incident asthma cases, respiratory disease symptoms within the past 3 months, and data collection wave. BMI, body mass index.

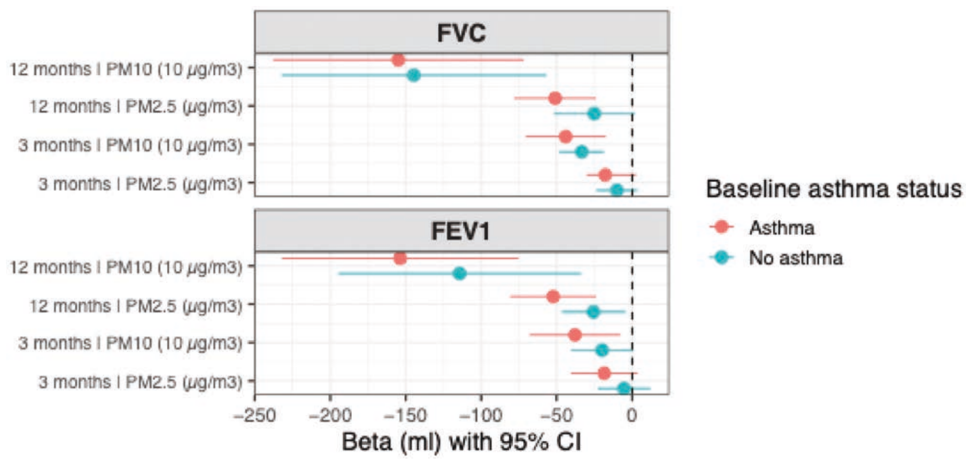

Figure 3. Association between particulate matter exposure and spirometry measures, stratified by baseline asthma status. Results were obtained from single-exposure multilevel mixed effects linear models, stratified by baseline asthma status. Each model adjusted for individual-level and school-level random intercepts, and adjusted for age, sex, height, BMI, spirometry staff, insurance type, recent respiratory symptoms, and data collection wave. BMI, body mass index.

condition.[29] Additionally, this cohort also experiences high rates of wheezing and bronchitis symptoms.[15] Consistent with previous findings from this cohort, which showed that PM exposure was associated with increased risk for wheezing and bronchitis symptoms in children with asthma,[15] our study further shows that PM exposure also has greater effects on lung function in asthmatic children. Children with asthma, who have more sensitive airways, may be particularly vulnerable to the harmful effects of air pollution.[50] Early onset asthma has also been identified as a significant risk factor for impaired lung function.[51] Interestingly, non-asthmatic children were similarly impacted by PM exposure, with equivalent reductions in FVC associated with PM_{10} levels. These findings suggest that while asthmatic children may be particularly vulnerable to the adverse health effects resulting from the shrinking Salton Sea, non-asthmatic children are also adversely impacted by PM exposure.

Our study examined both long-term and short-term PM exposure. While exposures during the two periods were highly correlated (corr ~0.75), we found that the long-term exposure to both $PM_{2.5}$ and PM_{10} had a greater impact on children's lung function. This may suggest that chronic exposure is an important driver of impaired lung health over time, although previous studies reported that both short-term and long-term exposure to PM could impact children's lung function.[26,52]

Animal studies suggest that exposure to desert dust might be linked to inflammatory damage to the lower respiratory tract.[53] This inflammatory response is believed to be driven by oxidative stress and the release of pro-inflammatory mediators in the respiratory epithelium.[53] Experimental studies with Salton Sea dust suggest that it may induce a distinct inflammatory response, characterized by innate immune activation, which differs from the typical allergic response observed in asthma.[54] Further studies are needed to identify the dust components driving these inflammatory patterns.

This study is one of the first to investigate the link between PM levels near the Salton Sea and children's lung function. We objectively measured children's lung function (FVC and FEV_1) using spirometry and leveraged an extensive monitoring network within the rural community. However, our study has some limitations. First, we estimated exposure by assigning PM monitor values to participants' residential addresses, which may not fully capture individual-level exposures. However, we compared the nearest monitor to each child's home with the nearest monitor to their school at every time point during the study period and found that in 95% of cases, these monitors were the same. Given this high overlap, using the home-based monitor is a reasonable approximation of PM exposure at both school and home. Second, given the observational nature of this study, residual confounding cannot be ruled out. Although we adjusted for key demographic and disease history variables, unmeasured factors—such as indoor air pollution and physical activity—may still influence the observed associations. Therefore, our findings should be interpreted with appropriate caution. Despite these limitations, our findings provide valuable insights into the potential health risks associated with air pollution from the Salton Sea. Given the unique and worsening environmental conditions in this region, coordinated actions from state and local agencies are urgently needed to reduce dust emissions and improve air quality. Future research should also focus on refining exposure assessment and conducting prospective studies to better understand the long-term health impacts of this environmental issue.

To conclude, this study found that higher PM concentrations were associated with lower lung function in children living near the shrinking Salton Sea. These findings raise important environmental health and justice concerns, as low-income rural communities of color in this region may be disproportionately affected by dust-related health impacts. As drying lakes and other non-combustion sources of PM become a growing issue worldwide, the associations we observed may also shed light on other rural or urban communities facing similar environmental challenges.

Conflicts of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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