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Air Pollution, Health, and Environmental Justice in Southern California's Salton Sea Region

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by

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ABSTRACT OF THE DISSERTATION

Air Pollution, Health, and Environmental Justice in Southern California's Salton Sea Region

by

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Ambient air pollutants including aerosols and gas phase pollutants has caused concerns for both air quality and public health, especially in regions of environmental injustice. The Salton Sea region located in southern California, is one such region characterized by high air pollution levels, asthma rates but low socioeconomic status. My dissatisfaction centers around evaluating and comparing the adverse health impacts of ambient air pollution exposure including $PM_{2.5}$, ozone and windblown dust, as well as characterizing ammonia emissions in the Salton Sea region.

In the first study, I examine disparities in air pollution exposure and associated health outcomes in the Coachella Valley. Two different measures of the health outcomes are used to investigate the connections between air pollution exposure and human health. I further investigate whether such relationships vary with socioeconomic status metrics. This research showed that more vulnerable communities are associated with higher levels

of $PM_{2.5}$ and higher emergency room visits, possibly indicating that high exposure, high vulnerability families are less likely to self-report diagnoses relative to more affluent communities.

In the second study, I developed a model to separate windblown dust observed in the Salton Sea region by their potential source regions and compare the health impacts of those different dust coming with a case crossover design. Results show increases in both respiratory and cardiovascular hospital admissions with increasing mole fractions of dust arriving from over the Salton Sea. Even stronger associations were observed for Salton Sea dust with algae events. These findings are important for air quality mitigation efforts in the region, as they point to the possible significance of water surface sources of toxic particulates alongside the windblown dust sources that currently receive the most attention.

In the third study, I characterize potential sources and emission patterns of ammonia in the Salton Sea region through a series of mobile lab measurements. As part of this work, I measured ammonia mole fractions near potential sources including cattle feeders and geo-thermal plants. This study fills a knowledge gap of ammonia emissions in the Salton Sea region and contributes to emission inventory development, a major goal of local researchers and policymakers.

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Chapter 1 Introduction

1.1 Air pollution and human health

Air pollution exposure is one of the leading threats to human health worldwide (Cohen et al., 2017; Khomenko et al., 2021; Lim et al., 2012; WHO, 2016). Both short- and long-term exposure to air pollutants such as fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10}) and ozone (O_3) have been linked to adverse health effects on human including both respiratory disease like asthma, chronic obstructive pulmonary disease (COPD) and lung cancer, and cardiovascular disease like stroke and ischemic heart disease (Anenberg. et al., 2010; Brook. et al., 2010; Dockery and Pope, 1994; Jerrett et al., 2009). In 2013, ambient air pollutants were classified as "cancer-causing agents" by The International Agency for Research on Cancer, which means it is carcinogenic to humans. According to the World Health Organization, air pollution is the 4th leading risk factor for death globally, 99% of the world's population live in places where air pollution levels exceed WHO guideline limits, with 6.7 million premature deaths annually linked to air pollution exposure worldwide (WHO, 2023). For the United States, the deaths associated with air pollution exposure is about 100,000-200,000 annually, which is higher than the total deaths from murders and car crashes (Thakrar et al., 2020).

1.2 Windblown dust

Windblown dust, also known as wind erosion or aeolian erosion, refers to the process whereby loose soil particles are lifted and transported by the wind. It's a common constituent of atmospheric particulate matter that can be transported over both short and long distances, causing regional and global effects in terms of air quality, climate, and human health (DeMott et al., 2003; Liaskoni et al., 2023). In recent decades numerous population level epidemiologic studies of dust storms have found a positive correlation between windblown dust and hospital admissions, emergency department visits, and mortality (Al et al., 2018; Rublee et al., 2020). Model simulations have further predicted increasing dust emissions in the future due to climate change and anthropogenic activities, especially in arid and semi-arid areas, thereby imposing additional health burdens on impacted downwind communities (Evan, 2019; Lababpour, 2020).

Considering the generation process of windblown dust that is generally driven by primary emissions from surface sources, dust emissions show strong correlations with underlying surface properties and meteorological conditions (Field et al., 2011; Okin, 2022; Usher et al., 2003). Thus, particles emitted from different surface types can differ greatly in terms of composition, size distribution, and other properties; variability in the resulting health impacts of windblown dust may be likewise source dependent. For example, exposure experiments to assess impacts of dust collected from different locations around the Salton Sea have found that the aqueous extracts from dust collected near the Salton Sea induced unique tissue inflammation, while extracts collected from a more remote desert location showed no such inflammation (Biddle et al., 2023, 2021). While more work is needed to further constrain the cause and mechanism of this inflammation, the unique inflammatory response shown in mice exposed to dust samples collected near the Salton Sea suggests the possibility of differing human health responses among the communities exposed to these ambient particles as well.

1.3 Lake spray aerosols

Lake spray aerosol refers to the particles and droplets that are generated when wind interacts with the surface of a lake, causing water to be lifted and dispersed into the atmosphere. This phenomenon occurs commonly in windy conditions, especially on large water bodies, and has gained increasing attention in recent years due to its role in atmospheric processes and climate dynamics. Lake spray aerosol can be a significant source of aerosols in the local atmosphere, influencing air quality, weather patterns, and cloud formation (Quinn et al., 2015). Additionally, lake spray aerosols can act as carriers to transport potentially toxic components from the lake surface to the atmosphere (Amiri-Farahani et al., 2021; May et al., 2018). While the mechanism and underlying epidemiological impacts of lake spray aerosols remain poorly constrained and highly uncertain, there are apparent mechanistic similarities with the more widely studied processes of sea spray aerosol (Harb and Foroutan, 2022). Recent work has highlighted the ability of sea spray aerosols to carry hazardous components including virus, bacteria and other important organic components from seawater as aerosol into the atmosphere (Fleming et al., 2009, 2007). This process could have important implications for the potential ability of lake spray aerosols in terms of transporting harmful components to the surrounding area through atmosphere and causing health impacts.

1.4 Ammonia

Ammonia (NH_3) is a gas composed of nitrogen and hydrogen atoms and is the dominant atmospheric alkaline species. Globally, the major sources of ammonia come from animals waste, fertilizers, biomass burning, crops, human populations, soils, industry processes and fossil fuels with agriculture contributing over 81% of total global emission (Damme et al., 2021; Wyer et al., 2022). Ammonia emissions have been linked to several adverse impacts on both air quality and human health. Ammonia reacts with various acidic compounds, such as sulfuric acid (H_2SO_4) and nitric acid (HNO_3), to form ammonium salts, which can contribute to the formation of secondary particulate matter and act as a key precursor of atmospheric fine particulate matter ($PM_{2.5}$) (Hristov, 2011). And $PM_{2.5}$ is a well-documented air pollutant and has been linked to various adverse health impacts. Beyond the indirect health effects caused by $PM_{2.5}$, inhalation of high concentrations of ammonia can also lead to respiratory irritation, lung damage, and exacerbation of asthma symptoms.

1.5 Air pollution exposure and socioeconomic status

Beyond the adverse health effects associated with air pollution exposure mentioned above, the magnitude of their impacts also depends on other covarying factors such as socioeconomic status, exacerbating health disparities in affected populations (Munoz-Pizza et al., 2020; Nascimento et al., 2021). Socioeconomic status (SES) is estimated using indicators like education level, poverty, linguistic isolation, health insurance coverage and race as a means of estimating individual or community-wide sociological, economic and demographic status and resilience. In general, groups with higher socioeconomic and demographic vulnerability tend to experience not only greater pollution exposure, but also enhanced vulnerability to that exposure itself (Hajat et al., 2015). For example, previous studies have found that communities with a higher proportion of minority residents and lower household income tend to experience higher levels of ambient $PM_{2.5}$ and children living in lower SES families tend to be at greater risk for respiratory disease (Gray et al., 2013a; Munoz-Pizza et al., 2020). This indicates the potential modification effects of socioeconomic status on the correlation between air pollution exposure and associated health impacts.

1.6 The Salton Sea

The Salton Sea is a saline, inland, terminal lake located at southern California's Riverside and Imperial Counties in the United States. The Salton Sea region, including the Coachella Valley located at the north end of the Salton Sea and the Imperial Valley located at the south end of the Salton Sea, has been characterized as non-attainment area for various air pollutants including $PM_{2.5}$, ozone and PM_{10} by USEPA for decades (USEPA, 2021). In addition to the air quality issue, this region also experiences high levels of asthma at a rate which is much higher than both the national and state state-level averages (Marshall, 2008). Beyond overall air pollution and public health burdens, disparities in pollution exposure, health outcomes and population characteristics are also apparent within the Salton Sea region itself (Miao et al., 2022). The eastern Coachella Valley that is located at the north end of the Salton Sea has been designated as one of the environmental justice communities by California Air Resources Board's (CARB) AB617 program. More specifically, this AB 617 program is focused on reducing exposures of communities most affected by air pollution.

On top of that, an even more serious issue is the shrinking of the Salton Sea. Due to increasing imbalances between inflows and evaporation, water levels of the Salton Sea have declined from 195 feet (about 60 meters) under sea level to the current height of 237 feet (about 73 meters) under sea level, exposing about 33 square miles (about 86 square kilometer) of previously submerged lakebed (Imperial Irrigation District, 2023). The newly exposed dry lakebed, also known as playa, is expected to emit large amounts of additional particulate matter (PM) and increase the frequency of dust events in this region (Parajuli and Zender, 2018a). According to previous study, without mitigation the Salton Sea water level will decline to 258 feet under sea level by the year 2047, exposing an additional 92,000 acres of playa, increasing dust emissions by 37,000 tons, and leading to an additional $37 billion in public health costs (Michael J. Cohen, 2014).

1.7 Overview of this dissertation

To investigate the air pollution, human health and environmental justice issues in the Salton Sea region, I designed three projects to study the following topics:

1. Disparities in air pollution exposure, socioeconomic status, and health among Coachella Valley communities
2. Source specific acute health effects of ambient dust exposure in the Salton Sea region

3. Ammonia emissions and distribution patterns in the Salton Sea region

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Chapter 2 Evaluating health outcome metrics and their connections to air pollution and vulnerability in Southern California's Coachella Valley

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Abstract

The ongoing desiccation of California's Salton Sea has led to increasing concerns about air quality and health for its surrounding communities, including the nearby Coachella Valley – a region already experiencing severe air quality and health disparities. Here we explore spatial air pollution and human health disparities in the Coachella Valley with particular attention to disparities arising across population characteristics including both socioeconomic and demographic vulnerabilities. We use two different measures of respiratory and cardiovascular health outcomes at the individual and census tract levels – one measure based on a randomly sampled telephone survey and the other measure based on emergency room visitation data – to investigate the degree to which these health outcomes are connected to air pollution and socioeconomic metrics. We further investigate biases and differences between the health outcome metrics themselves and suggest opportunities to address them in future analyses and survey efforts. We find that more vulnerable communities are associated with higher levels of fine particulates, but lower levels of ozone. While emergency visit rates show a significant positive correlation with both pollutants, no such association is found when using surveyed health

outcome data. The ratio of emergency visits versus survey rates shows a positive relationship with socioeconomic and demographic vulnerability, indicating that vulnerable communities are less likely to self-report diagnoses despite higher rates of respiratory or cardiovascular hospitalization. Additionally, survey respondents tend to show less vulnerability relative to their surrounding census-based demographics. These findings suggest the need for greater attention to health issues specifically within disadvantaged communities in the Coachella Valley, building upon and working within existing community networks and local resources, to better address current and projected health needs. Our findings also highlight disparities in air pollution exposure, health outcomes, and population characteristics in the Coachella Valley, providing context for crucial pollution reduction efforts in the face of increasing environmental threats.

2.1 Introduction

Ambient air pollution exposure is one of the leading threats to human health worldwide (Cohen et al., 2017; Khomenko et al., 2021; Lim et al., 2012; WHO, 2016). Both acute and chronic exposure to air pollutants such as fine particulate matter ($PM_{2.5}$) and ozone (O_3) have been linked to adverse human health outcomes, including respiratory and cardiovascular disease (Anenberg. et al., 2010; Brook. et al., 2010; Dockery and Pope, 1994; Jerrett et al., 2009). Evidence has further shown that the desertification of inland lakes can lead to increases in air pollution and associated health outcomes among local residents (Bennion et al., 2007; Cahill et al., 1996; Gao et al., 2011; Ussenaliyeva, 2020). Located in southern California, the Salton Sea is one such lake; due to increasing imbalances between inflows and evaporation, water levels of the Salton Sea have declined from 60 meters below sea level in the 1950s to the current height of 73 meters below sea level, exposing roughly 86 square kilometers of previously submerged lakebed (Pacific Institute, 2021). The potential for increasing emissions of particulate matter from this drying lakebed threatens to exacerbate air pollution and public health concerns in nearby communities already facing pollution exposure and vulnerability concerns (Frie et al., 2017; Biddle et al., 2021; Doede and DeGuzman, 2020; Johnston et al., 2019; Jones and Fleck, 2020; Parajuli and Zender, 2018).

The Coachella Valley (CV) at the north end of the Salton Sea (Figure 2.1 upper right), experiences high levels of air pollution exposure and socioeconomic and demographic vulnerability by national and state-level standards. It is characterized by extremely high levels of ambient coarse particulate matter (PM_{10}) throughout the year and is regularly designated for “serious” nonattainment area of the national 24-hour average PM_{10} standard (150 $\mu g/m^3$) set by the United States Environmental Protection Agency (USEPA, 2021). Additionally, transport from the densely populated Los Angeles-South Coast Air Basin (SoCAB) also drives elevated ozone pollution levels, contributing to average Coachella Valley ozone levels ranking around the 86^{th} percentile among California census tracts (Kim et al., 2016; OEHHA, 2021). In terms of the socioeconomic vulnerability, local observed poverty levels are relatively high, with measures of tract-level poverty (defined as the proportion of households with income below the federal poverty level) in the region as high as 99^{th} percentile statewide (OEHHA, 2021). Beyond overall air pollution and socioeconomic and demographic burdens, disparities in pollutant exposure, health outcomes, and population characteristics are also apparent within the Coachella Valley itself. For example, the asthma rate of adults in Palm Desert (a city located at the western part of the Coachella Valley, Riverside County) for 2016 is around 4% while rates for adults in Mecca (a city located at the eastern part of the Coachella Valley, Riverside County) are nearly five times higher at 20% (HARC, 2016). Poverty rates also vary widely, ranging from 17% up to 87% (U.S. Census Bureau, 2019). These metrics, collectively, suggest that any additional health risks posed by the shrinking of the nearby Salton Sea will occur alongside significant pre-existing vulnerabilities and disparities, challenging state and local policymakers to address the socioeconomic vulnerability and health divide apparent in the region.

Although the adverse health effects associated with ambient air pollution exposure have been widely confirmed by previous studies, the magnitude of their impacts may also be dependent on other covarying factors such as socioeconomic status (SES) and other population characteristics, exacerbating health disparities in affected populations (Forastiere et al., 2007; Munoz-Pizza et al., 2020; Nascimento et al., 2021). Population characteristics include both socioeconomic indicators such as education level, poverty, linguistic isolation, and health insurance coverage, along with demographic metrics such as race and age as a means of estimating individual or community-wide sociological, economic and demographic resilience and vulnerabilities (Baker, 2014). In general, higher socioeconomic and demographic vulnerability tends to be associated not only with greater pollution exposure, but also enhanced risks from that exposure itself

(Do et al., 2021; Hajat et al., 2015; Newell et al., 2017). According to Gray (2013), communities with a higher proportion of minority residents and lower household income tend to experience higher levels of ambient $PM_{2.5}$. Munoz (2020) reviewed 17 studies and found that SES indicators have higher modification effects on the relationship between air pollution and childhood respiratory disease in lower SES families, suggesting that children living in these families tend to be at greater risk for respiratory disease.

While high air pollution levels and asthma rates in the Coachella Valley have been a source of concern for decades, as it is in many similar environments globally that include inland lakes (e.g., Lake Chad in Africa, Lake Urmia in Iran), there is a paucity of research examining the connections between health outcome metrics, chronic air pollution exposure and demographic/socioeconomic vulnerability in these areas. To help fill this gap, this study examines health outcomes (respiratory and cardiovascular disease) and their connections to chronic air pollution exposure ($PM_{2.5}$, and ozone) and population characteristics (socioeconomic and demographic indicators), as well as observed differences between the health outcome metrics themselves. We hypothesize that, first, adverse human health effects resulting from chronic ambient air pollution exposure will show up as positive correlations between pollutant levels and health outcome rates; and second, that socioeconomic and demographic vulnerability exacerbates these adverse health effects, meaning that the impacts of air pollution exposure will be stronger in more vulnerable communities.

2.2 Data & Methods

We focus on $PM_{2.5}$ and ozone, along with five population characteristics (Table 2.1). These indicators are provided at the census tract level for the 102 populated census tracts in the Coachella Valley through the CalEnviroScreen 4.0 data portal (CES4) and the American Community Survey (ACS), along with individual population characteristic indicators collected via randomly sampled telephone surveys by HARC, Inc., a local nonprofit research organization in the Coachella Valley. While $PM_{2.5}$ levels are typically lower in the Coachella Valley (relative to national standards) than those of the coarser PM_{10}, the longer atmospheric lifetime of finer particles lends more confidence to the extrapolation of their spatiotemporal patterns, especially in regions with limited long term monitoring such as the Coachella Valley. We further include two different health data sets: randomly sampled telephone survey data as well as emergency visitation data collected by the California Office of Statewide Health Planning and Development (OSHPD) as compiled and distributed through CES4. Health outcome data sets are then combined with air pollution and SES data to investigate connections and correlations between them.

Table 2.1 Summary Statistics: Health outcome metrics, ambient air pollution and SES metrics at the census tract level (N is number of observations)

Variables	N	Min	Median	Mean	Max
Air pollution concentrations by census tract					
Annual mean concentration of $PM_{2.5}$ (averaged over 2015-2017), $\mu g/m^3$	102	6.03	7.11	7.01	7.72
Mean of summer months (May-October) of the daily maximum 8-hour ozone concentration (averaged over 2017-2019), ppb	102	51.53	60.39	60.47	63.06
Health outcome metric by census tract					
Emergency department visits for asthma per 10,000 (averaged over 2015-2017)	102	14.04	33.10	38.52	71.47
Emergency department visits for cardiovascular disease per 10,000 (averaged over 2015-2017)	102	5.76	12.00	12.76	21.39
Percent of people indicated they have been diagnosed of respiratory disease from the survey (Weighted data, 2016)	69	0.00	12.32	15.59	41.88
Percent of people indicated they have been diagnosed of cardiovascular disease from the survey (Weighted data, 2016)	69	9.54	47.80	47.67	91.92
Population characteristics by census tract (2014-2018)					
Percent of adults 25 and over with education less than high school	102	0.70	13.75	18.17	68.40
Percent of people speak English less than well	102	0.30	12.30	17.78	64.6
Percent of people with income less than the federal poverty threshold	102	1.00	10.20	13.59	39.30
Percent of people without health insurance coverage	102	0.40	10.50	10.62	31.50
Percent of people identifying as Hispanic or Latino	102	2.40	41.75	44.25	100.00

2.2.1 Air pollution data

Annual average concentration of $PM_{2.5}$ (average over 2015 to 2017) and ozone (average over 2017 to 2019) within the Coachella Valley were extracted from CES4, which uses ground monitoring observations and satellite data to infer concentrations at the census tract level within California. For $PM_{2.5}$ this takes the form of an inverse-distance weighted model combining surface concentrations obtained from California Air Resource Board's (CARB) air monitoring network database along with satellite-based concentrations derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite to estimate a weighted average concentration for each 1 km satellite grid cell. Annual averages for each year (from 2015 to 2017) are then calculated by first computing quarterly means and then averaging those quarterly means over the three-year period to avoid bias caused by seasonal patterns. Finally, estimated concentrations for each census tract are produced by averaging grid cell values within a census tract boundary. For ozone, CES4 uses a spatial interpolation method (ordinary kriging) to incorporate daily maximum 8-hour average concentrations collected from CARB's air monitoring network database to estimate summer (May through October, 2017-2019) ozone concentrations for each census tract (OEHHA, 2021). The census tract wide 3-year average annual $PM_{2.5}$ concentrations ranged from 6.0 $\mu g/m^3$ to 7.7 $\mu g/m^3$ and the 3-year mean summer months of daily maximum 8-hour ozone concentrations range from 51.5 ppb to 63.1 ppb (Table 2.1).

Figure 2.1 shows the spatial distribution patterns for $PM_{2.5}$ and ozone at the census tract level within the Coachella Valley, revealing strong and inversely correlated spatial gradients. Eastern Coachella Valley experiences higher concentrations of $PM_{2.5}$, while the west is more prone to elevated ozone levels transported from densely populated coastal regions. A subset of tracts closer to the middle of the valley experience moderate levels of each.

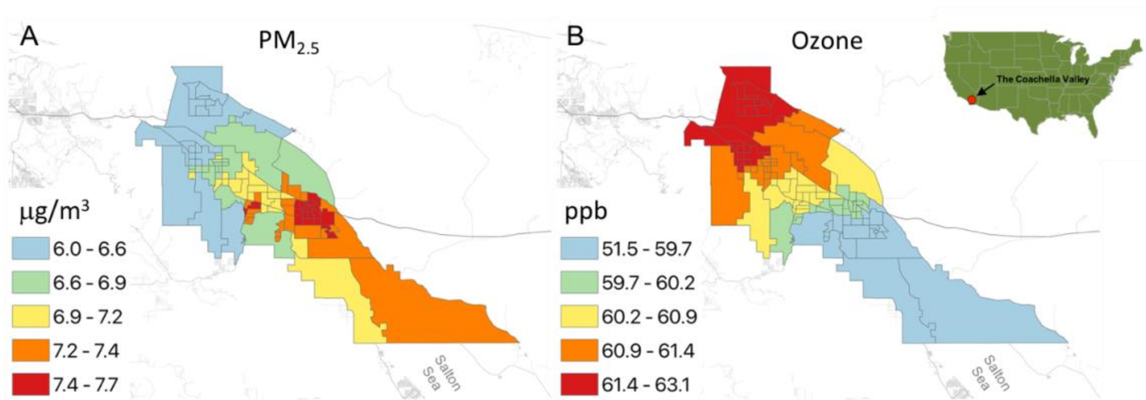

Figure 2.1 Spatial distribution patterns of $PM_{2.5}$ (A) and *ozone* (B) within the Coachella Valley. $PM_{2.5}$ is the annual mean concentration averaged over 2015-2017, µg/m^3; *ozone* is the mean concentration of summer months (May-October) averaged over 2017-2019, ppb.

2.2.2 Health data

Beginning in 2007, HARC has conducted community-wide health survey reports every three years. Surveys are conducted by a format of random-digital telephone survey and limited to private residents, such as houses, apartments or mobile homes, within the Coachella Valley area. Thus, people who are homeless, live in group settings (e.g., nursing homes, group homes), or who do not have a phone are not included in these surveys (HARC, 2016). As part of the "Major Disease" section of the survey, participants enter binary responses of either "1" (yes) or "2" (no) for each health outcome in response to the question "Have you ever been told by a doctor, nurse, or other health care professional that you have any of the following medical conditions?" Participants are also asked to provide their address (residence street and nearest cross-street) at the end of the survey.

For our analysis, we utilize the 2016 adult (age 18 and over) survey, HARC 2016, which was conducted from February 2nd to October 8th of that year and had approximately 2000 responses. We extract information on seven self-reported health outcomes from the raw survey data and integrate them into two categories based on the International Classification of Diseases, Revision 10 (ICD 10) common codes: respiratory disease (including asthma [J45] and other respiratory disease) and cardiovascular disease (including hypertension [I10], high blood cholesterol [E78.1], heart disease [I25.9], heart attack [I25.10] and stroke [I63.9]). Respondents who indicated they have any one of the diseases in these two categories are treated as reporting respiratory or cardiovascular disease. Thus, for health data from HARC telephone surveys, we investigate respiratory disease and cardiovascular disease as two health outcomes of interest.

In order to calculate the health rates at the census tract level and visualize the spatial patterns of survey reported health outcomes, we first geocode individual addresses to obtain latitude and longitude and assign each pair of coordinates into its corresponding census tract, thereby binning participant responses at the census tract level. We then calculate the survey response rates for the two health outcomes at the census tract level by dividing the number of people in that census tract reporting a diagnosis for the corresponding disease by the total number of respondents in that tract. Here, the number of diagnosed people and number of total respondents used in this calculation are weighted by age, sex, race and ethnicity to better represent region-wide demographic patterns (HARC, 2016). Through this calculation we derive one observation for each disease category per census tract. We use these calculated HARC survey response rates (survey rates) to represent the percentage of the surveyed population in each census tract reporting diagnosed health outcomes.

For emergency visitation data we use CES4 tract-level estimates based on emergency visitation data sets from OSHPD to provide emergency department visits for asthma and cardiovascular disease (CVD) averaged over the years 2015-2017 at the census tract level. Emergency visitation rates for both asthma and CVD are age-adjusted using five-year bins (0-4, 5-9, etc.) to normalize results among tracts exhibiting different age distributions (OEHHA, 2021). These age-adjusted rates are first spatially modeled to obtain estimates for each ZIP code and then reapportioned to census tract level. Additionally, a modeling method that incorporates both local and state rates information is utilized to estimate rates for ZIP codes with fewer than 12 emergency visits. Through the data provided by CES4, we again produce one observation for each health outcome per census tract. Since this emergency visit data covers the period of 2015 – 2017, we use this rate to represent the observed emergency visitation rate (EV rates) in 2016 in comparison to the HARC 2016 survey rate.

Figure 2.2 shows the spatial distribution of age-adjusted EV rates and weighted survey rates for health outcomes at the census tract level in the Coachella Valley. Emergency room visitation data shows higher levels to both the east and west, with lower levels in central regions, consistent with the hypothesis that elevated pollutant concentrations may be correlated with worsened health outcomes. Census tracts with the lowest EV rates appear to be clustered around central regions where neither $PM_{2.5}$ nor ozone pollution levels is particularly high. Survey rate spatial patterns, however, differ greatly from those of EV rates. While less clearly defined, survey rates for both respiratory and cardiovascular disease likewise break the east and west pattern shown in hospital data, showing a scattering of high and low levels across the valley. Some tracts in particular show a sharp contrast between health outcome metrics. For example, census tracts around Indio have the highest EV rates, while survey rates for the area are generally low. The differences in these spatial patterns highlight the difficulty in reconciling alternative forms of health outcome data, differences which may themselves be driven by patterns in exposure and vulnerability disparities, as well as individual strengths and biases unique to each data collection methodology.

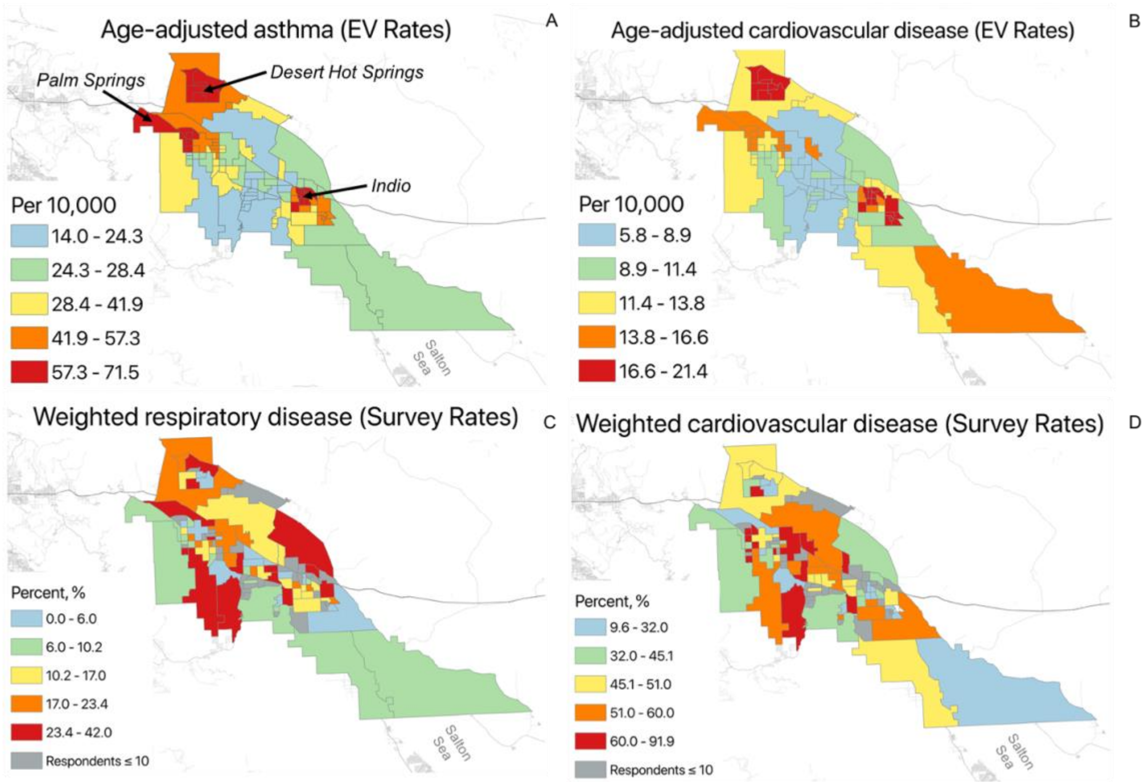

Figure 2.2 Spatial distribution patterns of EV rates and survey rates in the Coachella Valley. (A) Emergency department visits for age-adjusted asthma per 10,000 (averaged over 2015-2017); (B) Emergency department visits for age-adjusted cardiovascular disease per 10,000 (averaged over 2015-2017); (C) Demographic-weighted frequency of survey respondents indicating diagnosis of respiratory disease (2016); (D) Demographic-weighted frequency of survey respondents indicating diagnosis of cardiovascular disease (2016).

2.2.3 Population characteristics

Five-year estimates of socioeconomic and demographic indicators for the residents living in the Coachella Valley at the census tract level are obtained from the ACS. Socioeconomic status (SES) and demographic metrics used in this study include measures of education (percent of adults 25 and over with education less than high school), linguistic isolation (percent of residents who speak English less than well), poverty (percent of residents with income less than the federal poverty threshold), health insurance coverage (percent of residents without health insurance coverage), racial composition (percent of residents identifying as Hispanic or Latino), and age (percent of residents above age 55). For the purpose of this study, we define vulnerability as exhibiting higher values in defined socioeconomic and demographic metrics. For consistency with the temporal frequency of health outcome surveys we similarly use population characteristic data collected from 2014-2018 5-year estimate from ACS. In addition to the population characteristics collected from the ACS we also extract comparable socioeconomic and demographic related factors of individual respondents from the HARC survey including education level, linguistic isolation, household income, health insurance coverage, and racial identity for the statistical analysis of surveyed health outcomes and the comparison of population characteristics between tract-level ACS and survey data.

Figure 2.3 shows the spatial distribution of population characteristic indicators including education, linguistic isolation, poverty, health insurance coverage, racial composition and age at the census tract level in the Coachella Valley. On these maps, a darker red color for the six population characteristic metrics indicates increased vulnerability (e.g., census tracts with greater frequencies of poverty). In general, the spatial distribution patterns of the socioeconomic and racial indicators are visually similar to those of air pollution and EV rates: high vulnerability is found on the east and west edges of the Coachella Valley, while lower vulnerability census tracts are clustered around the middle. For the age distribution, tracts around west side tend to be populated by older residents (age 55+) relative to east side tracts.

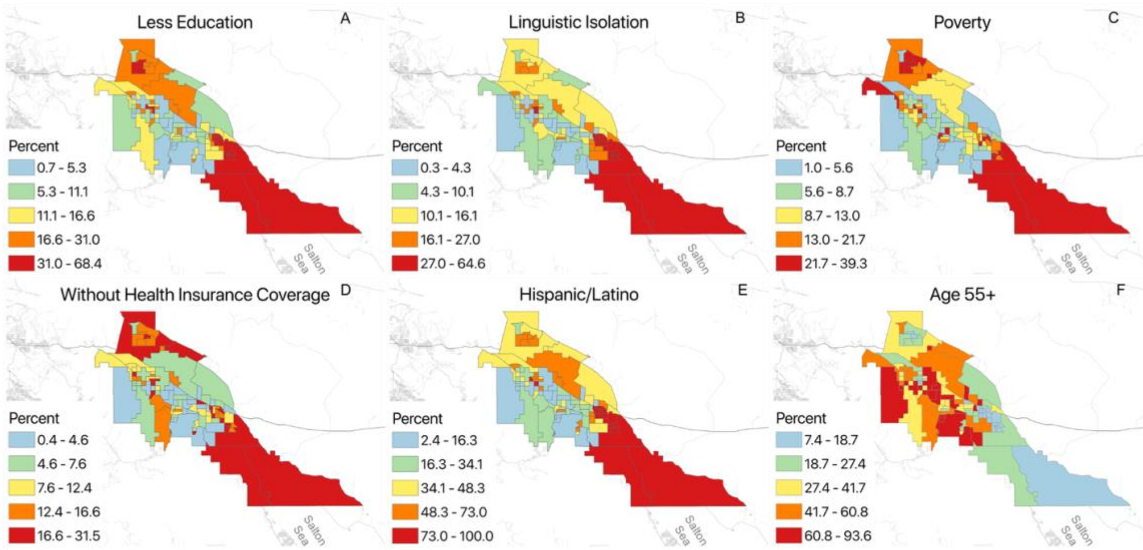

Figure 2.3 Spatial distribution patterns of population characteristics within the Coachella Valley (2014-2018). (A) Percent of adults 25 and over with education level less than high school; (B) percent of residents who speak English less than well; (C) percent of households with income less than the federal poverty threshold; (D) percent of residents without health insurance coverage; (E) percent of residents identifying as Hispanic or Latino; (F) percent of residents above age 55.

2.2.4 Estimation strategies

Since we have two different health metrics, emergency visitation data at the census tract level as well as survey-reported health data for individuals, we apply two different statistical methods to examine the relationship between ambient air pollution, population characteristics, and health outcome metrics. For emergency visitation data, we use multivariate linear regression to process our tract-level analysis. We use tract-level EV rates as dependent variables, while tract-level air pollution, population characteristic vulnerability (Pop), and their interactions are selected as independent covariates. To address covariance within population characteristic metrics, we create a single covariate calculated from the original five population characteristic indicators (census tract level education, linguistic isolation, poverty, health insurance coverage and racial composition) using principal component analysis. The principal component chosen (PC1) is the single orthogonal component defining most variability among the five, as well as the component most strongly correlated with health outcomes. To explore population characteristic-specific patterns, we separate and visualize each health outcome metric based on tract-level population characteristic tercile, showing separate health outcome boxplots for low, median and high socioeconomic and demographic vulnerability.

For the survey reported health outcomes, we use logistic regression to process our analysis at the individual level for all respondents, first filtering to only include respondents with health insurance (roughly 92% of all survey respondents). While health insurance coverage is a socioeconomic vulnerability of interest, the phrasing of the survey question used ("Have you ever been told by a doctor, nurse, or other health care professional that you have any of the following medical conditions?") includes the possibility of unintended bias towards those with the resources for obtaining such a diagnosis. We then combine surveyed population characteristic metrics into a single weighted score, similar to that developed for the tract-level analysis, and further include respondent age as an independent covariate. To partially address sampling bias inherent to the telephone survey methodology, we use a demographic-weighted value assigned to each respondent based on their reported age, sex, race, and ethnicity to match region-wide population values. Finally, we apply a logistic regression model using binary health outcomes as dependent variables, along with tract-level air pollution, vulnerability scores, and age as independent variables.

2.3 Results and Discussion

2.3.1 Population characteristic patterns of ambient air pollution exposure

The spatial patterns shown above can also be visualized in terms of population characteristics and ambient air pollution exposure by separating pollutant distributions according to socioeconomic and demographic vulnerability as shown in Figure 2.4. In general, due to typical spatial patterns in population characteristics and ambient pollution, areas of increased vulnerability are also associated with slightly higher ambient levels of $PM_{2.5}$ for some metrics, with an inverted pattern apparent for ozone. In other words, the most vulnerable communities in the Coachella Valley are generally more likely to be exposed to higher levels of $PM_{2.5}$ pollution, but lower levels of ozone in the Coachella Valley.

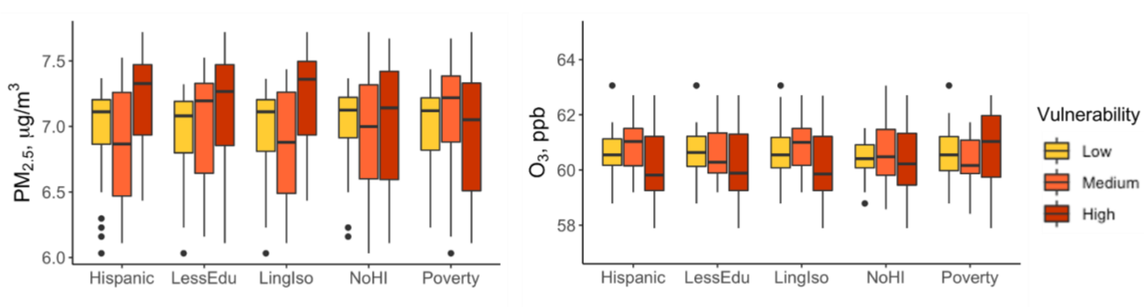

Figure 2.4 Population characteristic-specific patterns of $PM_{2.5}$ (left) and *ozone* (right). On the x axis, "Hispanic" means percent of people identifying as Hispanic or Latino; "LessEdu" means percent of adults 25 and over with education less than high school; "LingIso" means percent of residents who speak English less than well; "NoHI" means percent of residents without health insurance coverage; "Poverty" means percent of people with income less than the federal poverty threshold.

2.3.2 Emergency visitation health outcomes

The average age-adjusted EV rate for asthma at the census tract level in our study area is about 40 per 10,000, with a minimum of 14 per 10,000 and maximum of 72 per 10,000. The average age-adjusted EV rates for cardiovascular disease is about 13 per 10,000, with a minimum of 6 per 10,000 and maximum of 22 per 10,000 (Table 2.1). In general, the highest EV rate is about five times that of the lowest EV rate, which suggests health disparities within the valley itself.

Based on the results of normalized linear regression, EV rates for both asthma and cardiovascular disease show positive correlation with ambient air pollution exposure, but significant negative correlation with the interaction term combining ozone and $PM_{2.5}$ levels (Table 2.2). The normalized regression coefficients for $PM_{2.5}$ and ozone as predictors of asthma rates are roughly 0.19 and 0.31 respectively, while for cardiovascular disease the coefficients are around 0.12 and 0.25 respectively. The strong negative correlations between the $PM_{2.5}$-ozone interaction term ($PM_{2.5}$:ozone) for both asthma and cardiovascular disease EV rates (-0.754 and -0.632, both significant at $p \leq 0.001$ level) is indicative of the spatial patterns observed in central Coachella Valley tracts: regions where ozone and $PM_{2.5}$ somewhat overlap also show the lowest EV rates. The positive correlations observed between EV rates and individual air pollutants support the hypothesis that long term elevated air pollution exposure may increase EV rates for both asthma and cardiovascular disease, which is consist with findings from previous studies (Lin et al., 2021; Metzger et al., 2004; Peel et al., 2005; Rodopoulou et al., 2015; Stieb et al., 2009; Wang et al., 2021), while significant correlations with vulnerability, as well as with some vulnerability-pollution interaction terms, also indicates that increased exposure and vulnerability among low socioeconomic and demographic populations may also play a role.

Linear regression coefficients (Table 2.2) show significant positive relationship between EV rates and population vulnerability. Regression coefficients for population as a predictor of asthma and cardiovascular disease EV rates are around 0.39 and 0.52 respectively (both significant at $p \leq 0.001$ level). This significant positive correlation indicates that EV rates have strong connections with socioeconomic and demographic vulnerability: communities with lower socioeconomic and demographic status show significantly increased rates of asthma and cardiovascular disease emergency visit rates. Interaction terms linking pollutant levels and population are also positive, though less so than population alone, suggesting that population vulnerability may indeed worsen the effects of air pollution on health.

Although the connections between EV rates and air pollution exposure are in some ways consistent with expectations, emergency visits alone cannot capture the full range of pollutant impacts on population health. While emergency room visit counts are an objective and relatively accessible metric, they do not include those who may suffer negative health outcomes without requiring emergency services, or without access to them (Juturu, 2021). For this reason, tools such as the HARC telephone survey presented here may help to fill these gaps, as they are able to capture a potentially wider range of self-reported health outcomes.

2.3.3 Survey reported health outcomes

Of the 1633 survey respondents covered by health insurance, 255 (15.6%) indicated that they have been diagnosed with respiratory disease while 915 (56.0%) indicated that they have been diagnosed with cardiovascular disease. Averaging by census tract, respiratory disease reports range from 0% to 42% (census tracts with respondents equal or less than 10 are removed), while cardiovascular disease ranges from 9.6% all the way to 91.9% (census tracts with respondents equal or less than 10 are removed, Table 2.2). These ranges are in part symptomatic of low respondent numbers in some tracts, but are also consistent with the wide-ranging tract-level EV health outcomes.

Table 2.3 shows the normalized logistic regression coefficients linking air pollution exposure, vulnerability, and age to observed survey reported health outcomes. The normalized regression coefficients for $PM_{2.5}$ as a predictor of respiratory and cardiovascular disease are -0.066 and -0.133, respectively; the normalized regression coefficients for ozone as a predictor of respiratory and cardiovascular disease are 0.036 and 0.067, respectively. In general, we do not find a significant positive association between air pollution exposure and survey reported health outcomes. This is consistent with other studies finding little or no association between health outcomes and $PM_{2.5}$ or ozone exposure when using self-reported survey data (Bennion et al., 2007; Johnson and Parker, 2009; Wiggs et al., 2003; Zhang et al., 2016). For example, Wiggs et al. (2003) also used questionnaire-based health outcome data to examine the connection between ambient dust (PM_{10}) exposure and respiratory disease around the Aral Sea area, similarly finding an inverse relationship between long-term ambient dust exposure and reported health outcomes.

In addition to the weak correlation between survey-reported health outcomes and air pollutants, the association between those health outcomes and vulnerability score is weak and statistically insignificant, with normalized parameter estimates of -0.166 and 0.173 for respiratory and cardiovascular disease, respectively. The low magnitude and inconsistent sign of these relationships imply the importance of other mechanisms at play in the survey responses beyond the direct impacts of ambient pollutant exposure and vulnerability. In contrast, we find a strong positive correlation between survey reported health outcomes and respondent age, especially for cardiovascular disease which shows a coefficient of roughly 1.27 (significant at $p \leq 0.001$ level). The strong positive correlation between age and cardiovascular disease is reasonable and has been widely confirmed by previous studies (Lakatta, 2002, 1993; Wei, 1992)

Table 2.2 Connections between EV rates and ambient air pollution and SES

Variables	Asthma (SE)	Cardiovascular disease (SE)
$PM_{2.5}$	0.186. (0.102)	0.124 (0.105)
ozone	0.314* (0.148)	0.246 (0.152)
Pop[a]	0.390*** (0.081)	0.518*** (0.083)
$PM_{2.5}$:ozone	-0.754*** (0.113)	-0.632*** (0.116)
$PM_{2.5}$:Pop	0.248** (0.083)	0.132 (0.085)
ozone:Pop	0.243** (0.075)	0.145. (0.077)

a: Population characteristic vulnerability index (Pop) is calculated from the original five population characteristic indicators (education, linguistic isolation, poverty, health insurance and racial composition) using principal component analysis
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 2.3 Connections between survey rates and ambient air pollution and SES

Variables	Respiratory disease (SE)	Cardiovascular disease (SE)
$PM_{2.5}$	-0.066 (0.340)	-0.133 (0.270)
ozone	0.036 (0.347)	0.067 (0.249)
Pop[a]	-0.166 (0.307)	0.173 (0.230)
Age	0.075 (0.298)	1.274*** (0.277)

a: Population characteristic vulnerability score (Pop) is calculated by first normalizing each individual population characteristic indicator to uniform scale, then summing together.
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2.3.4 EV/Survey ratio

Since EV rates and survey rates each measure similar health outcomes via different mechanisms, we further explore the connections between these health outcome metrics and population characteristic metrics to explore possible connections between them. To this end, we divide EV rates by survey rates to produce a health outcome ratio which we then separate by census tract population characteristic metrics as before to examine socioeconomic- and demographic-specific patterns. Figure 2.5 shows the variation of EV/Survey ratio among different levels of vulnerability. In general, vulnerability shows a clear positive relationship with this EV/Survey ratio for both asthma and cardiovascular disease, though it is less clear in the case of asthma when comparing between medium and high tertiles. This relationship shows that increased vulnerability is associated with higher rates of emergency visits relative to survey reporting of diagnosed symptoms, further indicating that residents of vulnerable communities are far less likely to diagnose and report symptoms relative to their EV rates.

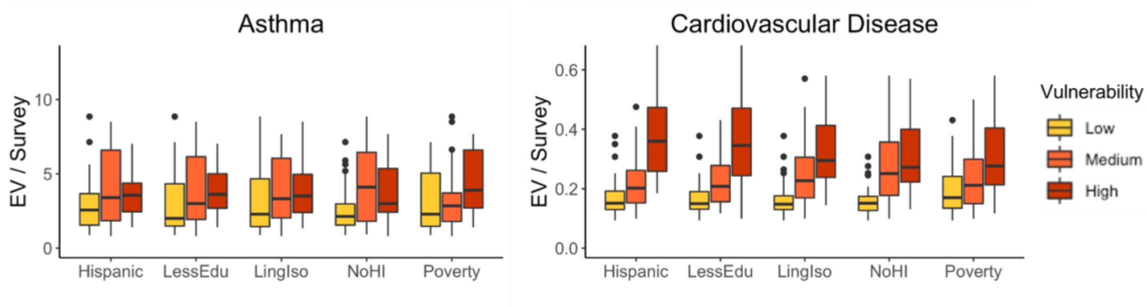

Figure 2.5 EV/Survey ratio of asthma (left) and cardiovascular disease (right) at different vulnerability levels.

This result has important implications for the measurement and mitigation of negative health outcomes in the Coachella Valley area, as it points to what may be a significant under-representation of vulnerable communities in non-emergency diagnoses and reporting.

2.3.5 Differences between EV rates and survey rates

The differences between EV rates and survey rates may be indicative of unique biases and data gaps inherent to each health outcome method, as well as measures that might be available to correct and account for them. To explore the representativeness of HARC survey respondents, we examine the socioeconomic and demographic distributions among all the respondents. We found that around 82.4% respondents with an education degree higher than high school, 94.5% respondents do not exhibit linguistic isolation, 91.8% respondents are covered by health insurance and 63.4% respondents do not identify as Hispanic/Latino. Comparison with tract-level demographics indicates that most survey respondents exhibit lower socioeconomic vulnerability than that of their surrounding communities, further suggesting a strong survey bias towards low-vulnerability populations. These results reveal a clear sampling bias in the survey; even with population-level weighting, survey respondents may not be representative of either the whole valley or its individual communities. These differences indicate that, while survey data may fill gaps in EV data by including a broad, self-reported response, less representation from those who may be most vulnerable to air pollution exposure may skew results, making comparison and integration between them problematic.

2.4 Discussion

This study focuses on communities at the north end of a shrinking inland saline lake, the Salton Sea, in southern California. The health issues shown in this region, alongside the threat of worsening air quality with the ongoing loss of water inflows, make it a region of critical importance for the development of health and environmental justice metrics, as well as mitigation strategies.

However, the Salton Sea is not a unique case worldwide. Inland saline lakes account for around 44% of the volume (and 23% of the area) of all lakes on our planet (Messager et al., 2016), and many of them are similarly shrinking due to a combination of increased water demand and changes in local climate (Williams, 1996). For example, the Aral Sea in central Asia has seen massive reductions in both lake area (by 74%) and volume (by 90%), turning its freshly exposed surrounding lakebed into new dust sources. The resulting increase in local dust events may, in turn, be driving multiple adverse human health outcomes including restrictive pulmonary dysfunction, respiratory disease, gastrointestinal symptoms and abnormal renal functions among nearby residents (Doede and DeGuzman, 2020; Kaneko, 2003; Kunii et al., 2010). Other examples include Lake

Urmia in Iran, Lake Chad in Africa, and the nearby Owens Lake in California, all of which have exhibited similar desiccation. (Bennion et al., 2007; Cahill et al., 1996; Gao et al., 2011; Wurtsbaugh et al., 2017). This trend, exhibited in similar environmental systems worldwide, points to the need to better understand the connections between air pollution exposure and human health, as well as patterns of exposure and socioeconomic vulnerability around such lakes.

Our study highlights the modification effects of socioeconomic and demographic vulnerability on health conditions, ambient air pollution exposure and the correlation between these two. We found that people with higher socioeconomic and demographic vulnerability tend to experience higher levels of $PM_{2.5}$ but relatively lower levels of ozone. These results are consistent with findings from previous studies by Gray et al. (2013) and Marshall et al. (2008) who similarly found connections between low SES, elevated levels of $PM_{2.5}$, and reduced levels of ozone. By the analysis between emergency visitations, air pollution exposure and population characteristic vulnerability, we find that higher socioeconomic and demographic vulnerability likely exacerbate the adverse health effects of air pollution, consistent with results from previous studies (Mathiarasan and Hüls, 2021; O'Lenick et al., 2017; Ou et al., 2008; Son et al., 2020). For example, in their reanalysis of the Harvard Six Cities Study Krewski et al. (2003) observed a more pronounced mortality risk from air pollution among people with lower education levels. O'Lenick et al. (2017) observed stronger correlation between air pollution exposure and pediatric asthma in high poverty level areas in Atlanta, Georgia. Son et al. (2020) found that several socioeconomic/demographic indicators including age, education and urbanicity were associated with higher risk of total mortality from $PM_{2.5}$ exposure. Through the EV/Survey ratio, we find that more vulnerable communities are less likely to report/diagnose symptoms relative to their emergency visitation rates, again in line with previous research reporting that vulnerability indicators such as education level is inversely correlated with self-rated health outcomes (Bobak et al., 1998; Crighton et al., 2003; Kennedy et al., 1998).

In this study, we find a strong positive correlation between emergency visitations and spatially varying ambient air pollution exposure, but no such association when we use survey-reported health outcomes. This may be explained by the sampling biases described above. While data sampling bias may be a limitation in the interpretation of health outcome correlations in this study, it also points to opportunities for improvement and future research directions. Statistical methodologies such as data filtering and resampling may help to enhance the value of survey data, especially within vulnerable communities. Through these kinds of techniques, responses from under-represented demographics can be weighted more heavily to better match target demographic ratios. Furthermore, seeking out communication, collaboration, and data collection opportunities within the communities least likely to either self-report or make use of emergency services will help policymakers and researchers better understand the specific health needs and opportunities to assist those who are most impacted by current and projected pollution in the Coachella Valley (Cheney et al., 2018; Farzan et al., 2019a; Kim et al., 2020; Rodriguez et al., 2020).

Many other factors may also contribute to errors and biases within collected data. While ambient air pollution has been identified as an effective indicator of multiple health outcomes, indoor pollution sources are increasingly recognized as crucial exposure vectors, making differences in employment type and location especially important for differentiating how much and what type of indoor pollution may be relevant (Sinclair et al., 2018). Patterns of travel and residency may also play a role, as more affluent communities may have a larger percentage of residents who leave the area completely for extended periods of time. This could have strong impacts on degrees of exposure, and therefore health outcomes expected from ambient air pollution in the valley.

2.5 Conclusions

In this study, we evaluate two different health outcomes metrics and their connections to chronic air pollution exposure and vulnerability metrics in the Coachella Valley. In general, the Coachella Valley shows strong patterns and disparities in air pollution exposure, health outcomes, and population characteristics. EV rates of asthma and cardiovascular disease show significant positive correlation with both $PM_{2.5}$ and ozone, but no such association is apparent when using surveyed health outcome data. This gap appears to have a strong socioeconomic and demographic signal, suggesting opportunities for data resampling and improved collection methodologies. Sampling bias in health outcome data sets, missing population characteristic factors, and other spatially significant influences may also contribute to errors and differences in results. Future work will further examine these differences and apply them to analysis of acute dust event exposure, as well as methods for risk mitigation for Coachella Valley residents

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Chapter 3 Source-Specific Acute Health Effects of Ambient Dust Exposure in California's Salton Sea Region

Acknowledgement of Co-Authorship

This work is completed with contributions from Yaning Miao, William C. Porter, Tarik Benmarhnia, Catherine Lowe, Timothy Lyons, Caroline Hung, Charles Diamond

Abstract

Windblown dust is an ongoing air quality and public health concern among residents living around California's Salton Sea, a region characterized by serious socioeconomic and health outcome disparities. Dropping water levels and unique biogeochemistry at the Salton Sea have raised concerns regarding the human health impacts of drying sediments exposed on shrinking shorelines, as well as potential lake spray emissions from the water surface itself. As particles emitted from different surface types can differ greatly in terms of composition, size distribution, and other properties, variability in the resulting health impacts of windblown dust reaching communities in the region may likewise be source dependent. Here we use observed coarse particulate matter ($PM_{2.5-10}$) concentrations, modeled back trajectories, and land surface data to estimate individual source region types for particulates observed at long term monitoring sites in the Salton Sea region. We then apply this data product to an analysis of source-specific acute health impacts using a time-stratified case crossover design with conditional logistic regression based on 171,465 cases recorded from 2008 to 2019. Through this methodology we quantify and compare the acute health effects of dust arriving from different directions and estimate likely source surfaces on respiratory and cardiovascular hospitalizations. Using a remote sensing chlorophyll-a data product we further investigate

the possible influence of periodic algal bloom events – a result of ongoing nutrient loading – on surrounding hospitalizations. Results suggest that a 10 μg/m^3 increase in coarse PM coming from over the Salton Sea is associated with an 8.4% (Relative Risk (RR) = 1.084, 95% CI: 1.029 - 1.138) increased risk of respiratory hospital admissions and a 3.8% (RR = 1.038, 95% CI: 0.940 - 1.135) increased risk of cardiovascular hospital admissions, increases that are greater than those for dust likely originating from other surface types. Furthermore, we find even higher RR values for dust associated with Salton Sea back trajectories during algae events: a 24.9% (RR = 1.249 95% CI: 1.065 – 1.432) increased risk in respiratory hospitalization and 18.8% (RR = 1.188 95% CI: 0.872 – 1.504) increased risk in cardiovascular hospitalization. Our findings suggest that exposure to dust possibly originating from the Salton Sea or surrounding surfaces is associated with increased respiratory and cardiovascular hospitalizations, especially during algal bloom events. Further research is needed to determine the underlying mechanisms responsible for these health impacts, as well as possible mitigation or intervention strategies.

3.1 Introduction

Windblown dust is a common constituent of atmospheric particulate matter that can be transported over both short and long distances, causing regional and global effects in terms of air quality, climate and human health (Claiborn et al., 2000; DeMott et al., 2003; Griffin et al., 2001; Jaffe et al., 2003; Jickells et al., 2005; Liaskoni et al., 2023; Rutherford et al., 1999; Salam et al., 2006; Toon, 2003). In recent decades, numerous population-level epidemiologic studies of dust storms have found a positive correlation between windblown dust and hospital admissions, emergency department visits, and mortality (Al et al., 2018; Jones, 2020; Merrifield et al., 2013; Middleton et al., 2008; Rublee et al., 2020; Tam et al., 2012; Vodonos et al., 2014). Model simulations have further predicted increasing dust emissions in the future due to climate change and anthropogenic activities, especially in arid and semi-arid areas, thereby imposing additional health burdens on impacted downwind communities (Evan et al., 2016; Goudie, 2014; Hooper and Marx, 2018; Lababpour, 2020). The southwest United States is a hotspot for such dust hazards due to the low vegetation coverage, arid conditions, and high population density (Crooks et al., 2016; Schubert et al., 2004; Seager et al., 2007; Tong et al., 2017). One land surface type increasingly responsible for these high dust levels in the southwest US is the dry lakebed, also known as playa, caused by the evaporation of inland lakes, a phenomenon likely to worsen air quality issues in already dusty arid regions (Bullard et al., 2008; Ge et al., 2019; Ginoux et al., 2012; Hahnenberger and Nicoll, 2012; Hossein Mardi et al., 2018; Pelletier, 2006; Reid et al., 1994).

The Salton Sea region, located in the deserts of inland southern California, is one such region. As lake levels continue to fall, the impacts of increasingly exposed lakebed sediments will occur among communities already facing significant air quality and human health disparities (Miao et al., 2022). Due to increasing imbalances between inflows and evaporation, water levels of the Salton Sea have declined from 195 feet below sea level to the current height of 240 feet below sea level, exposing about 27,000 acres of previously submerged lakebed (Imperial Irrigation District, 2023). The newly exposed playa is expected to emit additional particulate matter and increase the frequency of dust events in surrounding areas (Jones and Fleck, 2020b; Parajuli and Zender, 2018b). This increase will further impact communities already struggling with a major dust burden: the Coachella Valley at the north end of the Salton Sea has been categorized for "serious" nonattainment of the national 24-hour average PM_{10} standard (150 $\mu g/m^3$) set by the United States Environmental Protection Agency for many years (USEPA, 2021). During dust storms, the hourly averaged PM_{10} concentration can exceed 580 $\mu g/m^3$ around this region (Evan, 2019). Alongside these high dust levels, local residents also exhibit disproportionately high asthma rates relative to other comparable communities. Previous studies have reported an asthma rate over 20% among children living around the Salton Sea region – much higher than the national average of 8% and the state average of 14.5% (Farzan et al., 2019b; Marshall, 2017). Additionally, this region also ranks among the highest percentages statewide for emergency room visits related to asthma (OEHHA, 2021). According to Cohen et al. (2014), without mitigation strategies the Salton Sea water level will decline to 258 feet under sea level by the year 2047, exposing an additional 92,000 acres of playa, increasing dust emissions by 37,000 tons, and leading to an additional $37 billion in public health costs.

Unlike fine particulates, which often form in the atmosphere through gas-phase chemical reactions leading to secondary particulate formation, larger particles are generally driven by primary emissions from surface sources which show strong correlations with underlying surface properties and meteorological conditions (Field et al., 2011; Lee et al., 2012; Okin, 2022; Usher et al., 2003). Since windblown dust is significantly affected by land surface properties, and dust arising from different surface types can differ greatly in terms of composition, size distribution, and other properties, there may be significant differences in eventual human health impacts, even under otherwise identical concentrations and exposure levels. Though the differential toxicity of windblown dust emitted from different land surface is not well studied, toxicity of fine particles ($PM_{2.5}$) originated from different sources has been widely studied by previous studies. For example, previous study has found that fine particles produced from traffic related emission is more toxic than particles produced from other sources include biomass burning, coal combustion and road dust (Park et al., 2018) Even different $PM_{2.5}$ with the same mass concentrations may have different health impacts. For example, recent study suggested that when increase the same amount of concertation of wildfire $PM_{2.5}$ and non wildfire $PM_{2.5}$, wildfire $PM_{2.5}$ shows much higher impacts on respiratory hospitalization (Aguilera et al., 2021).Those findings have important implications on the variability in windblown dust on human health generated from different sources. Through recent studies using an environmental exposure chamber to compare the health outcomes of mice exposed to dust collected from different locations around the Salton Sea, researchers have found that the aqueous extracts from dust collected near the Salton Sea induced unique tissue inflammation, while extracts collected from a more remote desert location showed no such inflammation (Biddle et al., 2023, 2021). While more work is needed to further constrain the cause and mechanism of this inflammation, these results point to unique health risks associated with dust near the Salton Sea – health risks that could also be apparent in other population-level health outcome metrics such as daily hospitalization counts.

Alongside windblown dust originating over dry land surfaces, aerosol particles originating from the Salton Sea surface itself could also play a meaningful role in terms of ambient air quality and public health. Aerosols emitted from inland water bodies, such as the Salton Sea, are typically referred to as lake spray and are similarly associated with strong surface winds. While the details of lake spray aerosol production remain poorly constrained and highly uncertain, in part due to the diversity of lake chemical compositions globally, there are apparent mechanistic similarities with the more widely studied processes of sea spray aerosol production (Harb and Foroutan, 2022). In both cases it is believed that aerosol production is largely a direct consequence of bubble formation and subsequent bursting at the surface, a process that can then launch tiny, suspended droplets into the air (Quinn et al., 2015). Depending on their size and the strength of the winds around them, these emitted droplets can then potentially be transported great distances, with implications for downwind climate, cloud formation, and air quality (Amiri-Farahani et al., 2021; Athanasopoulou et al., 2008; Cochran et al., 2017).

As with land surface dust entrainment and emissions, lake and sea spray aerosols production are believed to be strongly and non-linearly associated with surface wind speeds. Above certain wind speed thresholds, breaking waves, bubble formation, and whitecaps will begin to produce airborne particulate fluxes. While this process is mechanistically quite complex, past modeling efforts have had some success in the development of relatively simple parameterizations tying these phenomena directly to windspeeds based on laboratory measurements (de Leeuw et al., 2011; Edward C. Monahan and Adrian H. Callaghan, 2015; Monahan and Muircheartaigh, 1980). Previous studies have used such parameterizations to assess the contribution of lake spray aerosol to particulate matter concentration over lakes and surrounding land surfaces (Amiri-Farahani et al., 2021; May et al., 2018). The impacts of lake spray particles will be dependent on their composition, which in turn will depend directly on lake surface water chemical and physical properties (Axson et al., 2016). This dependence may be especially relevant for the assessment of air quality and human health impacts of lake spray aerosol. For example, previous research has found that lake spray aerosol produced from Lake Michigan and Lake Erie water collected during high-algae conditions contains much higher levels of organic material than particles generated under low-algae conditions, implying a direct connection between surface water composition and that of the subsequently produced lake spray aerosol (May et al., 2018, 2016). This connection has been shown to be size dependent, with larger particles showing a greater overall fraction of organic material from contaminated surface waters.

Sediments in the Salton Sea act as a sink for contaminants, playing a vital role in sequestering pollutants through adsorption and accumulation processes, especially under reducing (anoxic) conditions. Vogl and Henry (Vogl and Henry, 2002) reveals a bulls-eye pattern where transition metals (Cd, Cu, Mo, Ni, Zn, Se, etc) are more enriched in permanently anoxic sediments at depth as well as some shoreline locations. Once reduced sediments become oxidized upon exposure to more oxygen, sequestered metals are likely to remobilize. The entrainment of dust from exposed playa areas can release these sequestered contaminants back into the environment, potentially amplifying pollutant levels in the surrounding atmosphere. Trace transition metals in $PM_{2.5}$ and PM_{10} have been documented to incite respiratory illnesses by inhalation and ingestion through oxidative stress contributing to alveolar injury and fibrosis (Bargagli et al., 2017; Zhao et al., 2021). Recent epidemiology studies have reported evidence of health risks associated with dust exposure and recreational water use at intertidal zones due to high microbial counts (in biofilms) with the availability of water, nutrients and relative isolation from predator disturbance (Abdelzaher et al., 2011; Sabino et al., 2014; Weiskerger et al., 2019; Whitman et al., 2014). Marginal intertidal zones host extremely dynamic and thriving microbial communities (evidence for enterococci) as the Salton Sea rapidly shallows while chemical and organic compounds accrete at the lake edges before they enter the lake or get left behind with reducing lake level. Further, higher iron content supplied from tributaries react with marginal intertidal sediments to form oxidized zones (red sediments containing iron oxides "rust") and iron monosulfide (black, pudding-like sediments). These zones are dominated by iron- and sulfur- metabolizing microbes, although their epidemiologic impacts have not been documented. The dynamic interaction between sediments, dust entrainment, and pollutant release highlights the complex nature of contaminant cycling in and around the Salton Sea.

Considering the current ambient air quality standards only focus on size and mass concentration, it's important to understand such differential risk depending on the source of emissions. Here we address this knowledge gap using observed PM, back trajectory modeling, and daily hospitalization data to examine and compare the acute health effects of windblown dust arriving from different source regions around the Salton Sea region, including the lake surface itself. Based on previous mouse model studies identifying unique health impacts from dust originating at or near the Salton Sea, we focus in particular on a comparison between dust associated with the Salton Sea relative to other surface types. To assess the significance of periodic algal bloom events, we further separate the Salton Sea PM fraction based on observed chlorophyl levels, thus quantifying possible connections between particles produced during these events and local health outcomes.

3.2 Method

3.2.1 Study area description

Our study area is centered around the Salton Sea (33.34, -115.85) in the southwest United States. This region includes two main residential regions: Coachella Valley of

Riverside County located at the north end of the Salton Sea and Imperial Valley of Imperial County located at the south end of the Salton Sea (Figure 3.1 left). The Salton Sea region is bounded to the west by the Peninsular Range and to the east by the San Bernardino Mountains and Transverse Range. This unique geographical location makes the Salton Sea region prone to regular wind events due to the pressure gradient between the valley and coastal regions (Evan, 2019). On the surface, major morphological soil types in this area are varied (IID, 2023), and include the Anza desert, Colorado river delta soils (largely used for agriculture), developed urban areas, and the shrinking Salton Sea itself. Combined with the high frequency of strong wind events, the dominance of dusty, emissive land surface types throughout the region makes it highly susceptible to dust storms.

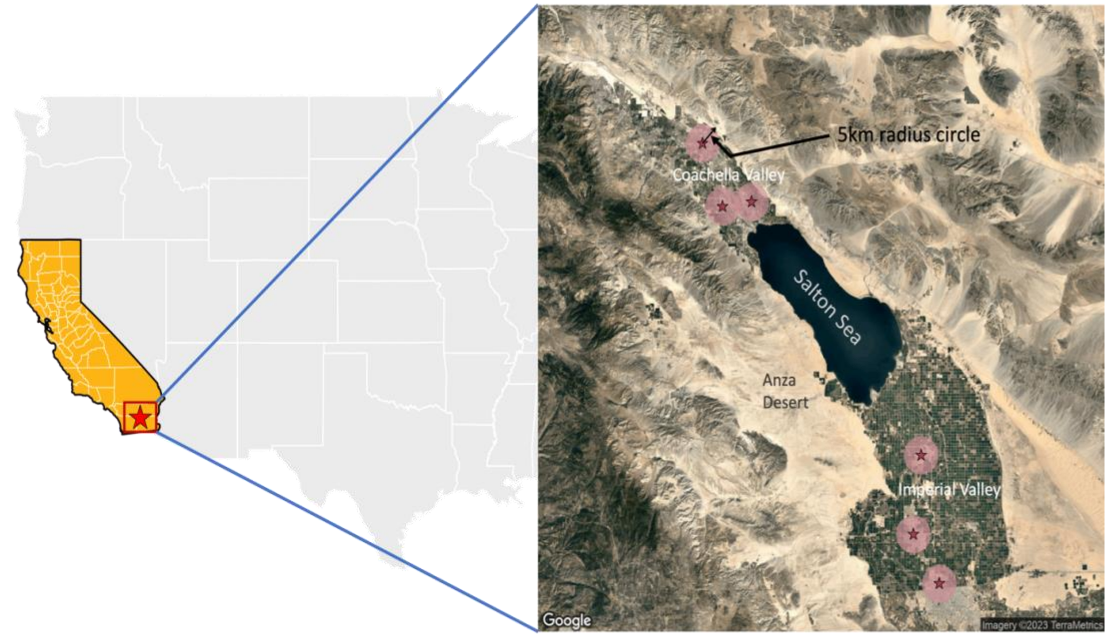

Figure 3.1 Location and geographic information of the Salton Sea region (Left). Location of EPA ground observation sites marked by red stars on the map (right). The black circles indicate the 5 km radius circle centered at each site.

3.2.2 Air quality data

We select six ground observation stations which is the best we could do to have multiple measurements around the Salton Sea from the USEPA Air Quality System (AQS) as our data sources for air quality observations, including three stations to the north of the Salton Sea and three to the south (Figure 1, right): Indio , Mecca, Torres Martinez, Brawley, El Centro and Calexico. We collected both PM_{10} and concentrations from the above six stations covering maximum time period from 2008 to 2019 (see Table 1, Figure S1)

To better represent windblown dust, which is mainly composed of larger particles, we use coarse particulate matter (PMc), which defined as particles with aerodynamic diameter between 2.5 and 10 micrometers for all dust related estimation in this study. Using PMc to represent dust has been widely used by previous studies (Perez et al., 2008). Due to limitation on hourly PMc data at our selected stations and study period, we developed a two-stage hierarchical regression model using hourly PM_{10} and PMc concentrations at Indio station from 2019 to 2022 to estimate the relationship between PM_{10} and PMc. We assume that this relationship is constant across all selected stations in this region and can represent previous year's relationship. Therefore, base on the correlation that estimated from the two-stage hierarchical regression model, we estimate hourly PMc concentration for all six sites from 2008-2019 based on hourly PM_{10} concertation that collected for the corresponding sites and time period.

3.2.3 HYSPLIT back trajectory

Using site observations and locations, we then apply the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory (ARL) to calculate back trajectories of PMc for each site. HYSPLIT is a complete system that designed to simulate the dispersion and trajectories of substances through the atmosphere and is often used in back trajectory analyses to identify the origins of air masses at particular places and times (Fleming et al., 2012; Stein et al., 2015). For this study, NCEP/NCAR Reanalysis meteorology data retrieved from NOAA ARL FTP Server is used to drive HYSPLIT dynamics.

To capture likely dust origin paths for hourly observations, we begin back trajectories every hour, on the hour, for each study station receptor site covering the entire 12-year study period. 8-h back trajectories are selected for this study assuming that most coarse-mode particles originate from relatively nearby. In order to better capture possible dust advection paths we calculate back trajectories from multiple heights above each station receptor site as demonstrated in previous work (Coz et al., 2009; Karaca et al., 2009; Koçak et al., 2009). The three different starting heights we used are 100 m, 500 m and 1000 m to represent a low, medium, and high elevation within the average planet boundary layer over southern California (Dimitriou et al., 2021; Rahn and Mitchell, 2016). To further build upon the nine trajectory points (eight backwards plus one arrival point) resulting from each individual trajectory, we further interpolate between hourly locations at 5-minute intervals, resulting in 97 points along each trajectory following interpolation. In summary, for an individual site, we run trajectories from 3 elevations each hour, 24 hours per day, with 97 total interpolated points per trajectory, adding up to 6984 back trajectory points per day per site. These points represent a simple modeled estimate of air mass paths preceding the observation of PMc at each site throughout each day.

3.2.4 Land cover categorization

In order to categorize possible windblown dust source surfaces we use 2019 CONUS Land Cover data from the National Land Cover Database (NLCD 2019), the most recent version of land cover data for the US from the U.S. Geological Survey (USGS). This dataset categorizes land surfaces within its domain into 20 different land surface types at a 30 meter resolution (Dewitz, J., 2021). For the purpose of this study, we extract a region from the 2019 CONUS Land Cover data covering the full range of HYSPLIT back trajectory data points and regroup the original surface types into ten categories representing the most frequent surfaces (Figure 3.2). To represent emissions from the Salton Sea itself, as well as its surrounding dried lakebed, we recategorize its original Open Water surface type into a unique “Salton Sea " surface category. Lacking data outside of the CONUS borders, we further define a new category for surface types in Mexico. Thus, the final ten surface categories used in this study include: Salton Sea, Developed (including “Developed, Open Space”, “Developed, Low Intensity”, “Developed, Medium Intensity” and “Developed, High Intensity” from original dataset), Forest (including “Deciduous Forest", “Evergreen Forest” and “Mixed Forest” from original dataset), Open Water (“Open Water” from original dataset as well as additional areas over the Pacific Ocean not included in the NLCD), Barren Land, Shrub (“Shrub/Scrub” from original dataset), Crop Land (“Cultivated Crops” from original dataset), Herbaceous (“Grassland/herbaceous” from original dataset), Mexico (defined as land surfaces south of US/Mexico border) and Others (including “Hay/Pasture”, “Emergent Herbaceous Wetlands”, “Woody Wetlands”, and “Perennial Snow/Ice” from original dataset). With this land cover information we assign each individual trajectory point a single surface type base on coordinate information for that trajectory point.

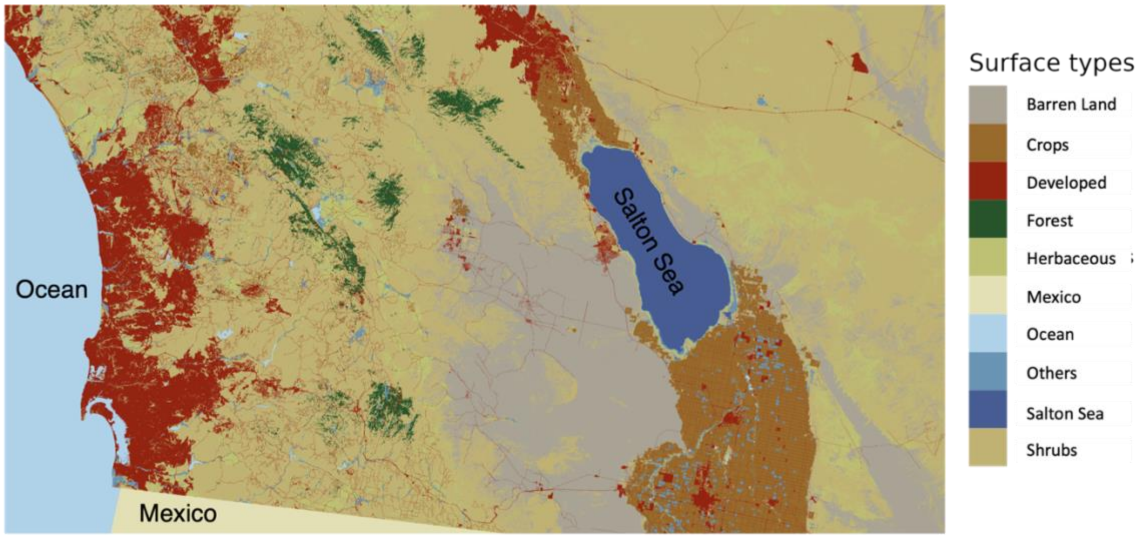

Figure 3.2 Surface types used in this study. Note, the area shown on this map is part of our trajectory covered region.

3.2.5 Trajectory point weighting factors

Dust emissions and lifetimes are affected by spatiotemporally varying factors, including wind speed, surface emissivity, and dry deposition (Grini et al., 2005; Pelletier, 2006; Zender et al., 2003). To improve representation of incoming dust source estimates, we weight our trajectory surface type frequencies to better capture the effect of these processes on the likelihood of observed dust originating from each back trajectory surface type.

Wind Speed: Windblown (or aeolian) dust production involves the erosion and transport of particles by the wind, and are initiated when effective wind speeds exceed thresholds determined in part by the erodibility of the surfaces below. While the physical mechanics of windblown dust emissions are non-trivial, in general they are higher under greater wind speeds. Dust flux to the atmosphere is typically assumed to be nonlinearly dependent on wind speed and the third or fourth power of wind speed has been widely used in common dust emissions models (Grini et al., 2005; Tegen and Fung, 1994; Zender et al., 2003). Beyond this nonlinear relationship, most dust emission parameterizations also require a wind threshold to be exceeded (threshold friction velocity), above which particles begin to detach from the soil surface (saltation events). The threshold wind speed can be calculated based on soil moisture, clay fraction, and air density, and it has been found that winds of at least 16-20 kilometers per hour are more likely to cause dust suspension in the Salton Sea region (Wasklewicz and Meek, 1995). Although threshold friction velocity has been widely used by dust models, there can be issues in accurately representing resulting dust emissions based on the mean gridded wind speeds typically provided by atmospheric dynamics models. Parameterizations and assumed wind speed distributions can be used to address limitations associated with such gridded data (Ridley et al., 2013).

Since greater wind speeds in general lead to higher dust emission, we add more weights for higher wind speeds. Based on the nonlinear relationship between wind speed and dust emission that utilized in dust models, we use the third power of wind speed (cubic wind speed) to parametrize the relationship between wind speed and dust emission. We do not apply a threshold wind speed or additional parameterizations to our hourly wind speed averages with the assumption that they would not add significant value to our weighting procedure, and sensitivity tests confirm that results are not sensitive to the use of thresholds in this step.

Soil Emissivity: Beyond the impact of wind speeds on dust emissions, land surface types including soil and vegetation coverage can also play a significant role in determining resulting emissions. Previous studies have shown that metrics such as surface emissivity can be a useful predictor of dust suspension and dust storm frequency (Bukowski and Heever, 2022; Dickey et al., 2023; A. L. Frie et al., 2017; Frie et al., 2019b; Xu et al., 2006). Soil erodibility represents the capability of soil to produce dust under a given meteorological forcing and it's one of the main variables to predict dust emissions in dust models (Zender et al., 2003). Soil erodibility maps, which store soil erodibility indices based on geographic information, have been widely used by recent dust models to represent dust emission potentials of different landforms/land surfaces at local, regional and global scales (Baddock et al., 2016; Bullard et al., 2011; Parajuli et al., 2014; Parajuli and Zender, 2017).

To place greater weight on more emissive surfaces we further weight back trajectory surface frequencies using soil erodibility data. Here we utilized the high resolution (roughly 500 meter) global sedimental supply map developed by Parajuli and Zender (2017) to represent the emissivity of different land surface types. Over water surfaces, such as the Salton Sea, erodibility values will be zero, since no windblown dust is possible. However, to capture the potential for lake spray aerosol, which has been shown to be a large contributor to coarse particles in other regions, we use the wind speed weighting factor to fill in the missing erodibility weighting factor over water surfaces. It should be noted that characterizing lake spray aerosol emissions at the Salton Sea is a major uncertainty and knowledge gap in this study. Additional work will be necessary to better constrain the relationship between wind speed and Salton Sea lake spray emissions.

Dry Deposition: Dry deposition is a dominant loss process for coarse particles in the atmosphere, especially in arid regions less impacted by precipitation (Bergametti et al., 2018). Particle deposition velocity is strongly correlation with particle size, and can vary from about 0.005 cm/s for 1 □m diameter particles (PM1) to 10 cm/s for 30 □m diameter particles (Foret et al., 2006; Petroff and Zhang, 2010).

For this work, as we focus on PMc, we assume a dry deposition velocity of 2 cm s-1, consistent with high-end estimates of previous studies (Ganor and Foner, 2001; Kubilay et al., 2000; Schneider et al., 1990). We then estimate time-dependent losses of PMc assuming a typical PBL height of 1.5 kilometers (Rahn and Mitchell, 2016), reaching a loss rate of 0.08% min-1. Finally, we use this loss rate to apply a depositional weighting factor, reducing the contribution of remote surfaces based on the length of time it would have taken dust emitted from that source to reach the receptor site station. This factor has the net result of prioritizing local emission sources over remote ones in estimating original sources of observed PMc. Initial calculated dry deposition factor is also normalized to zero to one for the weighting purpose.

All three weighting factors are first normalized separately and then multiplied together to get a combined weighting factor for each trajectory point. We further normalized the combined weighting factor to rescale it to zero to one. This normalized combined weighting factor is the newly weighted ratio indicating how much of the dust arrived at the observation station is from each trajectory point. Multiplying this weighting ratio by the PMc concentration at the receptor site station for each hour, we are able to estimate the mass of PMc contributed by each back trajectory point to the total mass concentration observed. Finally, the hourly PMc concertation for trajectory points are sum up based on surface type categories and averaged to daily average concentrations. This daily average PMc concentration of a unique surface type is defined as dust contribution from that surface type on a single day at a specific site.

3.2.6 Hospitalization data

Unscheduled daily hospital admissions for both respiratory and cardiovascular disease are collected from the Patient Discharge Data and the Emergency Department Data collected by the California Department of Health Care Access and Information. We used hospital admissions at the zip code level for our study period and areas of interest (Table 3.2, Figure A-1). Respiratory hospital admissions are referred to as a category that includes pulmonary diagnosis, such as asthma, chronic obstructive pulmonary disease (COPD), pneumonia and interstitial lung disease corresponding to the ICD 9 codes from 460 to 519 (Aguilera et al., 2021). For cardiovascular diseases, we included both cardiovascular and cerebrovascular events. Cardiovascular events were identified using ICD-9 codes 410:414 or ICD-10 codes I20:I25 which include acute myocardial infarction (MI) or other acute or chronic ischemic heart disease and ICD-9 code 428 and ICD10 code I50 which is for congestive heart failure. Cerebrovascular events were identified using ICD-9 codes 430:438 or ICD-10 codes I60:I69 which include hemorrhagic stroke, ischemic stroke, and occlusion of the precerebral and cerebral arteries.

To better match hospital admissions with air pollution data that collected from ground observation stations, we conducted kriging analysis with high time resolution PM_{10} data to estimate the distance within which the ground observation stations are the best representations of the surrounding air quality. The high time resolution PM_{10} data is collected from low-cost sensors (light-scattering particle counter by Dylos, Dylos 1700) installed as part of the IVAN Air Monitoring network (Figure A-2, left) (Identifying Violations Affecting Neighborhoods, https://ivan-imperial.org/air). IVAN air monitoring network includes around 40 air monitors to measure particle concentrations ($PM_{2.5}$ and PM_{10}). The data we used in this study was PM_{10} concentration that was collected every 5 minutes from August 1st, 2018 to August 30th, 2020. Based on these data, we fitted them into a variogram model to estimate the distance within which the pairs of points (monitors) are spatially correlated. According to the results from the variogram model, PM_{10} beyond a distance around 5 km the variogram starts to levels off indicating the pairs of monitors are not spatially corrected and the corresponding variogram values are around 0.05 (Figure A-2, right). This indicates that within our study area, the monitors are able to provide reliable data within a range of 5 km of PM_{10} and we assume this also applies to the EPA stations.

Then we filter out zip codes that fall into a 5 km radius buffer zone for each individual ground observation station (Figure 3.1, right, marked by red circle) and end up with: three zip codes (92201, 92203 and 92236) for Indio station, one zip code (92254) for Mecca station, one zip code (92274) for Torres Martinez station, one zip code (92227) for Brawley station, two zip codes (92243, 92251) for El Centro station and two zip codes (92231, 92249) for Calexico station. Finally, we sum up daily hospital admissions of all zip codes that we selected above for individual stations separately to represent the daily respiratory and cardiovascular hospital admissions corresponding to each station.

3.2.7 Statistical analyses

Associations between daily PMc from different surface types and hospital admissions for both respiratory and cardiovascular disease are examined using a time-stratified case-crossover design, a method that has been widely used for studying the health effects of short-term air pollution exposure based on acute health outcomes (Díaz et al., 2012; Lee and Schwartz, 1999; Zanobetti and Schwartz, 2005). It's essentially an ecological case-control design in which cases at a given time serve as their own controls using different and comparable time windows (Jaakkola, 2003; Janes et al., 2005; Maclure, 1991). Control days are selected using a monthly time-stratified method: control days are chosen from identical days of the week during the same month as each case (Deguen et al., 2015). For example, if there is a case on the first Wednesday of March on 2013, then the control days of this case are other Wednesdays within March, 2013. This control selection strategy accounts for long term trends, seasonality, and day of week effects, and also helps to avoid overlap biases (Deguen et al., 2015).

Since daily $PM_{2.5}$ and ozone may also have impacts on hospitalizations and are correlated with PM_{10} (Miao et al., 2022), we further conducted multi-pollutants models by introducing $PM_{2.5}$ and ozone into the statistical model as covariates. Daily $PM_{2.5}$ are taken from values calculated in the previous step, while daily ozone is collected from EPA AQS for all stations in this study area and period. We further adjust for meteorological variability by introducing daily heat index into the case-crossover model. The daily heat index is calculated from hourly air temperature and relative humidity (RH) based on the method developed by National Werther Service (NWS) (NOAA, n.d.)

(Table1, Figure S1). The hourly air temperature and RH are collected from MesoWest weather observation network (Horel et al., 2002b, 2002a) using the Jacqueline Cochran Regional Airport site (KTRM) located the north end of the Salton Sea and the Imperial County Airport site (KIPL) located at the south end of the Salton Sea. Daily heat index values calculated based on the data that collected from KTRM are shared by the three AQS ground observation stations located at the north end of the Salton Sea which include Indio, Mecca and Torres Martinez while daily heat index values calculated from KIPL site are share by other three AQS stations located at the south end of the Salton Sea which include Brawley, El Centro and Calexico.

We then introduce the lag effects of both air pollutants (the main PMc exposure and $PM_{2.5}$ and o3) and meteorology variables into the case-crossover model. We first calculate the relative risk (RR) on different lag days from lag0 to lag7 between hospital admission and different PMc separately as well as between hospital admissions and heat index (Figure S4). Overall, the PMc show positive correlation with both respiratory and cardiovascular disease until lag2. Thus, we select the 0-2 lag period to model the distributed lag effects of air pollution exposure.

Following a similar approach, we also choose lag0-2 for heat index, $PM_{2.5}$ and ozone to account for the lag effects from confounding factors.

Health effects of different PMc on the 0-2 lag period are expressed as the relative risk (RR) of hospital admissions associated with a 10 μg/m3 short-term increase in PMc with corresponding 95% confidence intervals. We measured the heterogeneity of PM effects of Salton Sea PM vs all other surfaces dust using Cochran's Q tests. All statistical analyses are performed using R Studio.

3.2.8 Salton Sea algae data

Daily near-surface concertation (in mg/m^3) of chlorophyll-a (chlorophyll) collected from NASA's ocean data product are used to represent the algae condition over the Salton Sea (Figure A-3). This near-surface concertation is calculated by the algorithm described here (Hu et al., 2019, 2012; O'Reilly et al., 1998; O'Reilly and Werdell, 2019) with the raw data collected by MODIS with sensor bands spanning the 440-670 nm spectral regime (EARTHDATA, n.d.). To examine the health effects of the Salton Sea algae bloom, we divide the Salton Sea dust (PMc coming from SaltonSea surface type) into two categories: Salton Sea dust with algae event and Salton Sea dust without algae event. We tested different ways of handling the chlorophyll data including log transformation of mean chlorophyll, log transformation of 90th percentile chlorophyll, daily average of the log transformed mean chlorophyll, daily average of the log transformed 90th percentile chlorophyll, and a metric that only count the number of pixels with chlorophyll above a certain threshold. The health effects of different metrics are very similar, and we finally decided to use the daily average of the lag transformed mean chlorophyll for each pixel which shows relatively higher and consistent relative risk for both respiratory and cardiovascular hospital admissions for later analysis (Figure A-5). Then we normalized this chlorophyll data throughout the whole time period of each AQS station to rescale it to 0 to 1. Finally, we multiply the concentration of Salton Sea dust with the normalized chlorophyll value to represent the Salton Sea dust that contains chlorophyll while with the (1- normalized chlorophyll value) to represent the Salton Sea dust that doesn’t contain chlorophyll. By doing this, we divided the Salton Sea dust into Salton Sea dust with and without algae bloom and examined the health effects of Salton Sea algae bloom with a case-crossover statistic model.

Table 3.1 Summary statistics of air pollutants, meteorology and algae data

	Time period	Min	Median	Mean	Max	SD
$PM_{2.5\text{-}10}$, daily average concentration in μg/m^3 *						
Indio	2008 - 2019	0.75	22.95	26.46	355.65	21.61
Mecca	2015 - 2019	1.57	30.89	37.15	636.17	34.33
Torres Martinez	2008 - 2019	0.00	42.77	54.23	8111.17	49.77
Brawley	2013 - 2019	0.26	31.75	39.42	415.23	36.46
El Centro	2015 - 2019	1.89	29.61	33.73	270.23	24.00
Calexico	2016 - 2019	0.86	37.15	42.76	427.94	29.16
PM_{10}, daily average concentration in μg/m^3						
Indio	2008 - 2019	3.08	30.35	30.35	386.17	23.94
Mecca	2015 - 2019	3.33	36.42	42.86	654.75	36.61
Torres Martinez	2008 - 2019	1.50	48.42	60.40	855.33	52.31
Brawley	2013 - 2019	1.61	39.21	47.56	446.68	39.72
El Centro	2015 - 2019	3.33	37.42	41.91	310.60	27.58
Calexico	2016 - 2019	1.71	47.60	54.68	463.83	34.43
$PM_{2.5}$, daily average concentration in μg/m^3 *						
Indio	2008 - 2019	1.31	7.31	7.53	34.52	2.85
Mecca	2015 - 2019	0.34	5.22	5.71	91.02	3.51
Torres Martinez	2008 - 2019	0.26	5.65	6.17	87.78	3.30
Brawley	2013 - 2019	0.76	7.44	8.13	50.00	4.01
El Centro	2015 - 2019	0.89	7.66	8.17	40.36	3.93
Calexico	2016 - 2019	0.73	10.22	11.92	170.99	7.98
Heat Index, daily average heat index **						
Indio	2008 - 2019	32.65	71.38	71.88	110.06	16.06
Mecca	2015 - 2019	34.47	73.51	73.57	110.06	15.48
Torres Martinez	2008 - 2019	32.65	70.97	71.53	110.06	15.65
Brawley	2013 - 2019	36.49	72.42	73.43	112.22	15.88
El Centro	2015 - 2019	39.63	73.12	73.95	112.22	16.43
Calexico	2016 - 2019	39.63	72.50	73.54	112.22	16.13
ozone, daily maximum of 8-hour running average, ppb						
Indio	2008 - 2019	2.59	40.27	39.26	87.30	16.27
Mecca	2015 - 2019	0.63	34.51	33.34	63.32	0.01
Torres Martinez	2008 - 2019	0	32.93	32.78	73.73	13.00
Brawley	2013 - 2019	5.84	30.35	30.99	68.29	10.76
El Centro	2015 - 2019	7.12	24.76	32.76	65.35	10.68
Calexico	2016 - 2019	4.45	32.83	32.86	64.23	11.29
Chlorophyll concentration over the Salton Sea,						
25^{th} percentile	2008 - 2019	0.00	0.00	0.23	20.65	1.68
Median	2008 - 2019	0.00	0.00	2.89	94.05	8.03
Mean	2008 - 2019	0.00	8.012	13.77	114.69	16.59
75^{th} percentile	2008 - 2019	0.00	0.00	11.76	199.46	22.12

*: Daily average concentrations of $PM_{2.5}$, $PM_{2.5\text{-}10}$ are calculated from estimated ratios of $PM_{2.5}$ and $PM_{2.5\text{-}10}$.
See more detailed information about the calculation process from methodology section.
**: Heat index is calculated from temperature and relative humidity. See more detailed information about the calculation process from methodology section.
SD: standard deviation

Table 3.2 Summary statistics of hospital admissions

	Time period	Selected zips	Total hospitalizations	Respiratory	Cardiovascular
Indio	2008 - 2019	92201, 92203, 92236	884,82	663,11	221,71
Mecca	2015 - 2019	92254	296,4	235,4	610
Torres Martinez	2008 - 2019	92274	117,43	928,8	245,5
Brawley	2013 - 2019	92227	231,43	182,44	489,9
El Centro	2015 - 2019	92243, 92251	321,03	248,13	729,0
Calexico	2016 - 2019	92231, 92249	130,30	870,2	432,8
All sites			171,465	129,712	417,53

3.3 Results

3.3.1 Dust fractions by surface types

This study in total collected and estimated 45 years hourly PMc from six AQS ground observation stations (Table 3.1) and simulated about 118,332,0 back trajectories accordingly. The west and east boundaries of all trajectory points are -121.60 and -111.91 of longitude while the north and south boundaries are 38.54 and 28.51 of latitude covering an area of about 726551 square kilometers (km^2) (the area is estimated from MRLC) mostly over southwest US including ten different surface types. Based on back trajectory analyses (Fig. 3), PMc observed in the Coachella Valley appears to come primarily from shrub and developed urban areas, while Imperial Valley dust has more contributions from croplands and from across the Mexican border. Dust passing over Salton Sea (herein referred as Salton Sea dust) accounts for a very small fraction compared to other surface types with the lowest fraction of 0.5% observed at Indio station and the highest fraction of 2.3% observed at Brawley station. In general, we found that stations located at the Imperial Valley have higher dust contributions from the Salton

Sea compared with stations located at the Coachella Valley and stations that closer to the Salton Sea get more dust contributed by the Salton Sea.

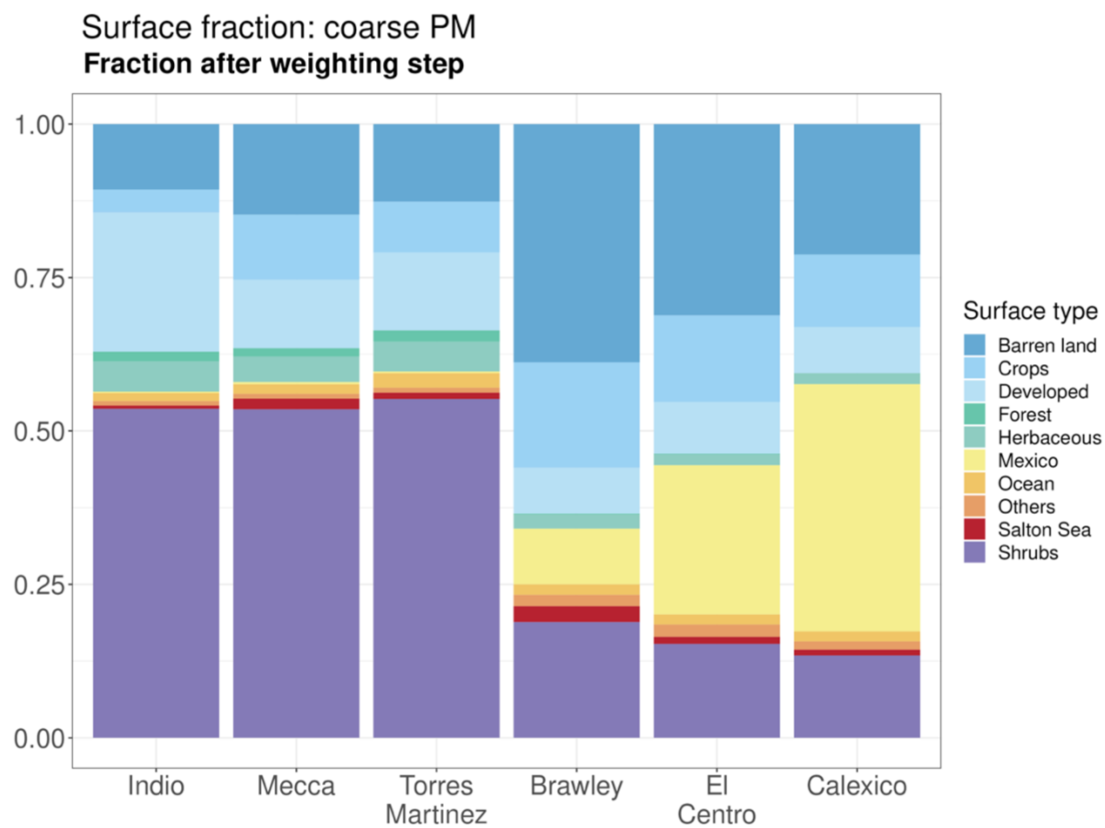

Figure 3.3. Dust fractions of different surface types by site.

3.3.2 Acute health effects of Salton Sea dust

In total, 129,712 hospital admissions of respiratory disease and 417,53 hospital admissions of cardiovascular disease were recorded between 1st January 2008 and 31st December 2019 from all selected zip codes (Table 3.2). We conducted case crossover analysis between hospital admissions and dust coming from different surface types to estimate the pooling health effects across all sites. Figure 3.4 (upper left and upper right) shows the pooled relative risks of respiratory and cardiovascular disease associated with

10 $\mu g/m^3$ increase in PMc coming from Salton Sea and all other surface types. According to our results, Salton Sea dust shows stronger health impacts on both respiratory and cardiovascular hospital admissions compared to non-Salton Sea surfaces. With a 10 $\mu g/m^3$ increase in PMc coming from Salton Sea are associated with 8.4% (RR = 1.084, 95% confidence interval (CI): 1.029 - 1.138) increased risk of respiratory hospital admissions and associated with 3.8% (RR = 1.038, 95% CI: 0.940 - 1.135) increased risk of cardiovascular hospital admissions (Table 3.3). While for PMc coming from all other surfaces, increasing 10 $\mu g/m^3$ in concentration only showed increased risk in cardiovascular hospital admissions (RR = 1.001, 95% CI: 0.994 – 1.008) but no positive correlation was found with respiratory hospital admissions.

3.3.3 Health effects of Salton Sea algae event

To investigate the health impacts of algae events in the Salton Sea, we separate the Salton Sea dust into two subgroups: Salton Sea with algae events and Salton Sea without algae events, and estimated the RR for these two groups plus the group includes all other surfaces. Figure 3.4 (lower left and lower right) shows the pooled relative risk of respiratory and cardiovascular disease associated with 10 $\mu g/m^3$ increase in PMc. Our results indicated that Salton Sea with algae events showed the strongest positive correlation with both respiratory and cardiovascular hospital admissions among all three groups, followed by Salton Sea without algae events and all other surfaces. A 10 $\mu g/m^3$ increase in Salton Sea dust with algae event were associated with 24.9% (RR = 1.249, 95% CI: 1.065 – 1.432) increase in respiratory hospital admission, but we did not detect a precise estimate for cardiovascular hospital admissions 18.8% (RR = 1.188, 95% CI: 0.872 – 1.504). Higher Salton Sea dust concentration without an algae event was still associated with increased risk for both respiratory and cardiovascular hospital admissions (Table 3.3). For dust coming from all other surfaces, we did not see clear positive association with either respiratory or cardiovascular hospital admissions.

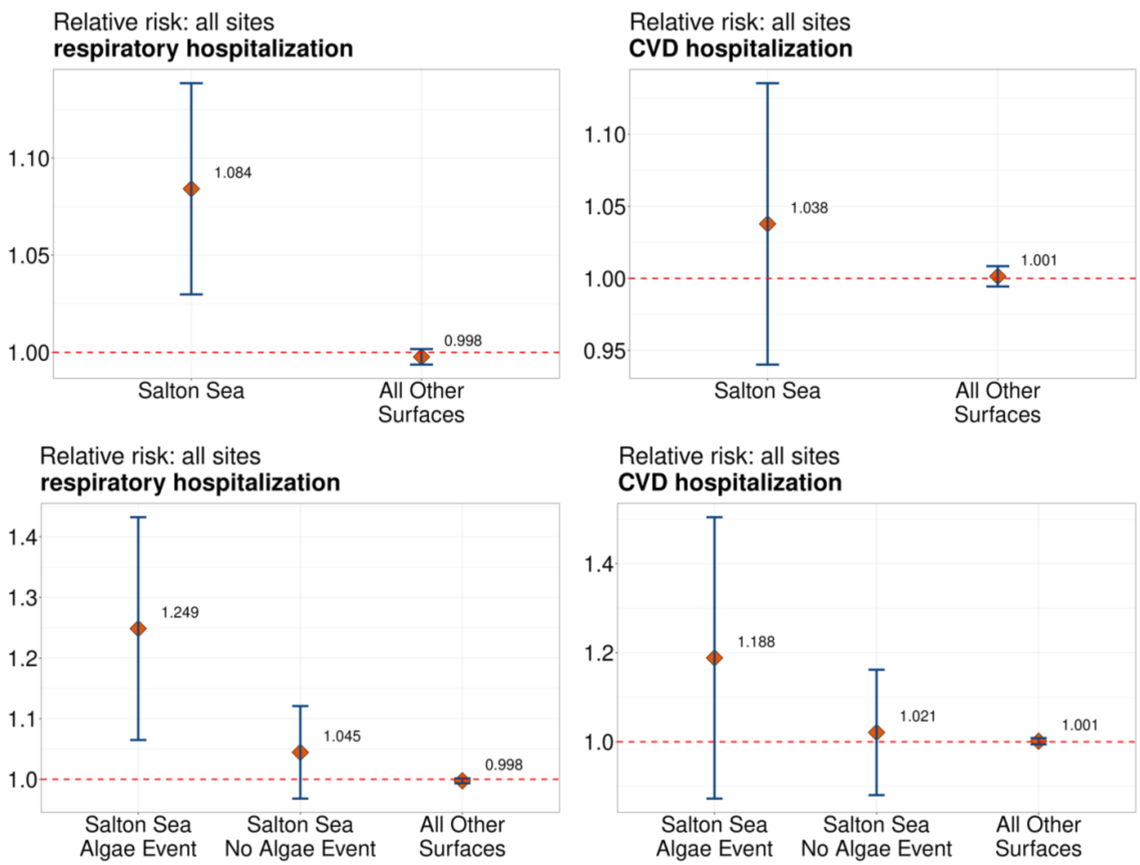

Figure 3.4. Pooled relative risk of hospitalizations associated with a 10 μg/m^3 short-term coarse PM ($PM_{2.5-10}$) increase and 95% confidence interval. Upper: relative risk of respiratory (left) and cardiovascular (right) hospitalization associated with 10 μg/m^3 increase in Salton Sea dust vs all other surfaces dust; Lower: relative risk of respiratory (left) and cardiovascular (right) hospitalization associated with 10 μg/m^3 increase in Salton Sea dust with algae event, Salton Sea dust without algae event vs all other surfaces dust.

Table 3.3 Pooled relative risks of hospitalizations with a 10 μg/m^3 short-term PMc increase

	RR	Lower 95% CI	Upper 95% CI
Salton sea dust vs non-Salton Sea dust			
Respiratory hospitalization			
Salton Sea	1.084	1.030	1.139
All other surfaces	0.998	0.993	1.001
Cardiovascular hospitalization			
Salton Sea	1.038	0.940	1.135
All other surfaces	1.001	0.994	1.008
Algae events			
Respiratory hospitalization			
Salton Sea with algae event	1.249	1.065	1.432
Salton Sea no algae event	1.045	0.968	1.121
All other surfaces	0.998	0.993	1.001
Cardiovascular hospitalization			
Salton Sea with algae event	1.188	0.872	1.504
Salton Sea with algae event	1.021	0.880	1.161
All other surfaces	1.001	0.994	1.008

3.4 Discussion

In this study, we examined and compared the association between daily dust coming from different surface types and hospital admissions related to respiratory disease and cardiovascular disease using 171,465 hospital admissions that occurred in Southern California's Salton Sea region in the US between 2008 and 2019. We found increases in both respiratory and cardiovascular hospital admissions with 10 μg/m^3 increase in Salton Sea dust. Even stronger associations were observed for Salton Sea dust with algae events. To our knowledge, this is the first ever study that examines the source specific acute health effects of ambient dust exposure in the Salton Sea region. And for the first time, we provide scientific evidence for the adverse health effects of Salton Sea dust and Salton Sea algae events on surrounding residents.

We first compared the health effects between Salton Sea dust and non-Salton Sea dust. Our results indicate dust coming from Salton Sea only accounts for a very small fraction among all surface types, but it shows stronger positive association with hospital admissions for both respiratory disease and cardiovascular disease. Regarding the RRs of Salton Sea dust which is represented by PMc ($PM_{2.5-10}$), our results are consistent with previous researchers studying the health effects of coarse PM (Adar et al., 2014; Castillejos et al., 2000; Chen et al., 2011; Nirel et al., n.d.; Schwartz and Neas, 2000). We found a statistically significant positive association between Salton Sea dust exposure and respiratory hospital admissions and this association is stronger than the association with cardiovascular hospital admissions. This may be explained by the lab results of Biddle et al., (2021); they exposed experimental mice to aqueous extracts of dust samples collected around the Salton Sea region, finding that Salton Sea dust extracts promote lung inflammation in mice and may synergize with allergic response. This suggests that there might be some specific composition in the Salton Sea dust that is more likely to trigger respiratory disease. In general, we find much stronger association of Salton Sea dust with hospitalizations compared with non-Salton Sea dust, and this may be related with the microbial components in the Salton Sea dust according to the results from the follow-up study by (Biddle et al., 2023).

When Salton Sea PM during algae events are isolated, even higher RR values for dust associated with Salton Sea back trajectories during algae events are observed. The observed health impacts of algae events on the Salton Sea may likely related with the lake spray aerosol which could act as a mechanism to transport potential hazardous compounds from lake water surface to the atmosphere and further disperse to the surrounding land causing human health impacts. Perhaps a baseline of potential chronic inflammation from dust inhalation/pre-existing health conditions, plus acute inflammation triggered by cyanobacteria/toxin inhalation, may help explain the data

Cyanobacteria themselves are gram-negative bacteria and express a protein called LPS that triggers our immune systems. Previous study found that cyanobacteria can infiltrate beyond the upper respiratory tract (nasal cavity), into the central airway (lungs) (Facciponte et al., 2018). The respiratory implications of dust exposure combined with the ability of cyanobacteria to enter the lungs as well may predispose residents to respiratory exacerbations leading to hospital admission. The effect of cyanotoxins on respiratory/hepatic function may potentially lead to manifestations of CVD. For example, Oscillatoria, one of the most frequently observed genera in both water and algal mat samples in the Salton Sea recently, have been found to release Microcystins (MCs). Microcystins (MCs) have been shown by previous study that can instigate CVD by prompting pathological alterations in the structure and/or operation of other specific organs or tissues, notably referred to as the indirect cardiovascular toxicity of MCs. We cannot exclude the possibility that the Salton Sea population of Oscillatoria are releasing these toxins. If algal blooms in the Salton Sea become more frequent given the warming climate, chronic exposure may be of concern.

Ambient dust from the Salton Sea considered in this atmospheric model are primarily sourced from two origins within an interconnected ecosystem: lake spray aerosols reflect the water quality degradation from harmful algal blooms while exposed playa sediments serve as a reservoir of pollutants sequestered while under water that underwent redox and chemical changes as lake dries. As both microbial, organic and inorganic contaminants are entrained as particulate matter and transported through the atmosphere, hospitalizations in nearby communities could be triggered by both wet and dry aerosols. Respiratory illnesses could be affected by allergic response to microbes and also physical inhibitions posed by inorganic compounds (e.g. gypsum shards affecting lungs) while cardiovascular responses are known to come from exposure to neurotoxins (such as those from harmful algal blooms).

The specific contaminants from the Salton Sea under investigation are products of the environmental degradation under existing water policies. The primary purpose of the Salton Sea as defined by the Colorado River Regional Water Quality Control Board serves as a receptacle for untreated agricultural return flow ("to receive and store agricultural drainage, seepage, and storm waters" (California State Water Resources Control Board, 2023). As a result, excessive phosphorus and nitrogen from fertilizers have entered into the system for the last century through agriculture return flow. Eutrophication processes drive the proliferation of algal blooms, with their subsequent decay contributing to the consumption of dissolved oxygen and release of sulfide and other metabolites in the bottom water column. The occurrence of algal blooms in the surface waters is a recurring phenomenon seen as water discoloration known as "Red Tides" (dinoflagellates containing chlorophyll-a) or "Green Tides" (diatoms containing chlorophyll-a and chlorophyll-c), elevated in summer months due to increased temperatures, light and density-stratification. Toxins released from harmful algal bloom are well-documented in the Salton Sea as associated with wildlife mortalities (Carmichael and Li, 2006; Reifel et al., 2002, 2001; Tiffany et al., 2001). While human health responses upon exposure to cyanobacteria toxins (cyanotoxins) have not been determined at the Salton Sea, the Regional Waterboard frequently issues advisories for humans to avoid contact with the lake water due to these toxins. These advisories are congruent with numerous well-documented epidemiological studies citing human illnesses associated with harmful algal blooms (Backer, 2002; Fleming et al., 2002; Pulido, 2016; Young et al., 2020). Natural toxins produced by algal blooms can be lethal and cause a wide range of both acute and chronic health effects upon human exposure through drinking water or eating food. However, exposure through moist or dry aerosols and respiratory contact has not been well-documented. Lastly, extremophiles such as halophiles and microbes related to sulfur-metabolism in the water column may also be associated with health responses although such cases have not been well-documented in the Salton Sea or general epidemiological cases.

More importantly, our results show consistency regarding the stronger association between Salton Sea related dust and hospitalizations. To test the sensitivity of weighting factors on the model performance, we did the following tests separately: for wind speed, we added threshold wind speed (3 m/s) and also tested with the 4^{th} power of the wind speed to represent the nonlinear relationship with dust emission; for the dry deposition loss, we tested with two more deposition velocities, 0.1 cm/s and 10 cm/s; for surface emissivity of Salton Sea water, we tested with 0 and 1. All the final results of RR are very similar with Figure 3.4 and consistently showing the stronger RRs for Salton Sea related dust. This suggests that our dust estimation model is relatively stable and less sensitive to the change of weighting factors.

We further examined the impact of different methods of handling algae data (chlorophyll including log transformation of different percentiles of the chlorophyll, daily average of the log transformed chlorophyll and a metric that only counts the number of pixels with chlorophyll above a certain threshold. RRs estimated through case crossover analysis based on those different methods are very similar and consistently showing stronger association with Salton Sea dust with algae events (Figure A-5). Additionally, we also remove summer months (June, July and August) and only keep summer months to test the hypothesis of whether the health effects are caused by temperature or algae. Our estimated RR consistently shows that Salton Sea with algae events has the strongest effects on hospitalization (Figure A-6).

One limitation of our study is the verification of our dust estimation model. In this study, we developed a new model to separate ambient dust by their source regions using trajectory information, land surface data and weighting factors. To our knowledge, no study has conducted source apportionment analysis for ambient dust with this method. The best way to verify model estimation is to compare model outputs with observational data. There are a couple of published papers studying the dust composition and sources in the Salton Sea region (Frie et al., 2017, 2019a). However, it is very difficult to verify our model with those studies due to 1) their use of compositional markers to define different sources while our model use land cover information to categorize our source regions; 2) their source types are very different from our source region types. Therefore, based on the current data availability, we are not able to compare our model estimation with observation data.

An alternative way to verify our model is to compare with other similar models. There are similar methods that also use trajectory information to identify source regions that have been widely used by previous studies. One is called potential source contribution function (PSCF) and the other one is called concentration-weighted trajectory (CWT). The PSCF estimates the proportion contributed by a given grid while CWT provides the concentration levels for a given grid. The key differences between the model we developed in this study with PSCF and CWT are 1) PSCF and CWT combine all trajectories over time and calculate the average ratio/concentration of all trajectory points for a give grid. This means that PSCF and CWT ignore the time and only conduct spatial calculation while our model has to keep time information for later time-based case crossover analysis; 2) PSCF and CWT weight each trajectory point equally but our model treat each trajectory points differently to account for essential factors including wind speed, deposition loss and soil emissivity that have strong correlation with dust emission and transportation. Weighting each trajectory point differently is also the most novel part of our model. Therefore, studies using PSCF and CWT are not good references for us to use for verification. Further studies are needed to verify our model results.

Another limitation of this study lies in the representation of Salton Sea dust. In this study, we define the Salton Sea dust as dust coming from the surface type of "Salton Sea" which is created based on the location of the lake. This method is able to capture most of dust coming from the Salton Sea, including those recently exposed by dynamic shorelines as lake level rapidly retreat, since the "Salton Sea" category defined by us covered almost all the Salton Sea (Figure 3.2). However, the limitation to this is that we are not able to tell whether the dust comes from the lake spray from the Salton Sea or the surrounding playa based on our method. The association between Salton Sea dust and algae events to respiratory or CVD hospitalizations do not imply causation nor reveal the specific contaminant that triggers health responses. This study does not attempt to disentangle health triggers to respiratory or cardiovascular illnesses between dry vs. wet aerosols, which have different transport pathways, authigenic compositions and affiliated or adsorbed surface materials that likely yield different health responses. Triggers may arise from compounds organic in nature (microbial, organics-rich sediment, pesticides) to those inorganic (trace metals, morphology of aerosol dust revealed through SEM image). Although most of the studies that examine the air pollution-related topics in the Salton Sea region focus on the playa (Dickey et al., 2023; Frie et al., 2017, 2019a; Parajuli and Zender, 2018b), lake sprays from the water is also important sources of the air pollution especially due to the fact that the water body is much larger than the surrounding playa and have deleterious health impacts (Biddle 2023). More importantly, the chemical and physical properties of aerosols emitted from the lake and playa can be very different since the aeolian process, surface conditions and chemical compositions vary largely between lake and playa. Therefore, it’s important for future studies to separate dust from the playa and lake spray to better understand which one is the dominant contributor to local air pollution and health issues.

Our results provide evidence for the adverse health effects of dust coming from Salton Sea especially during an algae event. This provides the fundamental scientific evidence for future research in the Salton Sea region and more studies are needed to confirm our findings. Future studies, perhaps those conducted within isolated, controlled laboratory environments (e.g., mice chamber studies using “contaminants” sampled from various components of the Salton Sea ecosystem akin to Biddle et al. 2023), could better differentiate health effects between wet and dry Salton Sea aerosols and further investigate transport mechanisms, triggering components and associated health responses. In particular, more research is needed to examine the chemical compositions, especially the microbiome groups of aerosols coming from the Salton Sea to better understand the chemical properties of Salton Sea aerosols. Additionally, further studies are needed to understand the environmental conditions surrounding an algal bloom at the Salton Sea and how those algae groups and potential toxins released impact surrounding air quality and public health. To further investigate transport mechanisms and host-pathogen relationships, a time-monitored study on the occurrence of algal blooms and sampling to analyze its toxins elucidate the linkage between toxins released during an algal event and transmission mechanisms to nearby communities. Similarly, sampling and analyzing the organic and inorganic contaminants within exposed playa (also, wet-dry transition at the intertidal zone) and ambient dust may highlight the importance of considering multiple pathways of exposure and their cumulative effects. It will be critical for future studies to investigate epidemiology impact of Salton Sea aerosols to reveal the underlying mechanism of the higher health risk of Salton Sea particles.

3.5 Conclusion

In conclusion, this study provides novel supporting evidence that coarse particles coming from the Salton Sea are associated with negative health outcomes for residents living in Southern California's Salton Sea region. These impacts appear to be particularly strong during periods associated with algal bloom events, suggesting that biogeochemical cycles within the water column affecting water quality may be important for understanding the health risks associated with regional PM_{10}. The presence of pollutants in the Salton Sea ecosystem has direct implications for both environmental health and human well-being. The interaction between algal blooms, pollutant release, and atmospheric transport underscores the potential for adverse health effects among local communities. The ecosystem is influenced by a complex interplay of pollutant sources (algal blooms from eutrophication and exposed playa dust), seasonal dynamics (temperature incited microbial reactions and rates as well as meteorological components such as wind intensity and directions), and sediment-mediated processes (sequestration of heavy metals under reducing, anoxic conditions at lake bottom and wet-dry zones at lake margins). The combined effects of algal blooms, eutrophication, redox conditions, and dust entrainment contribute to a multifaceted landscape of pollutant interactions. A holistic understanding of these dynamics as related to epidemiology is essential for effective management strategies (e.g., reducing nutrients in agricultural return flow into the lake). More work is needed to further explore the specific mechanisms responsible for the health effects revealed here, and to provide insights on ways to best address them for the benefit of local communities.

3.6 Acknowledgements

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Chapter 4 Exploring ammonia emission patterns and potential sources in the Salton Sea region via mobile in situ observations

Acknowledgement of Contributions:

This work is completed with contributions from Yaning Miao, William C. Porter, Francesca Hopkins, Kuai Le, Olga V. Kalashnikova

Abstract

Ammonia (NH_3) is an important atmospheric trace gas with implications for air quality and public health due to its role as a precursor to fine particulate matter ($PM_{2.5}$). The Salton Sea region in southern California is heavily engaged in agriculture, with Imperial Valley being a major vegetable producer and home to a substantial cattle population. To explore the ammonia emission patterns and potential sources, we employ on-road mobile laboratory measurements to collect real-time ammonia mole fraction in the region. Using a mobile observatory equipped with a cavity ring-down spectrometer and GPS receiver, two days of measurements were conducted across the region as a case study. Results confirm that ammonia emissions are elevated near cattle feedlots and geo-thermal plants, with increased atmospheric ammonia levels linked to fertilization and irrigation. Higher ammonia levels are observed in the Imperial Valley located south of the Salton Sea compared to Mecca in the north. Mecca displays distinct diurnal patterns, emitting more ammonia in the morning and less in the afternoon. Conversely, Imperial Valley shows consistently elevated ammonia levels throughout the day, lacking diurnal variation. This study provides valuable ammonia emission data to address existing

spatiotemporal emissions inventory gaps in the Salton Sea region and provide insights on local emissions and transport patterns.

4.1 Introduction

Ammonia (NH_3) is a colorless gas composed of nitrogen and hydrogen atoms and is the dominant atmospheric alkaline trace gas species. NH_3 can react readily with atmospheric acid species and is a key precursor of atmospheric fine particulate matter ($PM_{2.5}$), which has implications for both air quality and public health. Globally, the major sources of NH_3 come from animals, fertilizers, biomass burning, crops, human populations, soils, industry process and fossil fuels (Bouwman et al., 1997) with agriculture contributing over 81% of total global emission (Damme et al., 2021; Wyer et al., 2022). Previous studies have indicated that beyond the potential indirect health impacts caused by $PM_{2.5}$, exposure to agriculture-derived NH_3 may directly influence development of early asthma in young children, and has direct effects on the respiratory health of those working with livestock. Although the major NH_3 sources are well documented, the magnitude and trends of emissions from different types of sources and source regions are not fully quantified due to the high spatial and temporal variability and uncertainties on global and regional scales.

The Salton Sea region, located in southern California in the United States, has been characterized by heavy agricultural activity over the past century, especially for the Imperial Valley located at the south end of the Salton Sea. Imperial Valley agricultural areas consist of over 450,000 farmable acres and collectively produce roughly 2/3 of the vegetables consumed in the U.S. during winter months (Imperial County, 2019; Quandt, 2023). On top of that, the Imperial Valley is home to over 380,000 head of cattle, making it the top commodity (in terms of the gross value) in Imperial Valley (Imperial County Farm Bureau, 2023). Both vegetable farms and animal dairy facilities are well known NH_3 sources. In addition to agriculture activities, previous studies have reported that geothermal plants around the Salton Sea region make up a previously unreported source of NH_3 to the region (Tratt et al., 2011). Studies have shown that NH_3 mixing into areas of active photochemistry can form ammonium nitrogen (NH_3NO_3) and lead to high levels of particulate NH_4NO_3 in this region, accounting for a large fraction of total $PM_{2.5}$ mass (Kim et al., 2010; Kleeman et al., 1999; Nowak et al., 2012; Russell and Cass, 1986). Therefore, it is essential to measure atmospheric NH_3 mole fractions and identify NH_3 sources to better understand their representation in emission inventories and develop effective mitigation strategies for gas-phase and particulate pollution.

Although satellite sensors can be a powerful tool for identifying NH_3 emission plumes, it can be difficult to quantify and constrain NH_3 point sources relying only on remote sensing data products due to spatial resolution limitations (data product pixel sizes are often greater than 15 km). Thus, ground measurements remain of great importance for the full understanding of NH_3 point sources. Since NH_3 is not measured by typical long term air monitoring stations, mobile monitoring is a common methodology used to measure surface NH_3 mole fractions, and thereby infer local emissions. Additionally, one advantage of mobile monitoring also lies in high spatial resolution, especially important for better understanding spatial gradients near sources. Mobile monitoring has been widely used to address urban and regional air quality issues (Elser et al., 2016; Li et al., 2019; Pirjola et al., 2012; Popovici et al., 2021; Wang et al., 2011; Zhang et al., 2020). Recently, several studies have also utilized mobile monitoring to measure ground NH_3. For example, Eilerman et al., used a mobile lab to measure NH_3 and other trace gases from four concentrated animal feeding operations in northeastern Colorado in the U.S. (Eilerman et al., 2016). Similarly, Miller et al. characterized the spatial distribution of NH_3 dairy plumes in California's San Joaquin Valley with mobile monitoring (Miller et al., 2015).

To enhance understanding of the origins and spatial dispersion trends of NH_3 in the vicinity of the Salton Sea area, we employed an on-road mobile laboratory to perform real-time measurements of NH_3 mole fractions across the designated region. Precisely, the primary objective of this investigation is to support the calculation of NH_3 emissions specific to the Salton Sea region. This endeavor aims to advance the existing NH_3 emission inventory pertaining to this locale, thereby fostering improved accuracy for subsequent research endeavors concerning air quality.

4.2 Methods

4.2.1 Instrumentation

We used a mobile observatory to continually measure geolocated atmospheric NH_3 levels on-road. The platform is a Mercedes Sprinter van with dimensions of roughly 24 ft long, 7ft wide, and 10 ft tall. The mobile lab is equipped with a cavity ring-down spectrometer (G2103 Analyzer for NH_3/H_2O, Picarro, Sunnyvale, California) to measure

NH_3. The instrument samples air every second from an NH_3 inlet located at the top of the sampling mast. Outside air is pumped continuously through the ¼" Teflon tubing at a rate of 1.7 L/min. Coordinate information is collected by a GPS receiver (Garmin GPS 16X) mounted on the van's roof every second.

4.2.2 Observations

Two days of on-road NH_3 measurements were performed near the Salton Sea region in California on March 27 (day 1) and March 28 (day 2), 2023. Day 1 was conducted in the Imperial Valley from 11 A.M. to 6 P.M. local time (Pacific Standard Time, PST) covering an area from the south boundary of the Salton Sea to Brawley, and day 2 was conducted in the Coachella Valley from 9 A.M. to 5 P.M. local time, covering an area from 66th Ave to 70th Ave in Mecca, CA. Driving routes on day 1 were designed to sample near NH_3 plumes that were identified by previous aircraft campaign including cattle feedlots and geothermal plants, while driving routes on day 2 were designed to cover the same locations at approximately the same time as a concurrent aircraft campaign to explore NH_3 emission patterns around Mecca. During the sampling period, the driving speed was controlled at 5 mph to 10 mph.

4.2.3 Data processing

Original data were collected at approximately the same frequency, every second, for Picarro and GPS receiver (In some cases, Picarro recorded two values within one second). Since the time recorded by Picarro is about 10 minutes faster than the time recorded by GPS receiver (real clock time), we corrected the time information of Picarro before joining with the GPS data. In terms of the multiple values within one second that were recorded by Picarro, we chose the maximum value for that second to represent the NH_3 mole fraction for that second. All data were processed and analyzed through R version 4.2.1 (2022-06-03) on RStudio Server.

4.3 Results

4.3.1 Spatial distribution of NH_3 across the Salton Sea region

NH_3 mole fractions were highly variable across the Salton Sea region ranging from near background levels of about 10 ppb to 1224 ppb measured at the Brandt Cattle Co in Calipatria in Imperial Valley (Table 4.1, Figure 4.2). For the Imperial Valley, located at the south end of the Salton Sea, the minimum, median and maximum mole fraction of NH_3 observed is 15.54 ppb, 60.14 ppb and 1223.74 ppb respectively. We observed local NH_3 enhancement near many known NH_3 emissions sources in this region, including cattle feedlots and geo-thermal plants which is also highly in line with the NH_3 plumes that were identified by another previous airplane campaign (Figure 4.1). For Mecca, located in the Coachella Valley at the north end of the Salton Sea, the minimum, median and maximum mole fraction of NH_3 is 10.06 ppb, 18.08 ppb and 250.13 ppb respectively. Elevated levels of NH_3 mole fractions were observed in association with cropland, particularly when fertilization and irrigation activities happened during the sampling period. Most of the higher NH_3 mole fractions were observed on the southeast side of Mecca including the 67th Ave, 68th Ave and National Ave. The highest NH_3 mole fraction (about 250 ppb) is observed on Hayes St. when fertilization activity occurred. In general, observed NH_3 mole fractions of both background levels and emission sources in Imperial Valley are much higher than Mecca. Additionally, major emitters in Imperial Valley are cattle feedlots and geo-thermal plants while major emitters in Mecca are from crop fertilization and irrigation.

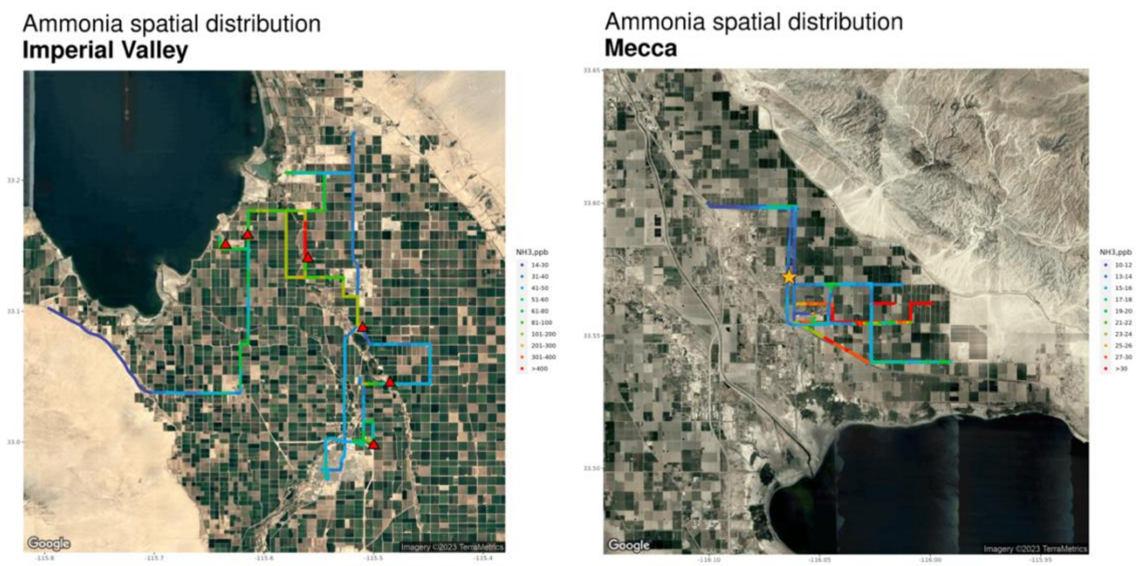

Figure 4.1 Spatial distribution of NH_3 measured in Imperial Valley (left) and Mecca (right). Red triangles marked on the left are potential high NH_3 emission locations identified by previous aircraft campaign; golden star marked on the right indicates the location of the SCAQMD Mecca site.

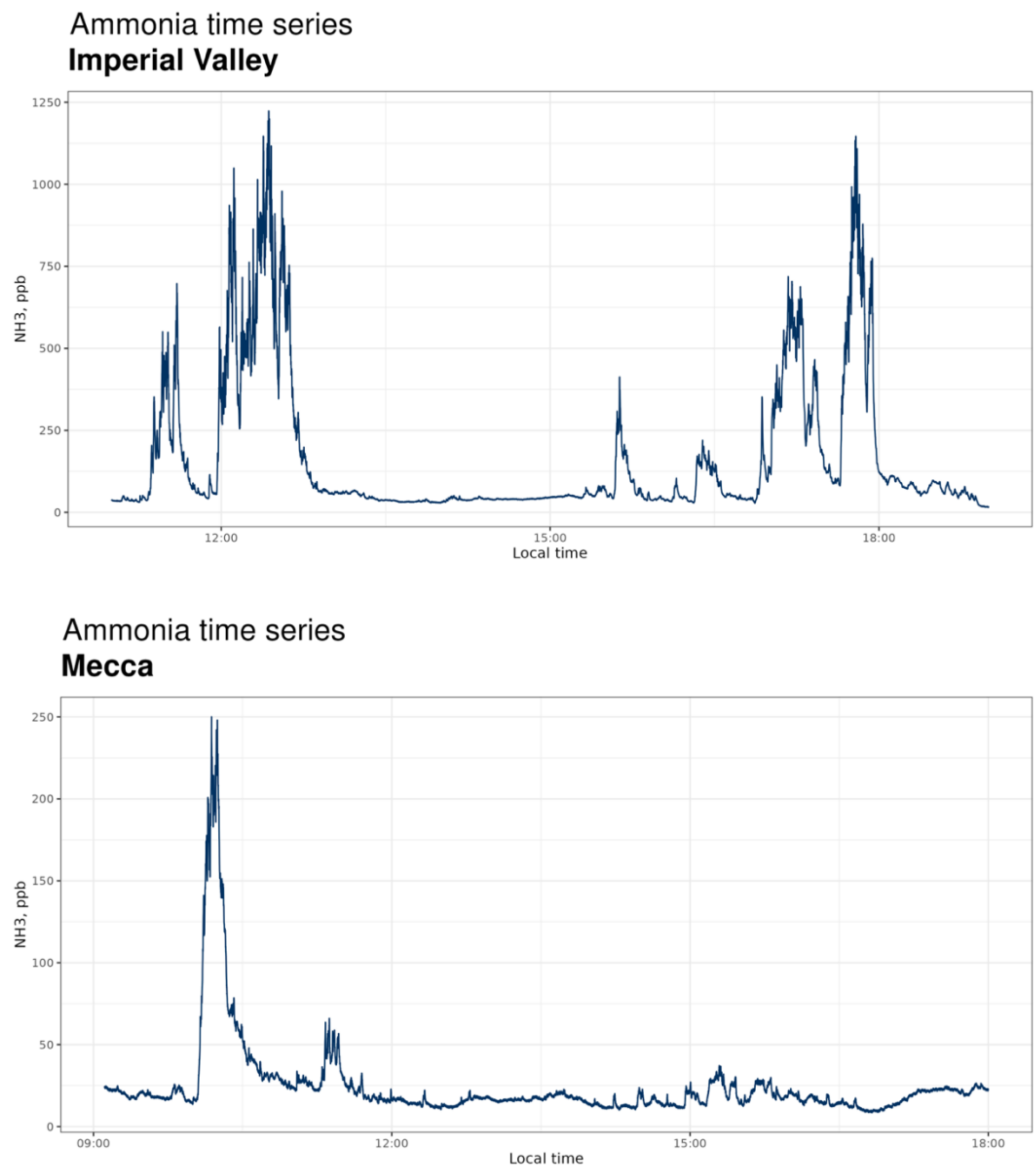

Figure 4.2 Time series plots of NH_3 measured in Imperial Valley (upper) and Mecca (lower)

4.3.2 Variability in spatial patterns over time

We used repeated measurements of some road sections and around some emitters for both Imperial Valley and Mecca to determine the variability in spatial patterns of NH_3 with time. On day 1 in Imperial Valley, we repeated measurements of a section of Brandt

Rd between W Sinclair Rd and W Eddins Rd at 11am (morning) and 17pm (afternoon) (Figure 4.3). In general, the morning section and afternoon section on Brandt Rd are very similar (Figure) with a mean NH_3 mole fraction of 565.23 ppb in the morning and 581.90 ppb in the afternoon (Table 4.1). On day 2 at Mecca, we observed higher NH_3 mole fraction in the morning section compared to afternoon section (Table 4.1). The biggest difference between morning and afternoon is observed around the Normas Nursery with the morning average mole fraction almost double of the average mole fraction of the afternoon. This higher morning NH_3 emission may be due to the fertilization activity in the nursery farm.

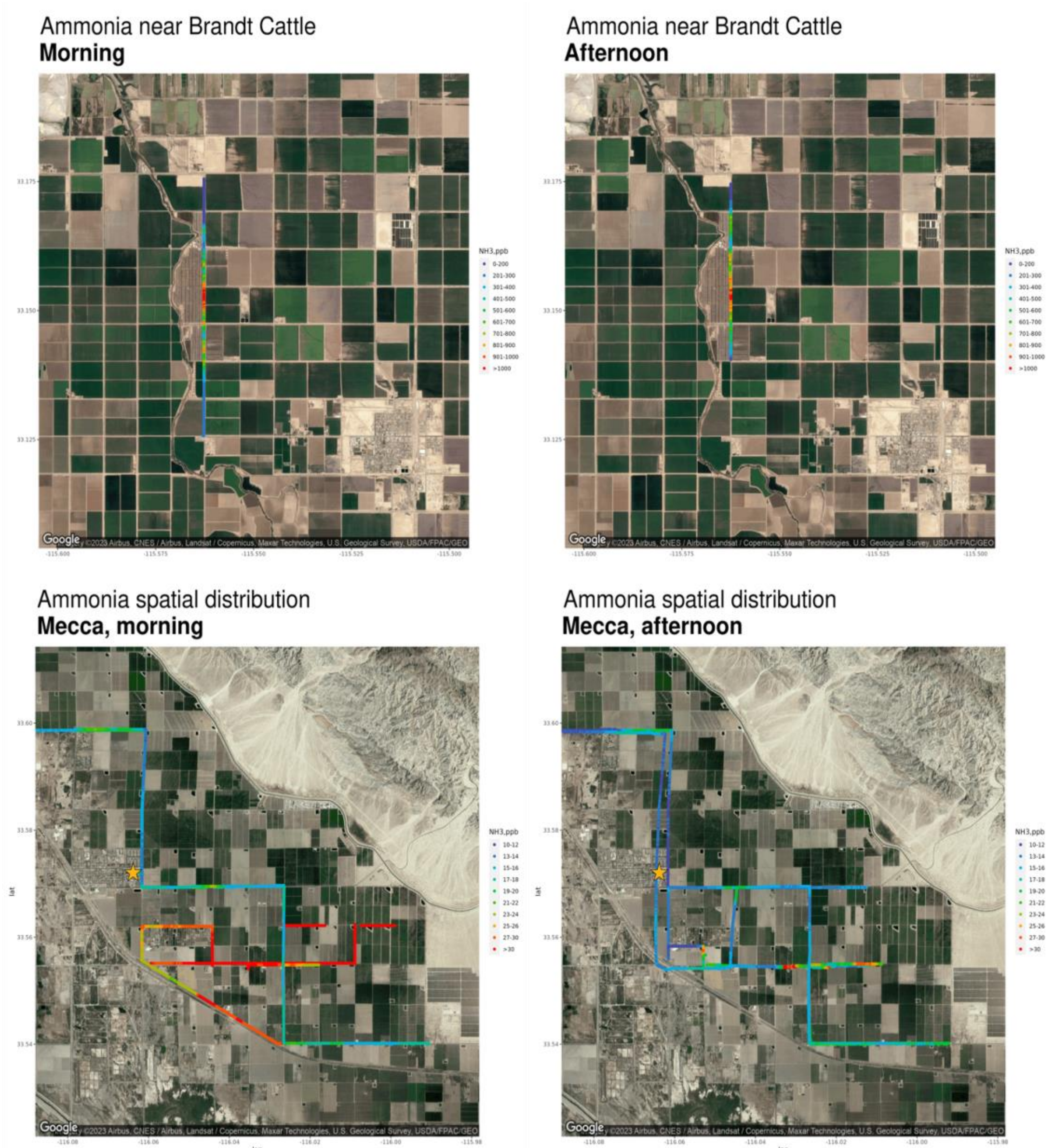

Figure 4.3 NH_3 emissions in the morning time (left) compared to afternoon time (right)

Table 4.1 Summary statistics of NH_3 mole fraction (ppb) measured around the Salton Sea region

	Min	Median	Mean	Max	SD
Imperial Valley					
Whole day on March 27th	15.54	60.14	166.80	1223.72	220.76
Brandt Rd, morning	54.04	552.54	565.23	1223.72	265.36
Brandt Rd, afternoon	102.60	603.7	581.90	1146.5	252.44
Mecca					
Whole day on March 28th	10.06	18.08	27.92	250.13	34.05
66th Ave, morning	13.62	17.55	18.88	25.81	3.31
66th Ave, afternoon	10.31	12.82	14.11	23.82	3.21
70th Ave, morning	14.04	18.51	19.65	32.61	3.67
70th Ave, afternoon	12.78	18.12	17.69	23.21	2.09
Normas Nursery, morning	21.64	26.62	26.80	33.78	2.99
Normas Nursery, afternoon	11.03	12.48	15.66	27.17	4.77

4.4 Discussion

We compared the spatial patterns of our observed NH_3 in Imperial Valley with spatial patterns observed by a previous aircraft campaign in this region. This aircraft campaign utilized a Thermal IR HyTES instrument deployed on NASA high-altitude ER-2 aircraft to measure NH_3 emissions over Imperial Valley in 2019. Major NH_3 sources identified by this aircraft campaign are marked as red triangles on Figure 4.1 (upper left). According to Figure 4.1, the elevated NH_3 emissions locations observed on road in Imperial Valley from the ground are highly in line with the potential NH_3 sources observed overhead by aircraft. Our measurements provide important information for the validation of high-altitude flight measurements from ground.

We also compared our measurements in Mecca with NH_3 emission patterns recorded by nearby ground observation station. The ground observation site that I used is the Mecca community air monitoring Station located at the Saul-Martinez Elementary School (Figure 4.1 upper right marked as golden star) and managed by South Coast Air Quality Management District (SCAQMD). Hourly NH_3 mole fractions from May 2022 to April 2023 at Mecca site were collected to estimate the spatial and temporal patterns of NH_3 in Mecca. Figure 4.4 shows the polar plot of hourly NH_3 mole fraction (left) and diurnal trend (right) of NH_3 observed at Mecca site. According to Figure 4.4, higher NH_3 mole fractions are usually observed at south east of the Mecca site which is consistent with on-road measurements also showing elevated NH_3 on the east side of Mecca. According to the NH_3 diurnal pattern, there is a clear increase of NH_3 mole fraction in the morning from around 5 am and arrives at the highest values around 9 am, then starts to decrease until around 3 pm, when the lowest values of the day are usually observed. This diurnal variation matches with the diurnal variation we observed with our measurements where we saw higher NH_3 mole fractions in the morning but lower mole fractions in the afternoon.

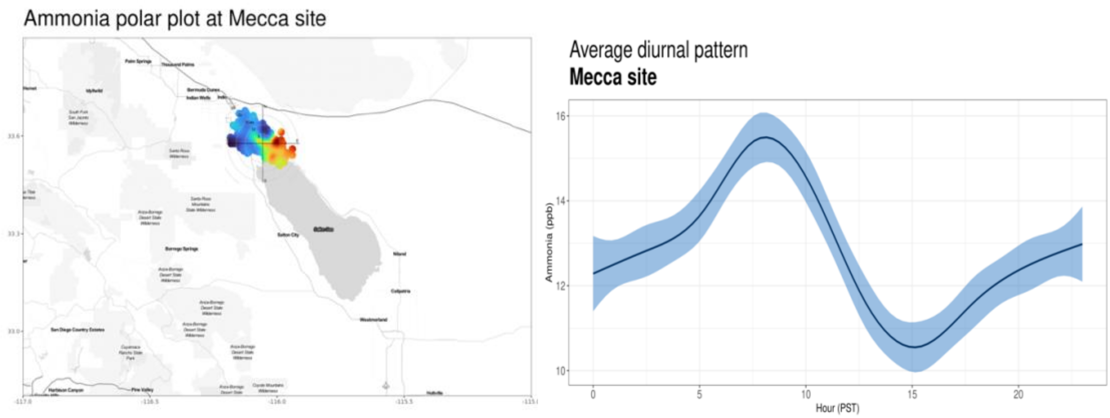

Figure 4.4 Hourly NH_3 mole fraction (ppb) measured by South Coast Air Quality Management District at Mecca site from May 2022 to April 2023. Left: NH_3 polar plot at Mecca site; right: NH_3 diurnal pattern at Mecca site

4.5 Summary

In this study, we used a mobile lab to measure on-road NH_3 mole fractions over the Salton Sea region. We observed elevated NH_3 mole fractions around cattle feedlots, geo-thermal plants as well as increased NH_3 mole fractions along with fertilization and irrigation activities. In general, higher NH_3 mole fractions were observed in Imperial Valley in the south end of the Salton Sea compared to Mecca in the north end of the Salton Sea. Observed NH_3 emissions show clear diurnal patterns in Mecca with higher emissions in the morning and lower emissions in the afternoon, but no such difference between morning and afternoon emissions were observed in Imperial Valley. Our measurements of the NH_3 mole fraction filled the knowledge gap of the spatial temporal NH_3 emission patterns in the Salton Sea region. Additionally, this work serves as a great validation for overhead flight and even satellite observation retrievals. Furthermore, this work provides valuable ground measurement data to improve the current NH_3 emission inventory in the Salton Sea region. For future study, a more comprehensive and high resolution modeling simulation as well as measurement from flights and satellites are needed to better understand NH_3 sources, emissions and impacts on surrounding air quality in this region.

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Chapter 5 Summary of this dissertation and recommendations for future works

5.1 summary of this dissertation

This dissertation characterizes and evaluates the air pollution, human health and environmental justice issues around the Salton Sea region.

In Chapter 2, I examined the relationship between air pollution exposure, health outcomes and socioeconomic status in the Coachella Valley. Two different health metrics - one measure based on a randomly sampled telephone survey and the other measure based on emergency room visits – were used to investigate the connections between air pollution exposure and health outcomes. The results suggested that more vulnerable communities are associated with higher levels of fine particulates, but lower levels of ozone. Significant positive correlation between emergency visits and air pollution exposure were observed but no such association is found when using surveyed health outcome data. I further developed a ratio, that is emergency visitation rate by survey rate, to examine the correlation between this ratio and socioeconomic status. The ratio of emergency visits versus survey rates shows a positive relationship with socioeconomic and demographic vulnerability, indicating that vulnerable communities are less likely to self-report diagnoses despite higher rates of respiratory or cardiovascular hospitalization. Lastly, when examine the socioeconomic and demographic distributions among all the respondents, I found most survey respondents exhibit higher socioeconomic status than that of their surrounding communities, which further suggests a strong survey bias toward high socioeconomic populations. These findings underscore the urgency of focusing on health issues, particularly in underserved communities within the Coachella Valley. To effectively address the current and future health needs, it is essential to collaborate and leverage existing community networks and local resources. Additionally, our research sheds light on the disparities in air pollution exposure, health outcomes, and population characteristics in the region. These insights provide valuable context for implementing vital pollution reduction initiatives to counter the growing environmental challenges.

In Chapter 3, I developed a model using observed coarse particulate matter ($PM_{2.5-10}$) mole fractions, modeled back trajectories, and land surface data to estimate individual source region types for particulates observed at long term monitoring sites in the Salton Sea region. Then designed a monthly time-stratified case crossover model to investigate and compare the acute health effects of dust arriving from different directions and estimated likely source surfaces on respiratory and cardiovascular hospitalizations. I further used a remote sensing chlorophyll-a data product to investigate the possible influence of periodic algal bloom on surrounding hospitalizations. We found increases in both respiratory and cardiovascular hospital admissions with 10 μg/m3 increase in Salton Sea dust. Even stronger associations were observed for Salton Sea dust with algae events. According to our findings, there is evidence indicating that exposure to dust, potentially originating from the Salton Sea or surrounding surfaces, is linked to higher rates of respiratory and cardiovascular hospitalizations, particularly during algal bloom events. Further research is needed to determine the underlying mechanisms responsible for these health impacts, as well as possible mitigation or intervention strategies

In Chapter 4, we employed a mobile laboratory to assess ammonia levels along roads in the vicinity of the Salton Sea area. Our findings revealed heightened ammonia discharges around cattle feed lots and geo-thermal plants. Moreover, we identified increased ammonia mole fractions linked to fertilization and irrigation operations. Generally, greater ammonia mole fractions were noted in the Imperial Valley, situated at the southern edge of the Salton Sea, in comparison to Mecca at the northern edge. This endeavor also offers substantial validation potential for aerial and satellite-based observations. Furthermore, it furnishes valuable ground-level measurement data to enhance the existing ammonia emission records in the Salton Sea vicinity. For forthcoming studies, a more comprehensive and finely detailed modeling simulation, coupled with measurements from aerial surveys and satellites, is imperative to gain a deeper comprehension of ammonia sources, emissions, and their impacts on the surrounding air quality within this region.

5.2 Recommendations and future work

In Chapter 2 where I studied the connections between air pollution exposure, health disparities and socioeconomic status, I found different correlations when utilized different health data. Therefore, I examined the ratio of the two different health metrics, that is, emergency visitation/survey at different socioeconomic levels. Results suggest that increased SES vulnerability shows both higher rates of emergency visits, and also lower rates of survey reporting of diagnosed symptoms. The disparity between these two methods may point to unique biases and data gaps of each method – more work is necessary to determine how to best optimize and integrate them together. Additionally, I found apparent demographic biases within the survey responses which opened the opportunity for resampling and correction.

Recommendations for future research:

(1) Try to include more respondents with lower socioeconomic status during survey sampling to avoid the demographic biases.

(2) Include more health-related questions to capture not only the diagnosed diseases but also people with potential symptoms, to better reflect the health impacts

(3) Use higher spatial and temporal resolution air pollution data to better reflect exposure levels of different communities.

In Chapter 3, I developed a novel model to separate ambient coarse particulate matter based on their source regions. I made a lot of assumptions to simplify the relationship between dust emissions and related weighting factors. Those simplified weighting factors improved model performance compared to no weighting factors, but still have limitations in terms of dust emission simulation. More work is need to be done in the future to improve the weighting process to better reflect dust/particle transport in the atmosphere. Also, when we define the Salton Sea category, we include both the Salton Sea water body and surrounding playa in this category. This makes it difficult to determine whether the observed health impact is caused by the lake spray aerosol from the water surface or windblown dust generated from the surrounding playa. Future studies need to examine the health effects of particles from playa and water surface separately. Lastly, due to data limitation, we are not able to validate the dust estimation model we developed in this study at the current stage. Future validation of this dust model can involve field measurement in the Salton Sea region.

Recommendations for future research:

(1) Validation of the dust estimation model of this study with filed measurements in the Salton Sea region.

(2) Improvements of the dust estimation model including: more weighting factors, include both “playa” and “Salton Sea water” surface types and filling missing surface types in the “Mexico” category are highly recommended

(3) Studies on the lake spray aerosols from the Salton Sea including the emissions, transport in the atmosphere, chemical and physical properties and eventual health effects are very essential.

(4) Research about the algae conditions and the fundamental mechanism of its air quality and health impacts is very important

In Chapter 4, I used a mobile lab and measured ammonia emissions in the Salton Sea region. The main purpose of this study is to provide ammonia emission data to improve emission inventory and for later air quality related studies in this region. The field campaign included in this study was conducted in March, therefore, it’s important for future studies to conduct more field measurement at different months/seasons to examine the time variation of ammonia emissions in this region. Additionally, it’s also very important to conduct high resolution model simulation to compare the observations with model simulation which has significant implications for model improvement.

Recommendations for future research:

(1) More measurements at different months/seasons

(2) Add high resolution model simulations to compared with the field measurements

(3) Studies on the impact of ammonia to local air quality and human health are also highly recommended.

Appendix A. Source-Specific Acute Health Effects of Ambient Dust Exposure in California's Salton Sea Region

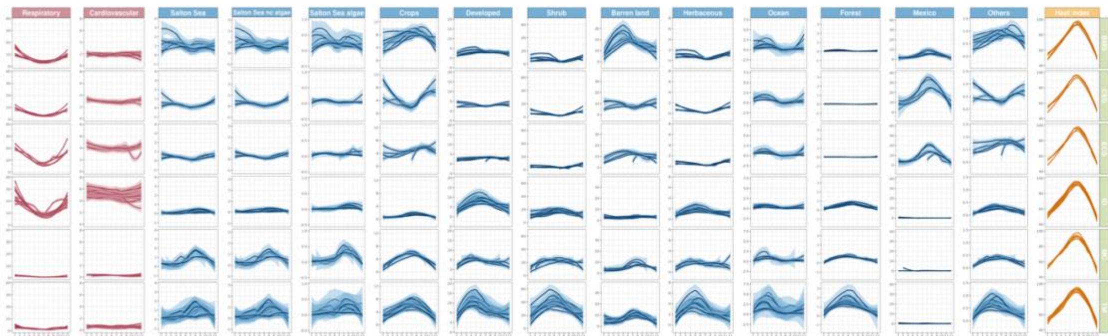

Figure A-1 Annual patterns of hospitalization, dust, and heat index by site

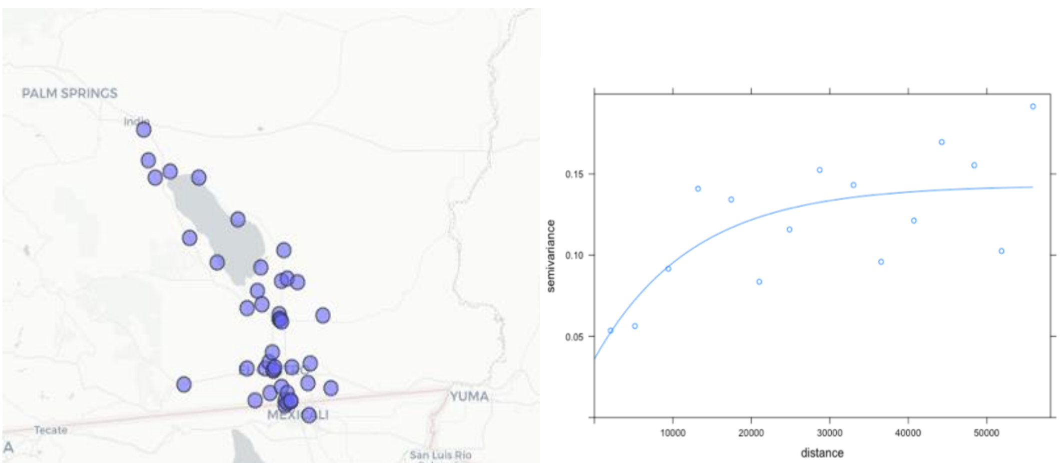

Figure A-2 Left: locations of low-cost sensors from IVAN network. Right: Variogram of PM_{10}. Each point is a lag of the variogram. The x-axis is the distance between two monitors and the y-axis is the calculated variogram values.

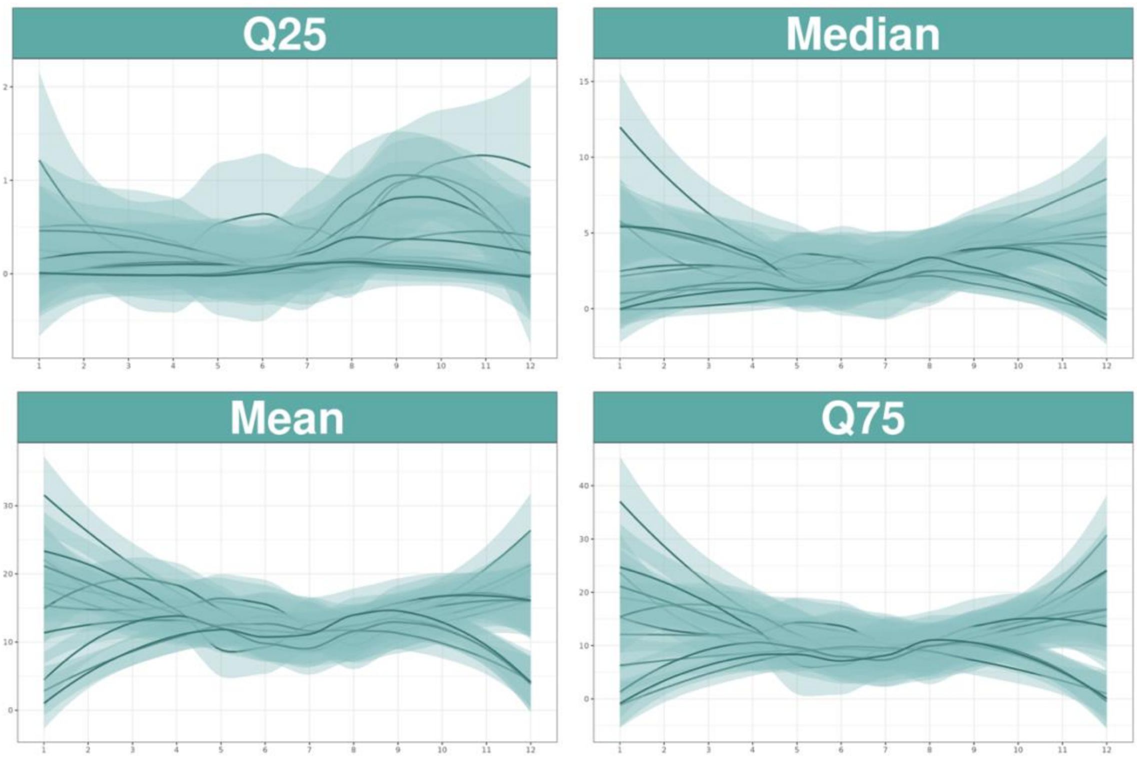

Figure A-3 Monthly variation of Salton Sea algae (chlor_a) at different percentile from 2008 to 2019

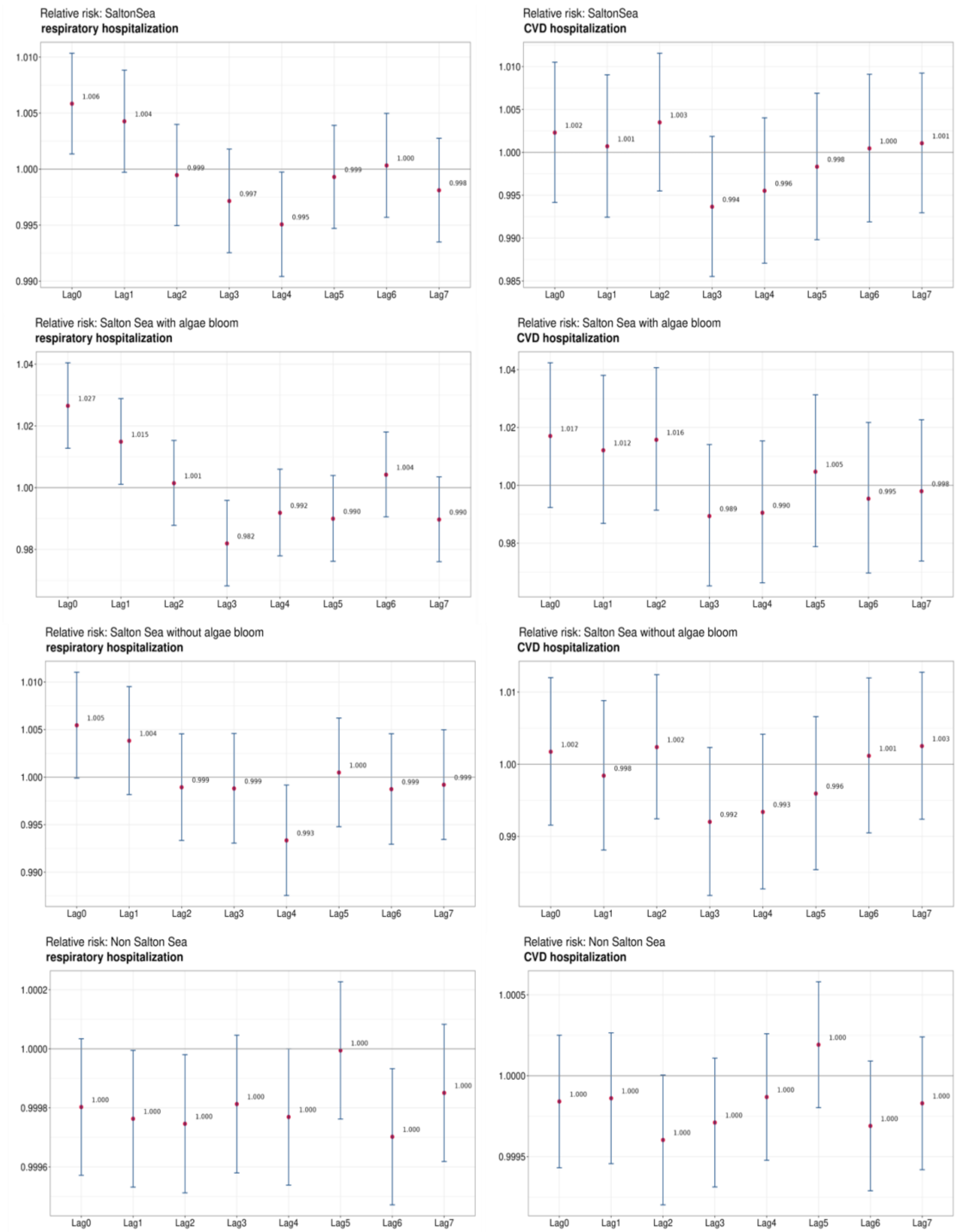

Figure A-4 Pooling relative risk of hospitalizations associated with a 10 μg/m3 short-term coarse PM ($PM_{2.5}$-10) and 10 degree of heat index increase and 95% confidence interval on different lag days from lag0 to lag7

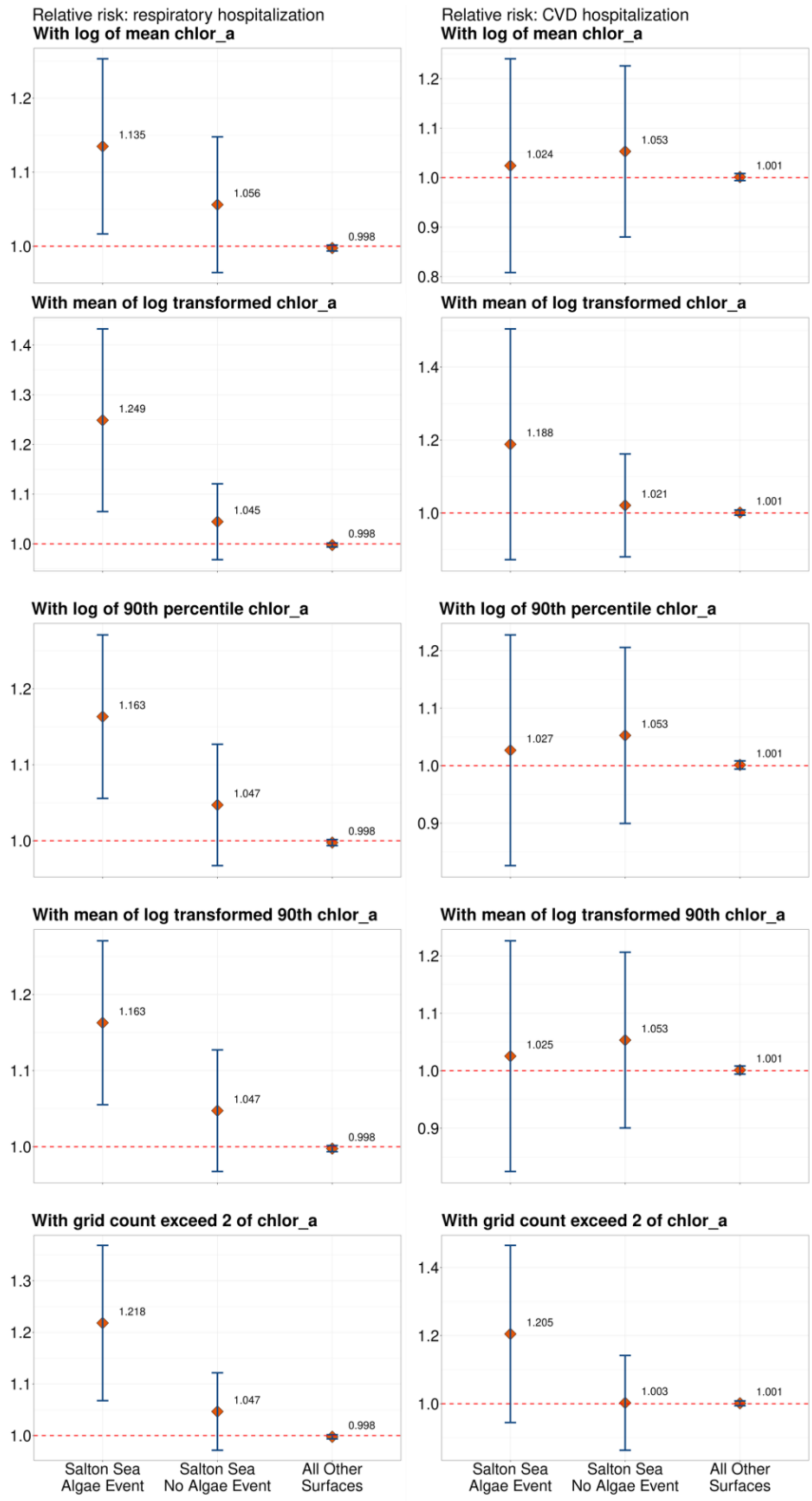

Figure A-5 Estimated RR with different chlor_a data

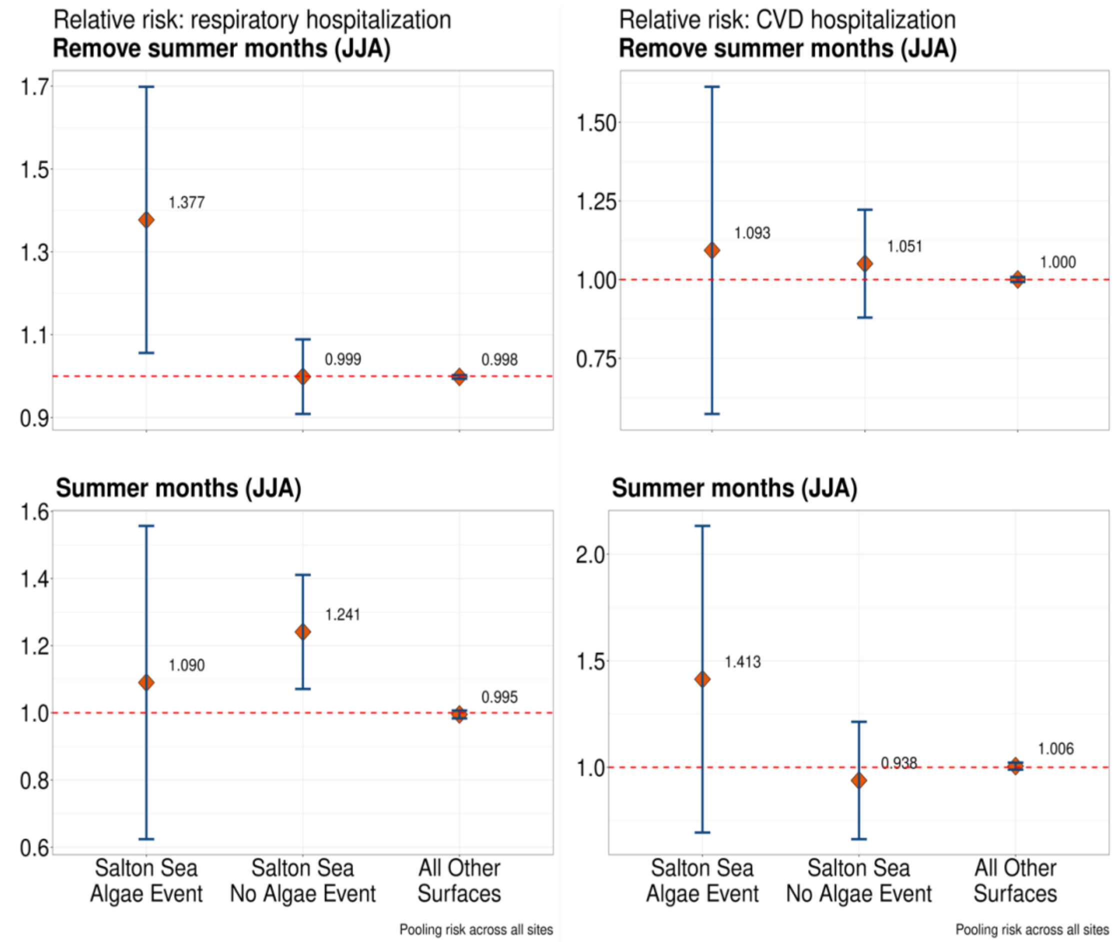

Figure A-6 Estimated RR with only summer months and remove summer months chlor_a data