The Impact of Drought and Airborne Pollutants on Pediatric Asthma in Imperial County, California, United States

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A Dissertation Presented to the Graduate Faculty
of the University of Virginia in Candidacy for the
Degree of Doctor of Philosophy

School of Nursing

University of Virginia
March 2020

There are two organisms whose processes of self-renewal have been subjected to human interference and control. One of these is man…The other is land.

– Aldo Leopold

Funding Sources

Funding for this dissertation was provided by the Southern Nursing Research Society Dissertation Grant and the University of Virginia Environmental Resilience Fellowship.

Acknowledgements

This dissertation was made possible by the outstanding members of my committee: Pamela DeGuzman, Robert Davis, Jessica Keim-Malpass, and Lawrence Band. Thank you for your wisdom, guidance, and commitment to this work and to my learning. A special thanks to Clay Ford and the countless data consultations that made this possible. A special acknowledgement is also owed to Stephan de Wekker for his assistance with data acquisition. And most of all to my family, for your constant love, support, and belief in me.

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Abstract

Background. The Imperial Valley region of Southeastern California has become one of the most productive agricultural regions in the state and has the highest rates of childhood asthma in California. The pediatric population is at a unique and increased risk of immediate and long-term negative health effects of asthma from air pollution. 2012-16 marked the worst drought in California, USA, in over a century. Imperial County's landlocked Salton Sea is almost entirely dependent on agricultural irrigation runoff, though the water level has diminished with drought conditions. Lakebed exposure may cause increased airborne particulate matter (PM), exacerbating asthma. Ongoing environmental changes increasingly require public health nurses to understand how environmental factors impact the health of vulnerable populations.

Methods. A proposed methodology is demonstrated for public health nurses to better understand and apply data from the HYSPLIT meteorological model to estimate the effect of airborne particulate matter from a single source. Emergency department admissions and diagnosis codes for asthma were obtained for children ages 2-18, alongside population data to create population-weighted ZIP code buffers. Trajectory analysis, dispersion modeling, and meteorological data were used to determine likely PM exposure days. Drought severity data were used to establish a relationship between drought, exposure, and admissions. Conditional Poisson regression was used to determine the risk of Salton Sea dust exposure to asthma and moderating effects of drought.

Results. There is a significant relationship between exposure from the Salton Sea and admissions on exposure days (ERR 18.70%, p=0.012, 95%CI=3.936–35.623). Moderation analysis for drought indicated no significant effect from two indicators (ERR

1.005%, 95%CI=-0.0.084–1.111, p=0.714; ERR 104.44%, 95%CI=8.44–285.426, p=0.316). This indicates the possibility of the Salton Sea's influence on pediatric asthma. The large confidence interval is notable, suggesting additional variables or pollutant sources, which is consistent with the study area, where several factors may contribute to air quality. Drought severity was not a significant moderator in the relationship between exposure and admissions, possibly due to the slow-response impact of drought that could not be captured.

Conclusions. Within public health and nursing, there is a need for broadening of skills beyond healthcare. Climate change-related environmental events are expected to disproportionately affect those with health disparities. Public health professionals are ideally positioned to assess environmental risk factors to vulnerable communities on a population scale.

CHAPTER 1: INTRODUCTION

The pediatric population is at a unique and increased risk of negative health effects from asthma. In children and adolescents with asthma, exposure to particulate matter in urban areas – in conjunction with ground heating, land degradation, and rising temperatures – has resulted in greater disease morbidity (Bayram et al., 2016; D'Amato & Cecchi, 2008; Ghio, Smith, & Madden, 2012), including increased emergency department admissions related to asthma and other cardiopulmonary diseases (Bayram et al., 2016). Compounding this exposure risk are the long-term health effects of poor air quality on lung development and function, deficits which have been shown to continue into adulthood (Gauderman et al., 2004, 2002). While there is a gap in current evidence that children in rural areas experience similar effects as their urban counterparts, there is evidence that the responsible compounds in urban pollutants also exist near agricultural areas (Gomez, Parker, Dosman, & McDuffie, 1992; O'Hara, Wiggs, Mamedov, Davidson, & Hubbard, 2000).

Not only are children at an increased lifetime risk for lung health and related diseases from systemic and local inflammation (Ghio et al., 2012), such as cardiovascular disease and cancer (Berman, Ebisu, Peng, Dominici, & Bell, 2017; Nelson et al., 2017; Powell, Krall, Wang, Bell, & Peng, 2015); children who are unable to participate in school or physical activities due to asthma are also at increased risk for secondary health and developmental consequences related to mental health, education, and obesity and related illnesses (Kohen, 2010; Oland, Booster, & Bender, 2017).

Future droughts and heatwaves are expected to rise in frequency and severity, disproportionately affecting those at highest risk for health disparities (Cook, Smerdon, Seager, & Cook, 2014; Costello et al., 2009; Griffin & Anchukaitis, 2014; O'Connor et al., 2014). California's most severe drought took place between 2012 and 2017,(Barreau et al., 2017; Griffin & Anchukaitis, 2014) of which four years were declared a government state of emergency. Droughts in similar areas have demonstrated the risk to human health (Gomez et al., 1992; Hefflin et al., 1991; Program, 1992; Smith, Aragão, Sabel, & Nakaya, 2014; Whish-Wilson, 2002; Wiggs et al., 2003), including the Aral Sea, considered one of history's most devastating environmental disasters (United Nations, 1992) and resulted in severe health consequences in the region, including widespread childhood respiratory illnesses (O'Hara et al., 2000; Whish-Wilson, 2002). While the health consequences specific to the California drought have not yet been evaluated, similar geographic and environmental features (Gomez et al., 1992; O'Hara et al., 2000; Wiggs et al., 2003) point to a potential future crisis in California that may resemble that which occurred in this and other locations.

Drought in Southern California may increase asthma-related morbidity in children. In 2011-2012, while the California drought was approaching peak severity (Griffin & Anchukaitis, 2014), Imperial County's rate of asthma-related emergency department admissions for children was among the highest in California and double that of the entire state (Arballo et al., 2014), putting nearly 52,000 children in the area at risk of health consequences from dry and dusty air (Bureau, 2015). During a drought or other environmental event, individuals in areas such as this inland county are disproportionately impacted due to financial burdens and health disparities: the 2013 median family income of Imperial County was over 25% below the median national family income, and 23.3% of families were below the federal poverty level, compared to 15.9% in the US (Arballo et al., 2014). As a result, families may be unable to afford to adhere to asthma guidelines or move away from the area in order to reduce children's exposure to poor air quality (Bureau, 2015).

Given the long-term respiratory complications in children as a result of air pollution, in addition to the area's substantial agricultural industry that has been affected by an abnormally dry climate, it is important to focus research efforts on the population that is most at risk from a lifespan and geographical perspective prior to the next environmental event. Within Imperial County is the Salton Sea, a landlocked geologic depression without natural feeding rivers. As a result of the arid climate, most water inflow originates from irrigation used for the 475,000 acres of farmland in Imperial Valley via two southern drainage streams within Imperial County and one northern stream, originating in Riverside County. Consequently, the water level of the Salton Sea is almost entirely dependent on agricultural irrigation runoff (Orlando, Smalling, & Kuivila, 2006), with 75% originating from agricultural drainage from Imperial Valley (Xu, Bui, Lamerdin, & Schlenk, 2016). Presently, the water level has been diminishing as a result of evaporation in the setting of decreased precipitation and river flow. Contamination with nitrogen compounds from farming, in addition to the increased area of exposed dry lake bed, have the potential to contribute to worsened asthma symptoms (Bloudoff-Indelicato, 2012).

Specific Aims

As one of the most medically underserved counties in California (Arballo et al., 2014), Imperial County provides an ideal context in which to research issues of environmental health and health equity. Thus, the specific aims were to (1) determine the role of geographic proximity to the Salton Sea as a risk factor for asthma exacerbations in Children living in Imperial County, and (2) evaluate drought severity as a moderator in the relationship between children's residence and their risk of asthma exacerbations within Imperial County.

Dissertation Organization

Chapter One of this dissertation serves as an introduction to this research and outlines the specific aims of the study. Chapter Two is the proposal initially used to describe the research plan for this dissertation. This research design and variable selection ultimately was altered based on the availability and quality of the secondary data obtained. Chapters Three, Four, and Five are publishable manuscripts generated from this study: Chapter Three discusses the background, history, and significance of the Salton Sea and the Imperial Valley region of Southern California, whose population share similar geologic and social characteristics to the Aral Sea Basin in Central Asia. Chapter Three also serves as the literature review for the current study, as there is a paucity of academic literature surrounding the study area in question. This manuscript has been submitted to *GeoHealth*, a journal whose scope concerns the emerging field of Planetary Health and GeoHealth. This field and framework are described in detail within this dissertation. Chapter Four provides a detailed description of the data collection procedures and methodologies for the environmental and spatial elements of this study and outlines a possible template for nursing and other health researchers to use when creating environmental exposure models. This manuscript will be submitted to *Public Health Nursing* as a template for other nurse scientists to utilize the current methodologies within other settings and study areas. Chapter Five provides a description of the health data used in this study and discusses its findings, including the consequences of the pediatric population's exposure to air pollution and drought severity as they relate to asthma-related morbidity. The manuscript from this chapter will also be submitted to *GeoHealth*. The dissertation is concluded in Chapter Six, and implications for nursing research are discussed.

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CHAPTER 2

Impact of Drought-Related Air Quality on Childhood & Adolescent Asthma in Imperial Valley, California: Southern Nursing Research Society Dissertation Proposal Funding Application

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University of Virginia School of Nursing

Submitted for funding from: Southern Nursing Research Society Dissertation Award

Abstract

Children are at a unique and increased risk from the health effects of asthma. In 2011-2012, as the California drought approached peak severity, Imperial County's rate of asthma-related childhood emergency department admissions was among the highest in California and double that of the state, putting nearly 52,000 children at risk of health consequences from polluted air. Future droughts are expected to rise in frequency and severity, disproportionately affecting those at highest risk of health disparities. Children are at an increased lifetime risk for related lung diseases, and those who are unable to participate in school or physical activities due to asthma are also at increased risk for secondary health and developmental consequences related to mental health, education, and obesity. The proposed retrospective study examines the consequences of poor air quality due to drought on asthma in children in Imperial Valley. Using a statewide health database, in conjunction with publicly available air quality, weather, land use, and drought severity data, multiple and spatial regression models will be used to evaluate the role of geographic proximity to pollutant sources in Imperial County as a risk factor for asthma exacerbations in children and to evaluate drought severity as a moderator in this relationship.

Specific Aims

The pediatric population is at a unique and increased risk from the health effects of asthma. In children and adolescents with asthma, exposure to particulate matter (PM) and volatile organic compounds (VOCs) in urban areas – in conjunction with ground heating, land degradation, and rising temperatures – has resulted in greater disease morbidity (Bayram et al., 2016; D'Amato & Cecchi, 2008; Ghio, Smith, & Madden, 2012), including increased ED admissions related to asthma and other cardiopulmonary diseases (Bayram et al., 2016). Compounding this exposure risk are the long-term health effects of poor air quality on lung development and function, deficits which have been shown to continue into adulthood (Gauderman et al., 2004, 2002). While there is a gap in current evidence that children in rural areas experience similar effects as their urban counterparts, there is evidence that the responsible compounds in urban pollutants also exist near agricultural areas (Gomez, Parker, Dosman, & McDuffie, 1992; O'Hara, Wiggs, Mamedov, Davidson, & Hubbard, 2000). Not only are children at an increased lifetime risk for lung health and related diseases; children who are unable to participate in school or physical activities due to asthma are also at increased risk for secondary health and developmental consequences related to mental health, education, obesity, and related illnesses (Kohen, 2010; Oland, Booster, & Bender, 2017). As airborne PM has the ability to cause systemic as well as local inflammation (Ghio et al., 2012), findings from this study may have implications for other health issues, such as cardiovascular disease (Berman, Ebisu, Peng, Dominici, & Bell, 2017; Powell, Krall, Wang, Bell, & Peng, 2015), and cancers later in life (Nelson et al., 2017).

Drought in Southern California may increase asthma-related morbidity in

children. In 2011-2012, while the California drought was approaching peak severity (Griffin & Anchukaitis, 2014), Imperial County's rate of asthma-related emergency department (ED) admissions for children was among the highest in California and double that of the entire state (Arballo et al., 2014), putting nearly 52,000 children in the area at risk of health consequences from dry and dusty air (Bureau, 2015). During a drought or other environmental event, individuals in areas such as this inland county are disproportionately impacted due to financial burdens and health disparities. The 2013 median family income of Imperial County was over 25% below the median national family income, and 23.3% of families were below the federal poverty level, compared to 15.9% in the US (Arballo et al., 2014). As a result, families may be unable to adhere to asthma guidelines or move away from the area to reduce exposure to poor air quality (United States Census Bureau, 2015). Given the long-term respiratory complications in children as a result of air pollution, in addition to the area's substantial agricultural industry that has been affected by an abnormally dry climate, it is important to focus research efforts on the population that is most at risk from a lifespan and geographical perspective prior to the next environmental event. Current understanding of poor air quality and lung health in both children and adults has concentrated mainly on urban emissions. However, urban studies point to similar health risks in the mostly agricultural Imperial Valley.

Future droughts and heatwaves are expected to rise in frequency and severity, disproportionately affecting those at highest risk of health disparities (Cook, Smerdon, Seager, & Cook, 2014; Costello et al., 2009; Griffin & Anchukaitis, 2014; O'Connor et al., 2014). Reduced precipitation and ground heating in an already-arid climate may cause an increase in airborne PM and VOCs and adversely affect lung health (Christian-Smith, Levy, & Gleick, 2015; D'Amato & Cecchi, 2008), particularly in children, who are more sensitive to their long-term effects (Gauderman et al., 2004, 2002). Droughts in similar areas have demonstrated the risk to human health (Gomez et al., 1992; Hefflin et al., 1991; Program, 1992; Smith, Aragão, Sabel, & Nakaya, 2014; Whish-Wilson, 2002; Wiggs et al., 2003), including the Aral Sea, considered one of history's most devastating environmental disasters (United Nations, 1992) and resulted in severe health consequences in the region, including widespread childhood respiratory illnesses (O'Hara et al., 2000; Whish-Wilson, 2002). While the health consequences specific to the California drought have not yet been evaluated, similar geographic and environmental features (Gomez et al., 1992; O'Hara et al., 2000; Wiggs et al., 2003) point to a potential future crisis in California that may resemble that which occurred in this and other locations.

The proposed retrospective study examines the consequences of poor air quality due to drought on asthma in children in Imperial Valley. Using a statewide health database, in conjunction with publicly available air quality, weather, land use, and drought severity data, the impact of regional drought conditions as they relate to asthma-related morbidity will be evaluated. The long-term goal of this research is focused on improving the lives of children and adolescents in a medically underserved region (Arballo et al., 2014). No other studies have elucidated the relationship between drought, air pollutants, and asthma exacerbation in this particularly vulnerable population. The Specific Aims are: (1) to determine the role of geographic proximity to agricultural activity in the Imperial Valley region of Southeastern California or the Salton Sea as a risk factor for asthma exacerbations in children living in or proximal to the Imperial Valley, after controlling for airborne pollutants and other geographic and environmental variables of land use and wind velocity (hypothesis: children living in proximity to agricultural activity in the Imperial Valley and the Salton Sea are at increased risk for asthma exacerbations); and (2) to evaluate drought severity as a moderator in the relationship between children's residence and their risk of asthma exacerbations within and proximal to Imperial Valley (hypothesis: the rate of ED visits as they relate to location and asthma in children is higher during more severe drought periods).

Background and Significance

The Imperial Valley region, contained within Southern California's Imperial County, includes the cities of El Centro and Calexico in addition to smaller, agriculturally-based towns. Imperial Valley's air quality is considered to be marginal with respect to ozone (O_3) levels (O'Connor et al., 2014), a factor previously found to be correlated with asthma-related hospital visits in urban areas (Moore et al., 2008). Additionally, the impact of anthropogenic climate change and drought on farmers in the Central Valley (north of Imperial Valley) has been mentioned in government reports (O'Connor et al., 2014), and a link has been suggested between asthma and agricultural chemicals such as pesticides (Nordgren & Bailey, 2016). However, there has yet to be any direct investigation into the impact of drought on respiratory disease in agricultural areas.

Imperial Valley has become one of the most productive agricultural regions in California despite its naturally arid climate (Orlando, Smalling, & Kuivila, 2006). The Salton Sea, located centrally within the Imperial Valley, is a landlocked geologic depression without natural drainage or feeding. As a result of the arid climate with little precipitation, most water inflow originates from irrigation for the 475,000 acres of farmland in Imperial Valley via two southern feeding rivers within Imperial County and one northern river, originating in Riverside County. Consequently, the water level of the Salton Sea is almost entirely dependent on agricultural irrigation (Orlando et al., 2006). Presently, the water level has been diminishing as a result of evaporation in the setting of decreased precipitation and river flow. Contamination with nitrogen compounds from farming, along with ground-level O_3 from high temperatures, have the potential to contribute to worsened asthma symptoms (Bloudoff-Indelicato, 2012). To date, the principal investigator has found there to be differences in coarse particulate matter measurements across the county during the proposed study years, indicating a geographic component of air quality differences and the potential for children near rural farmland to be more susceptible to asthma and lung disease (Doede & Davis, 2018).

Droughts in this area, while part of a naturally occurring cycle, are worsened by inefficient and unsustainable water use in the Imperial Valley by agricultural activities. In dry and severely dry periods, therefore, the excessive use of water for irrigation places additional stresses on the environment. <u>The broad goal of this present research is to investigate the extent to which drought conditions affect lung health in children in the area, especially those living near agricultural areas that may offer additional environmental risks.</u> Further analysis in the future may reveal that these lung health issues may be improved if irrigation water from the Colorado River is used more efficiently, thereby reducing the amount of dust that is kicked up from fallow farmland and the evaporated Salton Sea lake bed.

Although a recent study describing drought conditions across the US designated this region as lower risk for health complications during drought periods compared to other US regions, it is notable that the study only investigated the drought's impact on elderly adults through the analysis of Medicare data. In addition, this study provides only county-level estimates (Berman et al., 2017), while the proposed study offers a more granular view of health events within Imperial County. New research into the impacts of poor respiratory health in drought areas will provide a perspective on underrepresented environmental challenges at the local and regional levels. The future of health will require a more robust integration with environmental science research and policy, as drought is one of the most expensive natural events from a number of economic and public health vantage points (Cook et al., 2014). This must include, but certainly will not be limited to, the implications of population health as a result of the most recent California drought. Finally, this study has the potential to have broader implications for water policy, drought mitigation strategies, and health improvement for this and other populations.

Significance to the Pediatric Population

The health implications of the current environmental shift are vast – including but not limited to mental health, education, obesity, and related illnesses due to the inability to engage in physical activity – as a potential result of airborne pollutants (Kohen, 2010; Oland et al., 2017). In addition, in light of evidence that airborne PM has the ability to cause systemic as well as local inflammation (Ghio et al., 2012), findings from this study may have implications for other health issues, such as cardiovascular disease (Berman et al., 2017; Powell et al., 2015), and cancers, including lung cancers (Nelson et al., 2017). Although evidence of enduring impacts on childhood lung health into adulthood is isolated to urban areas, these research findings are an indication of the impacts that can be seen in all regions based on the similarities of air pollutants in both farmlands and cities. The deleterious effects of air pollution on lung health are more pronounced in children and adolescents with lasting health consequences: an eight-year longitudinal cohort study of children in urban areas of California found that poor air quality and the presence of aerosolized PM has long-term detrimental effects on pulmonary growth, function, and development during childhood and into early adulthood (Gauderman et al., 2004, 2002). Given the evidence of long-term respiratory complications in children and adolescents as a result of air pollution, in addition to the area's substantial agricultural industry that has been affected by an abnormally dry climate, it is important to focus research efforts on the population that is most at risk from a lifespan and geographical perspective prior to the next environmental event.

Research Design

This study will be based exclusively on secondary data analysis, and the data used will be exclusive to environmental, air quality, and patient information within the geographical boundaries of Imperial Valley, California, with the exception of those who must travel outside the county for medical attention but reside within Imperial County. Records will be requested from an existing database of California hospital patients in the ten years between 1 January, 2006, and 31 December, 2016. Public data related to drought and from air quality monitoring stations (AQMS) located within the geographic area of Imperial Valley, including the region's main city of El Centro, will also be obtained.

Office of Statewide Health Planning and Development (OSHPD)

In addition to publicly available air quality and drought data, individual-level information from this statewide hospital database will provide information pertaining to the healthcare utilization aspect of the study. OSHPD data will be used for each patient attending an ED from Imperial Valley to analyze the use of healthcare services as the result of childhood and adolescent asthma, prevalence of asthma, and basic demographic information of residents. OSHPD collects annual data from all registered hospitals and health centers in California regarding patient information, healthcare utilization, and diagnosis codes with the purpose of documenting the status of health and healthcare services use across the state.

Facility- and patient-level variables were selected for inclusion based on the study aims and the OSHPD data dictionary (OSHPD, 2017), ICD-9 codes are used for entries before the fourth quarter of 2015, after which point ICD-10 codes are used and will be converted to ICD-9 format ("2018-ICD-10-CM-and-GEMs," 2017). In addition to diagnosis codes for asthma, other diagnosis codes related to acute respiratory disease will be included to account for other known complications of airborne pollutants (Hefflin et al., 1991; Szyszkowicz, Kousha, Castner, & Dales, 2018). It is possible to obtain location data for patients visiting the ED at the ZIP code level. There are only two ED locations within Imperial County, both located centrally in the area's most populous city. However, in critical situations, children may be airlifted to the closest pediatric level-one trauma center, in San Diego. For this reason, data collection from EDs in Southern California will extend here and other hospitals bordering the county, relying on the patient ZIP code information to determine the patient's place of residence. Data related to children and adolescents, ages 2-18, will be collected from OSHPD data, as the difficulty with properly diagnosing asthma before two years old has been established (Wright, 2002).

United States Census

The population centroid of each ZIP code will be located and used in order to determine the central location of each ZIP code in accordance with population concentrations. This is due to the fact that some ZIP codes contain large areas that are sparsely populated. 2010 Census Block and ZIP code population data and geographic boundaries will be used for this calculation. Centroids will then be determined using the Median Center function in ArcMap in order to reduce the influence of outliers (a complication from calculating the mean center). As the Salton Sea is one hypothesized source of dust related to lung health, the Euclidean distance will be measured from the established population-weighted centroid of each ZIP code to the nearest point on the Salton Sea boundary.

United States Drought Monitor (USDM)

Drought severity data will be used to establish a relationship between drought, air quality, and the effect of these factors on lung health and healthcare utilization. The USDM is widely used and accepted within the field of environmental science as well as public health (Berman et al., 2017). The USDM is an amalgam of several established drought indices, each of which incorporate various drought indications (National Drought Mitigation Center, 2017b). The drought severity is calculated as weighted sum of the percent of an area that is in or worse than one of five categories, denoted as D0 (abnormally dry) to D4 (exceptional drought [National Drought Mitigation Center, 2017a]).

California Air Resources Board (ARB)

The ARB dataset offers public data for weather and air pollutants that will be assessed in this study. AQMS data is available in daily (O_3) or six-day (PM_{10}, $PM_{2.5}$) intervals from five AQMSs in Imperial Valley (Air Resources Board, 2015). AQMS data will be correlated with health and drought severity data. Air quality data will be taken from the AQMS closest to the population-weighted centroid of the patient ZIP codes. Wind speed and direction will be assessed to determine the extent to which dust from the Salton Sea may contribute to airborne pollutants. Hourly wind data is also available from the California ARB. These stations are the same AQMS that will be used to collect air quality data.

To address the potential impact of dust blown from the Salton Sea as well as other dust sources, the predominant wind direction will be taken for each data collection period from daily records. Analysis of wind speed and direction data will be performed following methods by Bertazzon, Johnson, Eccles, & Kaplan (2015). The wind rose will be divided at 45°, 135°, 225°, and 315° so that the four quadrants will be centered on each cardinal direction (i.e., northern winds will be characterized by those falling between 315° and 45°). Recorded hourly wind speeds will be averaged over each sampling period.

Normalized-Difference Vegetation Index (NDVI)

The NDVI will be used to analyze land use and vegetative cover. Vegetative ground cover in agricultural areas will be measured with relative spectral response from remote sensing data to determine the proximity to active or fallow farmland and, thus, the likelihood of airborne PM within an area and time period (United States Geological Survey, n.d.). NDVI data (MOD13Q1.006 dataset) will be obtained from the NASA/USGS EarthExplorer interface (United States Geological Survey, 2018). This predictor variable for dust sources will be generated with wind rose data. Circular buffers of specified distance will be drawn around each AQMS location and will take into account the total number of potential dust sources (i.e. agricultural fields derived from land use data), and inclusion of wind data will take into account the potential dust sources that fall within (upwind of) the prevailing wind direction quadrant.

Study Area and Population Characteristics

As the Imperial Valley region of Southern California has a primarily Hispanic population, research conducted in this setting is also extremely valuable from the perspective of examining the health and quality of life of children and adolescents of marginalized populations. Individuals who identify as Hispanic or Latino make up the country's largest minority group, and the disproportionate number of childhood asthma cases in this population has contributed to health disparities, including a 21% increase in hospital charges due to asthma compared to any other ethnic group (Carter-Pokras, Zambrana, Poppell, Logie, & Guerrero-Preston, 2007). However, due to established inconsistencies in self-reported race and ethnicity data and the known ethnic and genetic complexities of those who identify as Hispanic or Latino (Salari & Burchard, 2007), the decision has been made to omit the variable of race/ethnicity from data collection here. Instead, variables associated with area-level socio-economic characteristics will be used, as these characteristics also have the ability to predict health outcomes.

Data Analysis

Units of Measurement and Sampling Period

The units of measurement for each variable to be used in this study are presented in the table below. While the unit of analysis for ED admissions may be adjusted once information from the OSHPD protected data set is available, the units of measurement for the remaining (environmental) variables has been pre-determined based on the means of prior data collection. While most airborne pollutants and wind velocity data are available on an hourly or daily basis, coarse and fine particulate matter from the five air quality monitoring stations in the study area are only collected every six days. In addition, the examination of proximal sources of dust will rely on analysis of the NDVI. NDVI data is collected via satellite images, and as such, data is only available for the study area every 16 days. Finally, the use of drought data, which will be added to the final model, is reported every seven days. Therefore, the period of 48 days has been chosen as the sampling period based on these variables, as this is the least common multiple for each data set collection period. Using this number will help to avoid errors in estimation that may arise from data interpolation that would be necessary for the use of smaller time increments. As the study time period covers ten years, it is believed that there will be a sufficient number of data points for analysis.

Sample Size Justification

While the available sample size is not known for the OSHPD data set, it is expected that ED visits are greater in number than the sample size needed based on the region's population and asthma prevalence rate (Arballo et al., 2014). This study is interested in prevalence and risk factors across a wide area, and as such, all available data matching inclusion criteria (i.e., appropriate age, location of residence, and diagnosis codes) will be used in this analysis. Because exact sample sizes will not be available until after approval of the data request, a post-hoc power analysis will be performed to assure that the statistical inferences are supported. In the highly unlikely event that statistical power is not reached, a request will be made to expand the data to additional years.

Regression Models

The relationship between geographic location, exposure to particulate matter and chemical species, and rate of ED visits for asthma exacerbation will be examined using diagnosis codes provided by OSHPD data. Due to small populations in some areas, this will be measured as the rate of ED visits in children as compared to the childhood population of each ZIP code as estimated by the US Census. Following Berman et al.(2017), air quality data will be taken from the AQMS closest to the population-weighted centroid of the patient ZIP codes, as some ZIP codes contain large areas that are sparsely populated. Due to the limited geographical scope of this study, USDM estimates of drought severity will be equal for all ZIP code observations. NDVI measurements will also be recorded using a distance buffer from this population-weighted centroid, as population density in the area associated with certain land use types (e.g., desert areas are more sparsely populated compared to urban or agricultural areas). This will help to control for an erroneous effect of distant desert sands on the outskirts of a ZIP code area.

Therefore, the regression equation to be used for this aim will take into account the environmental predictors of air pollution readings (NO_x, PM_{10}, O_3), distance from the Salton Sea, NDVI within the specified radius, wind direction (categorical, based on assigned cardinal direction), and wind speed. Air pollutant impacts on ED visits will be assessed alone and as interactive terms to determine if there is a dominant pollutant in each geographic area responsible for asthma exacerbation. In order to assess the impact of proximal dust from agriculture (as measured by NDVI) alone versus proximity to the Salton Sea alone, ED visits will be measured controlling for NDVI within the wind quadrant associated with the ZIP code centroid's relationship to the Salton Sea.

The impact of drought severity will also be assessed. As drought conditions are applicable over large areas, a single drought severity category will be applicable to the entire study area at each sampling period. The variable of drought severity will be added into the regression analysis above in order to examine its moderating effects on ED visits for childhood asthma.

Study Limitations

A known obstacle in calculating community-level characteristics such as environmental exposures or individual health is the obligation to use area-level estimations as proxies for the individual while controlling for known information about the patient or family (Barry & Breen, 2005). The ecological model also introduces the possibility that confounding variables, known or unknown, may exist in the surrounding environment. This study will only analyze air quality data as collected by outdoor stations. Therefore, effects of indoor air pollution, with the exception of household tobacco smoke in certain models, will not be taken into account because the available data sets lack this information. Nevertheless, the nature of this investigation as an exploratory study will serve to inform more specific, patient-level, prospective research. Such investigations will therefore have the ability to ask more pointed questions about the nature of interactions between the environment and lung health.

Protection of Human Subjects

In conjunction with the approval from the University of Virginia Institutional Review Board, the study protocol will be reviewed and approved by the Committee for the Protection of Human Subjects within the California Health and Human Services (HHS) Agency for the purpose of obtaining protected data from a secondary database. At this time, the University of Virginia IRB has granted this study exempt status, pending confirmation from the California HHS IRB. As the data obtained will be de-identified upon receipt, use of this data is predicted to qualify as minimal risk to participants and exempt from full board review.

Time Frame/Schedule of Activities

As this study exclusively involves secondary data analysis, a timeline of data collection will not be a major factor. However, the approval of human subjects protection organizations outside of the PI's home university places a time delay on the acquisition of protected data. In the interest of time, therefore, the analysis of data will be broken into two phases based on the level of data protection. The projected timeline for the study in its entirety includes IRB approval from the University of Virginia and California Health and Human Services, data acquisition, analysis, and dissemination. In the context of the timeline to be examined through secondary data, the focus will be on data collected between the years 2006 and 2016. During this time, the State of California transitioned from what is considered to be normal hydrological and meteorological conditions to a period of severe drought. The years 2012-2017 had the most severe drought in over a century. By collecting data both before and during this time period, it will be possible to compare health effects not only during levels of drought severity, but also during normal or relatively normal time periods.

Calendar Year	**2018**			**2019**		
IRB submission & approval						
Acquisition & analysis of public data						
Request & receipt of protected data						
Analysis of protected data						
Data analysis & dissemination						

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CHAPTER 3

The Disappearing Lake: An Historical Analysis of Drought and the Salton Sea in the Context of the Planetary Health/GeoHealth Framework

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Key Points

- Comparisons between the Imperial Valley and the Aral Sea environmental disaster may be drawn to identify the potential human health hazards.
- In the Imperial Valley, financial and health disparities may make exposure to airborne toxic particles near the diminishing Salton Sea an unavoidable consequence of the inability to move away from the area.
- A Planetary Health/GeoHealth perspective is needed to evaluate the region in a context of human health and sustainable resource allocation.

Abstract

The Imperial Valley region of Southeastern California has become one of the most productive agricultural regions in the state. It also has the highest rates of childhood asthma in California. Lack of precipitation in the Imperial Valley has caused the water level of the Salton Sea to recede to a record low since its formation in the early 1900s. Previous studies of wind and dust deposition conducted in other regions have shown how reduced precipitation, ground heating, and the diminishing water level in an arid climate pose a risk of exposing previously-sequestered toxic chemicals to open air, adversely affecting lung health. The purpose of this study is to draw historical parallels between the Aral Sea and Salton Sea in the context of geomorphology, ecology, human health, economics, and human migration, to inform an assessment of environmentally related health impacts of those living in the Imperial Valley region. Future droughts and heatwaves are expected to rise in frequency and severity, and may disproportionately affecting those impacted by financial and health disparities. Future research must include the implications of population health in the context of Planetary Health and GeoHealth as a result of the most recent drought and the receding water levels of the Salton Sea.

Introduction

In 2011 and 2012, while the California drought was approaching peak severity, Imperial County's rate of asthma-related emergency department admissions for children was among the highest in California and double that of the entire state (Arballo et al., 2014), putting nearly 52,000 children in the area at risk of health consequences from dry and dusty air (United States Census, 2015). Human activity and the construction of elaborate infrastructure for irrigation has led to the Imperial Valley region (contained within Southeastern California's Imperial County) to become one of the most productive agricultural regions in California despite its naturally arid climate. The water level of the Salton Sea, located centrally within Imperial County (Figure 1), has been diminishing, in part as a result of evaporation, and decreased precipitation and river flow. California's most severe drought took place between the years 2012 and 2017 (Barreau et al., 2017; Griffin & Anchukaitis, 2014), including four of those years under a government-declared state of emergency.

Contamination of the Salton Sea with fertilizer and pesticide compounds from agriculture have the potential to contribute to worsened asthma symptoms (Bloudoff-Indelicato, 2012) and may already be placing children at risk for diminished lung health. In an arid climate, a reduction in precipitation and associated ground heating (resulting from the diminishing water level and exposed lake bed) can increase airborne particulate matter, which is known to adversely affect lung health (Christian-Smith, Levy, & Gleick, 2015; D'Amato & Cecchi, 2008). Airborne pollutants impact long-term lung health of children and adolescents who live in areas with high pollution rates and are more susceptible due to increased time spent outdoors (Gauderman et al., 2004, 2002). Today, Imperial County has the highest rates of asthma in children compared with the entire state of California. Future droughts and heatwaves are expected to rise in frequency and severity. Climate events often disproportionately affect those already impacted by financial and health disparities, and may be more severe for individuals living in lower-income communities with fewer resources to avoid or respond to environmental changes [Cook, Smerdon, Seager, & Cook, 2014; Costello et al., 2009; Griffin & Anchukaitis, 2014; O'Connor et al., 2014]).

Figure 1. Satellite imagery of the Imperial Valley within California's Imperial County and nearby Salton Sea.

Health-related consequences of the California drought in this region specifically is understudied. Comparing the region to health impacts of droughts in similar, highly-studied regions allows an assessment of the potential health impacts of drought in

Imperial County today. A number of notable consequences from droughts and resource mismanagement worldwide have contributed to detrimental health effects in humans (Gomez, Parker, Dosman, & McDuffie, 1992; Hefflin et al., 1991; Kelley, Mohtadi, Cane, Seager, & Kushnir, 2015; Smith, Aragão, Sabel, & Nakaya, 2014). Notably, regional characteristics, desiccation, and drought-related health impacts of the Aral Sea Basin in Central Asia have been well documented and offer multiple opportunities for comparisons to the Salton Sea and the health risks that are placed upon residents of the Imperial Valley. In this paper, the phenomenon of the Aral Sea, including its geomorphological properties, economic history, political context, and pathways of human exposure to toxic contaminants as a result of drought and water over-allocation are explored in the context of its similarities to the Salton Sea's current state of desiccation and decline. The purpose of this study is to draw historical parallels between the Aral Sea and Salton Sea in the context of geomorphology, ecology, human health, economics, and human migration, to inform an assessment of potential environmentally-related health impacts of those living in the Imperial Valley region.

The Planetary Health/GeoHealth Framework

The Planetary Health/GeoHealth framework provides an ideal context for the current research. The emerging field is based on the assumption that human, animal, and ecosystem health should be addressed jointly in order to address the root causes of environmental decline and human disease (Frumkin, 2017). This emerging framework suggests that human health is affected by a set of environmental conditions and that the disruption of natural and ecological systems by human activity are the drivers of environmental changes, including pollution, biodiversity loss, land degradation, resource scarcity, and climate change. These drivers interact in complex ways, both with each other and with proximate causes of human health effects, including exposure to natural hazards (Myers, 2017). The health and integrity of the Salton Sea's local ecosystem should be considered within the context of the health of the population living near the Salton Sea, and likewise, the population's health should be considered within the context of possible environmental conditions and exposures.

Historical Context: The Aral Sea

The disappearance of the Aral Sea during the 1960s and1970s has been referred to as a "quiet Chernobyl" (Glantz & Figueroa, 1997) and has been referred to as one of the worst environmental events of the past century (United Nations Environmental Programme, 1992). Accelerated by unsustainable irrigation and water management practices during the mid-1900s, the Aral Sea underwent a desiccation process that resulted in a statistically significant increase in respiratory disease in countries surrounding the Aral Sea and beyond (O'Hara, Wiggs, Mamedov, Davidson, & Hubbard, 2000; Wiggs et al., 2003). In addition, residents in the region experienced higher rates of cancer, hepatic and renal diseases, and pregnancy complications than ever before in this region, resulting from toxic chemicals in drinking water from farm runoff (Whish-Wilson, 2002).

Geology, Water Allocation, and Agricultural Economy of the Aral Sea Basin

The Aral Sea is an endorheic lake in Central Asia, crossing the current country borders of Kazakhstan and Uzbekistan, that is primarily supplied by two major rivers, the Syr Darya and Amu Darya, for the supply of water in the setting of an arid continental climate (White, 2013). The early 1900s marked a spike in productivity for the region, supporting large fishing and cotton industries that were a major supply of food and exports for Russia (White, 2013). This quickly necessitated the diversion of water from the Syr Darya and Amu Darya rivers toward irrigation for agriculture. Following the Second World War, The Aral Sea Basin underwent further development, referred to as “the Stalin plan for remodeling nature” (Grigoryev, 1952, p. 170), as the Soviet Union was driven by the desire for self-reliance in the production of all crops necessary to support its population (Whish-Wilson, 2002). The plan centered on an increase of the production of water-intensive crops in the area, particularly cotton, and, to a lesser extent, wheat and maize.

The agricultural developments and production of the Twentieth Century were bolstered by way of manmade canals to divert water from the Aral Sea’s major feeding rivers to irrigation ditches (Aus Der Beek, Voß, & Flörke, 2011; Indoitu et al., 2015; Lee & Jung, 2018; Shukla Mcdermid & Winter, 2017; White, 2013). Priority for water resource allocation was given almost entirely to the production of crops, including the emptying of nearby reservoirs to cover any deficit (O’Hara, 2000), and effectively ending the nomadic tradition of indigenous populations in favor of settling and cultivating farmland in the setting of increased immigration of farmers to the area (White, 2013).

Aral Sea Desertification

The Cold War Era intensified the Soviet Union's need to increase irrigation and cultivation of the land independently, and by the 1980s, the Soviet Union was the second-largest exporter of cotton in the world (White, 2013). An increased demand for irrigation to support the cotton economy continued to divert river water from the Aral Sea, and by the 1980s, no river water reached the Aral Sea during average or dry years (Whish-Wilson, 2002). Between 1960 and 1989, the Aral Sea's water volume diminished by over half (White, 2013).

Soviet-era irrigation practices, combined with high evaporation during the summer months, has left behind a nearly dry and empty lake basin (Figure 2) (Indoitu et al., 2015). Today, the Aral Sea totals less than half of its surface area and a quarter of its volume since the 1960s (Lee & Jung, 2018), and the salinity of the remaining water has reached levels similar to ocean water (Crighton, Elliott, Upshur, Van Der Meer, & Small, 2003). The resulting Aralkum Desert has seen significant increases in extreme air temperatures and overall summer air temperatures (Indoitu et al., 2015; Shukla Mcdermid & Winter, 2017). Aus Der Beek and colleagues (2011) have concluded that while global climate change alone has been a factor in the desertification of the Aral Sea Basin, direct interference in the form of abstractions from the water supply have contributed to approximately 86% of the Aral Sea's dramatic reduction in its water level.

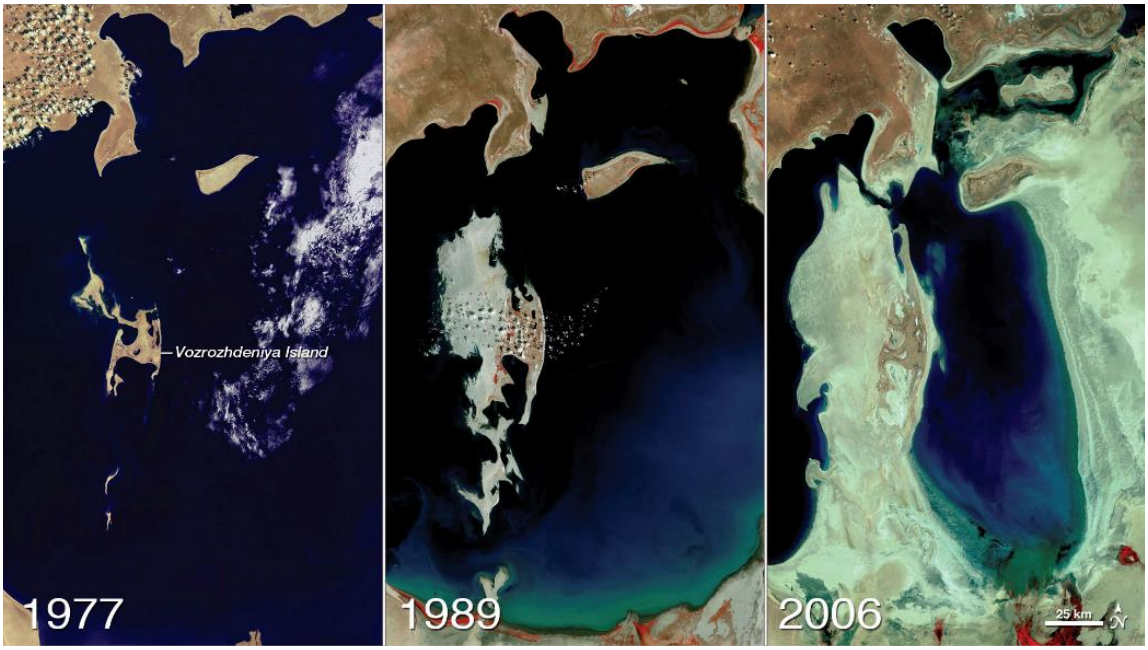

Figure 2. False-color Landsat satellite images showing the gradual desiccation of the Salton Sea. Source: NASA Earth Observatory (NASA, 2012).

Human Health and Economic Impacts of the Aral Sea's Desiccation

As soon as the early 1900s, the ecological ramifications of increased irrigation and agricultural activity on human health began to emerge. In addition to salinization of soils from the river water, massive diversions of water to farmland areas saturated the water table and created increased areas of swampland, contributing to malarial outbreaks in the region (White, 2013).

In addition to the desertification of the Aral Sea Basin, the overambitious agricultural development on the part of the Soviet Union included the use of toxic pesticides, fertilizers, herbicides, salts, and other chemicals, such as the organophosphate phosalone and organochlorines PCB, Toxaphene, Lindane (HCH), and DDT (Crighton et al., 2003) in amounts far higher than were used elsewhere in the Soviet Union (White, 2013). Most notably, the chemical TCDD (an active ingredient in Agent Orange and a known human carcinogen) was deployed in cotton fields (White, 2013). These chemicals made their way to the Aral Sea and were confined underwater, later to be exposed as the water level diminished (Indoitu et al., 2015).

The dry lake basin in present day can distribute these chemicals across distances reaching up to 500 kilometers (Indoitu et al., 2015) in what has come to be known as "white dust storms:" clouds of toxic dust produced when combined with dry weather and strong winds" (Figure 3). White dust storms have been increasing in frequency and severity in the Aral Sea Basin (Indoitu et al., 2015; Shukla Mcdermid & Winter, 2017) at the same time that they have become less frequent in the general area (Indoitu et al., 2015). As a result, the rate of dust deposition, containing high concentrations of toxic chemicals, are among the highest in the world (O'Hara et al., 2000) and have infiltrated not only the air but also the water and food supply pathways (Crighton et al., 2003; Kaneko et al., 2003).

Recent evidence (outlined in Table 1) demonstrates the multiple human health and environmental effects that have arisen as a result of the Aral Sea's desiccation process. Furthermore, the recession of the Aral Sea's water level between 1960 and 1970 (Crighton et al., 2003) and the resulting increase in water salinity caused the collapse of the region's fishing industry in what remained of the Aral Sea. This forced mass out-migration from the area and lasting high rates of unemployment and economic hardship (Crighton et al., 2003). In the setting of economic collapse and health concerns, those who were able to do so migrated away from the area, leaving behind a marginalized population that did not possess the resources to relocate (White, 2013).

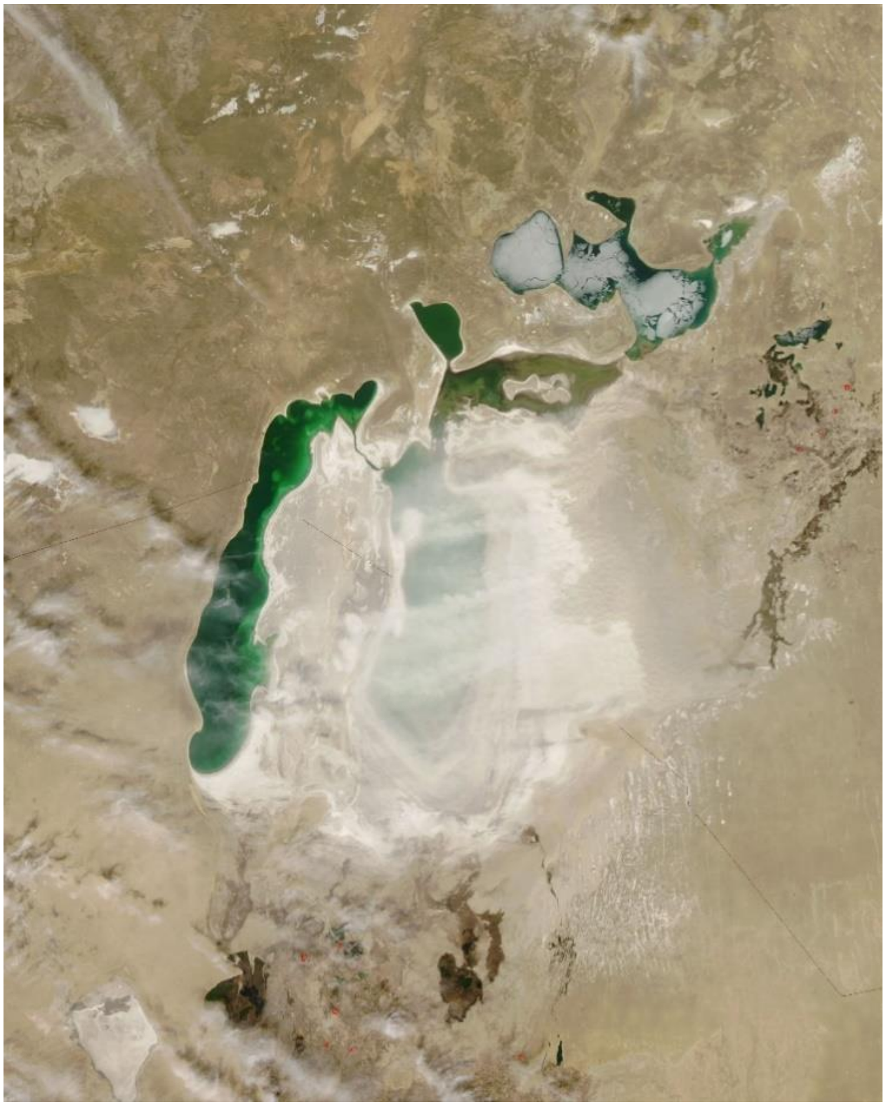

Figure 3. “White dust storm” over the Aral Sea. Source: NASA Earth Observatory (NASA, 2007).

Table 1. Review of the environmental and human health impacts in the region of the Aral Sea Basin.

Authors	Study Area	Health Assessment	Environmental Assessment	Findings (Health)	Findings (Environmental)	Study Limitations
Bennion et al. (2007)	Karakalpakstan, Uzbekistan	Questionnaire-based assessment of household exposures and self-reported respiratory health (asthma, allergic rhinitis, pneumonia) Pulmonary function (FEV1) collected via portable spirometer	Dust deposition rates (PM_{10} and $PM_{2.5}$) within 5 km of study populations	Some evidence for an inverse relationship between FEV_1 and dust exposure, but no significant relationship was found	Highest rates of dust deposition occurred during the summer months and in the region closest to the original shoreline. No significant variation between PM_{10} vs. $PM_{2.5}$ fractions.	Unable to test difference between asthma and allergic rhinitis. Cross-sectional study does not allow for testing for children with wheezing
Crighton et al. (2003)	Karakalpakstan, Uzbekistan	Questionnaire-based assessment of perceived environment, social support networks, psychosocial health, and self-rated somatic health (geneal)	None	High rates of poor self-rated health Respondents were more likely to have poor self-rated health if they were concerned about environmental problems and had an intermediate or higher education level.	None	Lower-than-expected ratings of poor health and environmental may be due to mass out-migration from the region, leaving behind those who were less concerned about these issues.

Authors	Study Area	Health Assessment	Environmental Assessment	Findings (Health)	Findings (Environmental)	Study Limitations
Indoitu et al. (2015)	Aral Sea region	None	Remote sensing observations (satellite imagery, ozone mapping spectrometry) to track frequency, size, and sources of dust storms and aerosol concentrations over the region	None	The Aral Sea dry lake bed has been a strong source of dust emissions since 2000 and has included the northern and southern desert areas as dust sources. Dust storm frequency, composition, and structure have changed as a result of the Aral Sea desiccation process. Dust emissions originating from the Aralkum desert are capable of traveling hundreds of kilometers.	Absence of meteorological monitoring stations on the dried Aral Sea surface
Kaneko et al. (2003)	Kazalinsk District, Kazakhstan and control area	Questionnaire-based assessment of overall health, gastrointestinal symptoms Renal tubular cell injury as measured by urine sampling	None	Significantly higher prevalence of gastrointestinal symptoms, abnormal renal labs in children living in the Aral Sea region.	None	Unknown specific cause for renal tubular dysfunction found in the study area.

Authors	Study Area	Health Assessment	Environmental Assessment	Findings (Health)	Findings (Environmental)	Study Limitations
Kunii et al. (2010)	Kazalinsk District, Kazakhstan and control area	Questionnaire-based assessment of household exposures and respiratory symptoms (pneumonia, chest infection, wheeze)	None	Significantly higher prevalence of wheeze and restrictive pulmonary dysfunction among subjects in the Aral Sea region compared to those living farther away. No significant difference for asthma or obstructive pulmonary dysfunction.	None	Confounding factors related to measurement bias during questionnaire e administration and weather-related variability in pulmonary function performance
O'Hara et al. (2000)	Eastern Turkmenistan	None	Airborne dust deposition rates (PM_{10}) and physical/chemical composition	None	Dust deposition rates were higher desert in monitoring sites than those closer to the Aral Sea. PM_{10} values were greater at sites near to irrigated areas compared to the desert. High levels of organophosphate were found across sites and were highest in irrigated areas, despite the cessation of pesticide spraying.	None noted

Authors	Study Area	Health Assessment	Environmental Assessment	Findings (Health)	Findings (Environmental)	Study Limitations
Wiggs et al. (2003)	Karakalpakstan, Uzbekistan	Questionnaire-based assessment of household exposures and respiratory symptoms (chronic cough, wheeze, asthma) Pulmonary function (FEV_1) collected via electronic volume-flow spirometer	Dust deposition rates (PM_{10}) within 5 km of study populations	Children living closer to the former shoreline had a lower prevalence of respiratory health problems compared to main agricultural and urban areas.	Summer months experienced conditions (temperature, precipitation, wind patterns) that were conducive to increased sediment erosion and dust transport, especially in the northern portion of the study area. During the dusty season, deposition rates of PM10 far exceeded US EPA standards.	Likelihood that dust is not the only environmental factor that may cause changes in human health. Dust deposition data indicates multiple potential sources of dust Monthly aggregate data may mask short-term effects on health caused by single dust events(Wiggs et al., 2003)

Of the area making up the former Soviet Union, the Aral Sea region has been recorded as having the highest rates of tuberculosis, far exceeding the classifications of an epidemic outbreak (Wiggs et al., 2003). Based on evidence of dust deposition patterns as demonstrated by Bennion et al. (2007) and Wiggs et al. (2003) and surveys of respiratory symptoms and illness, it is possible that dust in the Aral Sea region was the cause of these symptoms. Infant mortality rates in the region are among the world's highest, exceeding 100 deaths per 1,000 live births (Wiggs et al., 2003). In children, autopsy results have shown a strong relationship between proximity to the Aral Sea region and lung tissue changes, including fibrosing alveolitis and damage of interstitial lung tissue (Kunii et al., 2010).

California's Imperial Valley and the Salton Sea Basin

In the region of the Aral Sea Basin, the economic, environmental, and human-health impacts on the local population is a warning for a present phenomenon. Though not connected by people or place, the Aral Sea and Salton Sea regions are comparable through similar geologies, economic goals, strains on the natural systems, and impacts of the local and regional environments on human health.

The Salton Sea: Geology, Water Allocation, and Agricultural Economy

The Salton Sea in California's Imperial County, like the Aral Sea, is an endorheic geologic depression located at the northern end of the Imperial Valley and lies over 200 feet below sea level (Cohn, 2000). The Salton Sea was preceded by the much-larger ancient water body, Lake Cahuilla, which underwent repeated expansion and contraction due to repeated flooding from the Colorado River during prehistoric times and ultimately dried up completely by the 16th Century (Cohn, 2000; Laylander, 1995). The resulting Salton Sea Basin (also known as the Salton Depression) remained dry until 1905, when a faulty canal gate, meant to corral the Colorado River for irrigation, flooded the area and resulted in what is currently the Salton Sea (Cohn, 2000; Xu, Bui, Lamerdin, & Schlenk, 2016). At 35 miles long, up to 15 miles wide and holding approximately 7.5 million acre-feet of water, it is currently the third-largest saltwater lake in North America (Cohn, 2000).

As with the Aral Sea's two main feeding rivers, the Imperial Valley's Colorado River serves as the main water source for large human developments in an arid climate and is bolstered by a complex system of canals. Seven states in the Southwestern United States – five of which are some of the fastest growing states in the country – depend on the Colorado River, whose major landmarks include Lake Mead and the Hoover Dam (which supplies the Las Vegas area) in addition to the Salton Sea. Though the Salton Sea's heyday was marked by beachfront properties and images of the Hollywood elite visiting the "miracle in the desert" on holiday, this massive body of water has no natural feeding rivers to maintain its water level due to the accidental nature of its modern existence (Goodyear, 2015; Xu et al., 2016).

In the midst of its time as the center of a booming tourist destination, the original purpose of the Colorado River canal system also gave way to a flourishing agricultural industry, thanks to the seemingly endless supply of water from the river. Use of water from the Colorado River, as with the Amu Darya and Syr Darya of the Aral Sea Basin, was propagated by the United States government, incentivized by the prospect of irrigation and agricultural production in an area offering a year-round growing season (Arballo et al., 2014).

Though the mechanisms of water inefficiency in agriculture between the Aral and Salton Seas differ politically – one a result of the Soviet Party's economic and political need for increased production, and one that has been maintained by a political chokehold held by local farming lobbies on the government's sustainability efforts – the result in both areas has been an unsustainable use of water resources toward the production of water-inefficient crops in the context of the local climates due to the lack of incentives for conservation.

The Colorado River was first turned into a source for California agriculture during a particularly wet year, setting off a history of excessive and unsustainable water use (The Economist, 2014). The sense of water from the Colorado River as a birthright to farmers was carried forth by the Law of the River agreement in 1922, which established California's share of the River's water (shared by Colorado, Nevada, and Utah) and set the price of its agriculture-designated water at $0.20 per gallon (Goodyear, 2015). In Imperial Valley in 1924, the Salton Sea was designated as an agricultural sump as a result of irrigation runoff from nearby farmland. Despite the naturally dry climate and relative lack of a natural local water supply, the low price of water – left unchanged to this day – did little to discourage the production of water-intensive crops and use of flood irrigation by farmers in the area (Goodyear, 2015).

The once-thriving beachfront communities along the Salton Sea, dependent on the ebbs and flows from farmland irrigation, eventually became ghost towns, their piers for jet skis and fishing now ending hundreds of feet from the receding shoreline. Despite the fate of these vacation towns, water from the Colorado River continued to feed the vast swaths of farmland in the Imperial Valley, at one point pulling approximately 5.2 million acre-feet of water from the Colorado River (Cohn, 2000). Today, the Imperial Valley is still one of California's most productive agricultural areas and holds the largest water right from the Colorado River (Arballo et al., 2014). As a result of the arid climate and irrigation from the 475,000 acres of farmland in Imperial Valley (Cohn, 2000; Orlando, Smalling, & Kuivila, 2006), 75% of water inflow to the Salton Sea now originates almost exclusively from agricultural drainage from Imperial Valley via two southern streams in Imperial County and a third originating from Riverside County, to the north of the Salton Sea. (Orlando et al., 2006; Xu et al., 2016)

Desiccation, Ecological Impacts, and Current State of the Salton Sea

As in the Aral Sea region, the lack of precipitation in the Imperial Valley region has caused the water level of the Salton Sea to recede (Figure 4). Years of recent water scarcity have forced farms to conserve of water, and in 2013, half a million acres of farmland were left fallow due to drought conditions (Economist, 2015). This led to the reduction of irrigation runoff into the Salton Sea and is compounded by the natural evaporation from the water surface.

Though not a direct comparison to Amu Darya and Syr Darya rivers, whose natural water supply was diverted away from the Aral Sea for irrigation nearby, the impact on the two seas' salinity and ecology are comparable. The Salton Sea's water level is currently at a record low in the modern era. Since its creation, the sea has become home to abundant populations of water fowl, including some endangered species,

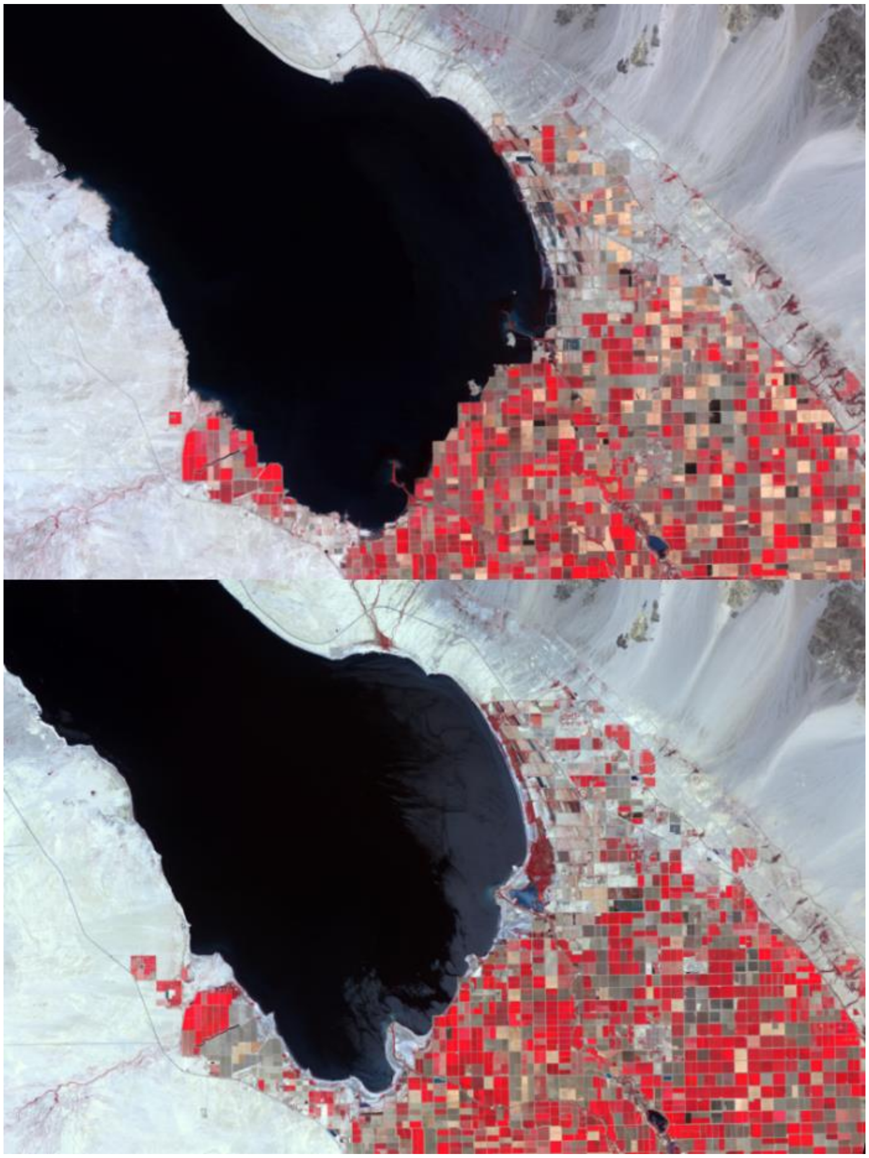

Figure 4. Evidence of the Salton Sea's diminishing shoreline from 1984 (top) to 2015 (bottom). Source: NASA Earth Observatory (NASA, 2015).

that are dependent on this body of water along the Pacific flyway (Cohn, 2000). However, salinity of the lake, most recently measured at 45 grams per liter, is already 25% more saline than the Pacific Ocean (King, Etyemezian, Sweeney, Buck, & Nikolich, 2011). This, combined with frequent algal blooms and depletion of the water's dissolved oxygen content, has made survival a challenge for most animals that call the lake home (Cohn, 2000; Kaiser, 1999). The loss of this habitat is significant, as the loss of

California's natural wetlands due to human development has made the Salton Sea a critical ecological resource (Cohn, 2000).

Drivers of Human Health Impacts of the Salton Sea's Desiccation Process

The existence of the Salton Sea in its current state is more than an eyesore or an ecological conundrum; the Salton Sea may also be the source of current, and likely future, health risks to the nearby human population. Similar geographic and environmental features (Gomez et al., 1992; O'Hara et al., 2000; Wiggs et al., 2003) between the two water bodies and regions suggest a link between these features and adverse health consequences in California that may resemble that which occurred half a world away. Evidence of human health impacts resulting from drought conditions in the Imperial Valley of Southern California is limited to anecdotal evidence in the form of newspaper articles and editorials highlighting the respiratory health of residents in the area and the impact of health disparities on families' inability to effectively cope with environmental risk factors (Bloudoff-Indelicato, 2012; Goodyear, 2015; Ketcham, 2012).

Local socioeconomic statistics suggest that residents in the Imperial Valley are susceptible to poverty-related health risks associated with living in the region. During a drought or other environmental event, individuals living in areas such as this inland county may be disproportionately impacted due to financial burdens and health disparities. The 2013 median family income of Imperial County was over 25% below the median national family income, and 23.3% of families were below the federal poverty level, compared to 15.9% in the United States (Arballo et al., 2014). Individuals and families with fewer economic resources may be unable to adhere to asthma guidelines or move away from the area in order to reduce exposure to poor air quality (Bureau, 2015).

Diminishing water levels in the Salton Sea poses a risk of exposing previously-sequestered toxic chemicals to the open air. Both the Aral and Salton Seas are terminal lakes in dry, arid climates. The use of agricultural chemicals on nearby farmland in both regions has accumulated in each region's body of water, and these previously-submerged chemicals have been increasingly exposed to the open air due to water evaporation. Studies have found these chemicals in the air in the area surrounding the Aral Sea. Rivers feeding the Salton Sea drain pesticides, including DDT, chlorpyrifos, dieldrin, PCBs, selenium, and toxaphene, among other toxins (de Vlaming et al., 2004; Orlando et al., 2006; Xu et al., 2016). . Although the Salton Sea's desiccation process is still in its beginning stages, previous studies of wind in the Imperial Valley and dust deposition from the Salton Sea's borders (King et al., 2011) have shown that the diminishing water level poses a similar risk of exposing previously-sequestered toxic chemicals to the open air as evaporation continues.

The similarities between the Aral and Salton seas are further evidence of the human effects of drought in a region that is geographically and climatologically similar to the Salton Sea and which went through very similar farming and irrigation practices like those happening near the Salton Sea. Although the parallels between specific characteristics of both populations are not exact, both regions contain or have contained populations who are socioeconomically vulnerable to climate conditions, in part due to their inability to relocate. Residents of the Imperial Valley may only have started to see health effects of drought only in recent years. However, historical evidence presented here suggests that attention needs to be paid to the future public health impacts of environmental pollutants on the Imperial Valley population, and water resource allocation policy should be reconsidered as a measure to impact public health.

Table 2. Review of environmental testing in the Salton Sea and Imperial Valley region.

Authors	Environmental Assessment	Measurements	Findings
de Vlaming et al. (2004)	Presence of insecticides in water of Salton Sea's contributing rivers (Alamo River and New River)	Toxicity testing of water using mortality rates of three aquatic species	Toxicity of water samples was due to organophosphate insecticides, chlorpyrifos, and diazinon
King et al. (2011)	Relationships between season, soil properties, and windblown dust emissions	PM_{10} dust emissions; soil sampling for moisture content, and chemistry.	Some degree of seasonality in Salton Sea's dust emission potential among soft crusts, producing significant dust emissions from winter to early spring, as well as minimally fluctuating emissions from dry wash surfaces No correlation between PM_{10} emissions and soil composition/texture, though dry wash sites consistently produced higher PM_{10} emissions compared to other landform types.
Orlando et al. (2006)	Presence of pesticides in water and suspended sediment in Salton Sea's contributing rivers	Gas chromatography/mass spectrometry for detection of organochlorine pesticides	Over 75% of samples contained chlorpyrifos, DCPA, EPTC, and trifluralin. Samples from the Alamo River contained maximum dissolved concentrations and contained greater numbers of pesticides compared to the New River samples. Maximum concentrations of carbofuran, chlorpyrifos, diazinon, and malathion were higher than US EPA aquatic life benchmarks.
Xu et al. (2016)	Presence of contaminants in Salton Sea water, its feeding rivers, sediment, and fish tissue	Toxicity testing of water;	Water and sediment samples showed contamination by DDTs, PAHs, chlorpyrios, pyrethroid insecticides, copper, and chromium. While tributary river water was more contaminated than water in the Salton Sea, the Salton Sea's sediment showed higher levels of contamination than river sediment. Fish tissue samples showed contamination of DDTs, selenium, and chlorpyrifos.

The "Costs of Inaction" in the Salton Sea Region

The Aral Sea environmental crisis and its consequences on the local economic climate as well as human health and migration have been studied extensively with the aid of many years' hindsight. In the area surrounding the Salton Sea, the full extent of its impact on human health and the environment have yet to be fully observed. In a 2014 report, Cohen (2014) outlined the projected "costs of inaction" from a range of issues that may provide insight into the price of the decline of the Salton Sea region (i.e., the estimated costs to the public if no large-scale mitigation efforts are implemented). Notably, the report found that the cost of dust emissions on the local population's health could amount to up to $37 billion USD (2014 through 2047) and between $10 and 26 billion in non-use value costs in terms of ecological and habitat worth.

Discussion

In an effort to increase agricultural productivity, the governments in the Aral Sea and Imperial Valley regions introduced policies that included widespread irrigation projects and other support systems for agriculture at the expense of sustainable practices. In the Aral Sea basin, productivity was driven by Soviet demands and resulted in a diversion of natural feeding rivers toward agricultural land. Farmers in the Imperial Valley responded to market demands for produce and were motivated by the low price of water to produce water-intensive crops and have turned the area into one of the most productive regions in the country for agricultural products. As a result of placing unreasonable demands on the environment during non-drought periods, the misuse of water resources in the Aral Sea basin has led to a collapse of the agricultural system and the economy upon which it depended. Similarly, the high productivity of the Imperial Valley's agricultural economy, relative to the state of California, suggests the consequences of drought may impact the US on a broader scale. California is the most populous state in the US with the country's largest economy, accounting for 12% of the population and 13% of the nation's GDP (Young, 2016). In addition, the socioeconomic status of many residents of the area implies that in the event of a public health crisis, additional strain will be placed on public healthcare payors, such as Medicaid and Medicare. The combination of these factors provides substantial risk for impacting a large section of the country's healthcare and economic sectors.

A Case for Further Exploration in the Context of Planetary Health

Evidence of the occurrence of anthropogenic change to the environment in other areas of the world, as well as the human health and economic impacts of these changes, provides a scientific premise for the investigation of similar environmental impacts on the health of California residents. Presently, California's Governor has lifted the state of emergency due to the recent drought, initiated in 2014 (State of California Department of Water Resources, 2017). This easement should be interpreted cautiously, and not as a prediction of unfaltering future improvement of conditions. The years of 2012-2016 marked the state and region's worst drought in over a century (Griffin & Anchukaitis, 2014). Droughts associated with anthropogenic climate change are expected to recur across North America (Cook et al., 2014; Costello et al., 2009; Griffin & Anchukaitis, 2014; O'Connor et al., 2014).

Conclusion

The Salton Sea shares several major characteristics with its historical partner, the Aral Sea, and suggests that the health impacts of agricultural activity in the Salton Sea region must be studied in the context of human interference with an ecosystem and water availability as a result of unsustainable farming practices.

Climate change and the increase in respiratory disease incidence and severity (Sarfaty et al., 2015) calls for the need of further interdisciplinary research within the emerging field of Planetary Health/GeoHealth or the impact of the health of the Imperial Valley's ecology on the respiratory health of its residents. Since the 1970s, droughts worldwide have been longer and more severe. Future droughts and extreme heatwaves are expected to continue to rise in frequency and severity, disproportionately affecting those already impacted by health disparities (Costello et al., 2009; O'Connor et al., 2014).

New research into the impacts of poor respiratory health in drought areas will provide a perspective on underrepresented environmental challenges at the local and regional levels. The future of health will require a more robust integration with environmental science research and policy, as drought is one of the most expensive natural events from a number of economic and public health vantage points (Cook et al., 2014). This must include, but certainly will not be limited to, the implications of population health associated with the most recent California drought and the receding water levels of the Salton Sea. The Planetary Health/GeoHealth framework addresses this intersection between human and ecosystem health. Planetary Health/GeoHealth functions within other fields, including agriculture, economics, and urban planning, among others, as well as the health and environmental sciences. In the context of Imperial County and the Salton Sea, this may also extend to the more efficient utilization of water resources for irrigation.

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CHAPTER 4

Linking Pollution Effects to Vulnerable Populations: Application of Meteorological Methods to Planetary Health Research

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Abstract

Objective. Ongoing environmental changes increasingly require public health nurses to understand how environmental factors impact the health of populations. One approach to researching these impacts is incorporating environmental research methods to determine associations between harmful exposures and health. We use the Salton Sea in Southern California as a demonstration of how environmental exposure can be examined using air parcel trajectory analysis. **Design.** We demonstrate a methodology for public health nurses to better understand and apply data from the HYSPLIT meteorological model to estimate the effect of airborne particulate matter from a single source. **Measurements.** We propose a method for tracking air parcel trajectories to populations: selection of meterological data to identify air parcels, geographic identification of population centers, generation of trajectories, classification of trajectory dispersions, adjusting for atmospheric stability, and merging environmental variables with health data.
Conclusions. Within public health and nursing, there is a need for broadening of skills beyond healthcare. Climate change-related environmental events are expected to become more commonplace and disproportionately affect those populations impacted by health disparities, like the population examined in this research. Public health professionals are ideally positioned to assess environmental risk factors to vulnerable communities on a population scale.

Key Words: Environmental Health; Air Pollutants; Population Health; Trajectory Model

Introduction

Planetary health is an emerging field concerned with both the health of human populations and the natural ecological systems that support and sustain human health (Horton & Lo, 2015). These concepts are embedded in the assumption that human, animal, and ecosystem health must be addressed jointly and that to fully understand human health and its complex determinates, the physical and biological processes of the natural environment must be understood as well (Frumkin, 2017). Consequently, planetary health is a field that studies the intersection of many disciplines, including public health, as well as issues of poverty, inequality, nutrition, climate change, and land use, among others. Within the context of these multidimensional determinants of health, ongoing environmental changes on a planetary scale can lead to associated health impacts that increasingly require public health professionals to understand how certain environmental factors impact the health of vulnerable populations. One approach to researching these impacts is to incorporate available environmental and meteorological research tools and methods to determine associations between harmful exposures and health outcomes.

Airborne particulate matter that arises from pollution, such as pesticides or urban activity, has a detrimental effect on the health of proximal populations (Gauderman et al., 2004; Landrigan et al., 2018; Prunicki, Nadeau, Prunicki, Nadeau, & Parker, 2016). An important concept in studying how these particulates travel is the understanding of the movement of a theoretical volume of air, known as an air parcel. Air parcel pathways are modeled in meteorological research using trajectory analysis to estimate the three-dimensional paths originating from or moving over a specified location for a selected time period. Trajectory models previously have been used to predict pollution concentrations or hotspots (Davis et al., 2009; Sitanggang, Asti, Syaufina, & Khotimah, 2017) and airborne allergen exposures, among others. One of the more commonly-used trajectory analysis models is the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al., 2015), which uses publicly available meteorological data sets to trace an air parcel trajectory from a selected origin point (latitude, longitude, and starting height) over a specified period of time. Once the trajectory is estimated, longitudinal health data can be used to determine the breadth and dimension of the impact on population health in an area proximal to its path. The HYSPLIT model, therefore, offers an additional tool beyond local air quality monitoring stations to make inferences about the impact of regional air quality and potential exposure to pollution sources on population health.

To aid understanding of the use of these methods, this study focuses specifically on Imperial County, California, United States. We were motivated by the prevalence of emergency department visits for pediatric asthma in the study area, which we hypothesize have been exacerbated by recent drought conditions and subsequent exposure of dust particles and other potential contaminants from the Salton Sea (Doede, DeGuzman, & Davis, 2020). Imperial County is also one of the most medically underserved areas in California with a higher-than-average poverty rate (Arballo et al., 2014), creating additional challenges for those experiencing negative health sequelae of pollution exposure. Using data from our analysis of airborne particles from the Salton Sea on regional childhood asthma exacerbations, this paper describes a methodology for preparing and using data from the HYSPLIT meteorological model for estimating pollutant exposures within a population.

Methods

Effective models for estimating pollutant exposures must be grounded in accepted methodologies in meteorological and environmental science. We developed a six-step method for tracking pollutant air parcel trajectories from the Salton Sea to vulnerable populations in Imperial County: (a) selecting meterological data sources to identify air parcels, (b) identifying geographic population centers, (c) generating air parcel trajectories, (d) determining and classifying trajectory dispersions, (e) adjusting the model for daily atmospheric stability, and (f) merging the environmental variables with health data.   Note that the specific application of this model to health outcomes is discussed elsewhere (Doede et al., 2020).

Choice of Meteorological Data Set

The first step in the process described in this paper is the selection of the data set containing meteorological information about the area as the source for the air parcel trajectory model, as well as the trajectory model's origin points. The North American Regional Reanalysis (NARR) data set was obtained from the United States National Oceanic and Atmospheric Administration (Mesinger et al., 2006). Among other variables the NARR includes the wind speed, wind direction, height, and pressure data required as input for HYSPLIT. This data set was chosen for its accessibility within the model as well as the high resolution provided for the current study area, with climatological data provided on a 32-kilometer grid. The NARR is a commonly-used dataset for a variety of regional modeling studies (Atamanchuk, Koelling, Send, & Wallace, n.d.; Jiang et al., 2020; Lee, Chen, Kumar, Zhang, & Kleeman, 2020; Seo, Krajewski, & Qi, 2020).

As the method described in this paper was specifically designed to determine the extent to which air parcels that originate from the Salton Sea's exposed lakebed contribute to emergency department admissions for asthma, the selection of origin sites for the HYSPLIT trajectories was based on the likelihood of the presence of exposed dust or dust contaminated by runoff from nearby agriculture. To that end, origin sites were chosen based on sediment deposition potential (King, Etyemezian, Sweeney, Buck, & Nikolich, 2011). In addition, it is known that the New and Alamo Rivers carry water from agricultural irrigation runoff into the Salton Sea within Imperial County. Therefore, the known presence of pesticide deposition into the Salton Sea Basin (LeBlanc & Kuivila, 2008) was also taken into consideration when selecting these locations. Figure 1 illustrates the locations of these sites along the southern and western edges of the Salton Sea.

Establishment of Population Centers and Exposure

The second step was to identify the geographic boundaries for the population centers of interest. As this study attempted to retrospectively examine the health effects of a past drought event in the study region, the information available for the study population was limited to retrospective secondary data provided by a hospital database for the state of California (OSHPD, 2017). Patient-level residence information from this database is limited to the ZIP code of the patient. Imperial County is large, and ZIP codes in this county contain vast areas of desert that are sparsely populated. Therefore, it was necessary to identify where air parcel trajectories were intersecting with residential areas, i.e., where airborne particulate matter may have caused an exposure to humans.

We addressed this using a population-weighted geographic buffer – a circumscribed area surrounding populated areas – for each of the county's ZIP codes so that only the air parcel trajectories that crossed over populated areas would be considered an environmental exposure. To determine the location of the more densely populated regions of each ZIP code, 2010 US Census Block population data were used to create these geographic buffers using the Directional Distribution (Standard Deviational Ellipse) tool in ESRI's ArcMap (Environmental Systems Research Institute, Inc., Redlands, California). This allowed the central tendency of the population centroid and the distribution of the population around that centroid to be mapped as an ellipse polygon (Figure 1).

Taking into account the concentration of population centers in cities and towns within the current county and the lack of populated areas in the surrounding desert areas, the spatial polygons comprising each population buffer cover one standard deviation of the population over the population-weighted centroids. This tool provides a method of accounting the majority of the population's likely location within these buffers without including sparsely or non-populated regions as areas of exposure.

Trajectory Generation

Using the data and origin points previously selected and described above, the air parcel trajectories were generated from the HYSPLIT model using the SplitR package in

R Studio (SplitR version 0.4.0.9000 [Iannone, 2019]; R Studio version 1.1.383). Trajectories were initiated every six hours from each of the chosen origin points from a starting height of five meters. The latitude, longitude, and elevation of the air parcels were reported each hour for a duration of twelve hours, at which point the air parcel would, in most cases, have traveled outside the boundaries of the study area. Trajectory graphics, provided by the SplitR package (shown in Figure 2), were then converted to a data frame so that the latitude and longitude components could be checked against the population-weighed buffers.

Dispersion Modeling and Classification of Trajectories

To account for dispersion of air particles as well as their overall trajectory, a dispersion model was developed to create a plume, showing the increased likelihood that pollutants from a source may have diffused along a wider path from the center of the trajectory over time. Unlike the aforementioned trajectories, which determine the most likely location of an air parcel at any given time, a dispersion model utilizes the same meteorological data to determine how the concentrations of a pollutant vary by inherently estimating their potential dispersion over time and space.

HYSPLIT dispersion models were run using the NOAA HYSPLIT-Web (Internet-based) interface to account for the non-linear distribution of particles about the mean trajectory position. Dispersion plumes were not calculated for the entire period of record owing to the extensive amount of time required to produce each trajectory run. Thus, a random sample of days was selected to represent the trajectory climatology, and this limited data set was used as the basis for classifying the remaining days over the entire study period. Plumes from the dispersion run sample were classified using a manual synoptic classification approach (Hondula et al., 2013; Keim, Meeker, & Slater, 2005; Yarnal, 1993) and assigned to one of twelve categories based on visual inspection of spatial attributes and patterns, including shape, direction, and strength of the wind pattern (Figure 3). This included an "unclassified" category, which contains trajectories that could not be easily assigned to a single, distinct weather pattern.

The HYSPLIT trajectories corresponding to the date and time of the dispersion sample were then extracted from the full trajectory data set, and for each of the dispersion categories, a mean latitude and longitude was calculated for each hour of the trajectory. These mean latitude and longitude centroids became the "control trajectories" against which all other HYSPLIT trajectories in the full data set were compared. The trajectories were classified by calculating the Euclidean distance between the geographical position of each HYSPLIT trajectory and the corresponding hour for each of the twelve control trajectories (i.e., the position of the air parcel after the first hour of a trajectory run from the full data set was compared to the first-hour positions of each control trajectory, and so on), as the HYSPLIT model was run for twelve-hour durations. Each hour during the trajectory run was assigned a distance to the centroid position of each control trajectory for its corresponding hour. To assign each HYSPLIT trajectory to a dispersion category, the sum of the hourly distances between the actual trajectory's location and control trajectories' locations was calculated for each dispersion group's centroid. The minimum value of these calculated sums was then used to assign that trajectory to a dispersion group.

This approach is relevant to pollution research because the likelihood of the trajectory path of any given parcel crossing a populated area (as depicted by the ZIP code population buffers) is much lower than an exposure that incorporates the likely spread of a plume. In effect, the trajectory represents the centroid of the flow, whereas the dispersion model accounts for the spatial variance or error.

Ventilation Coefficient

In addition to the establishment of exposure vs. non-exposure days using latitude and longitude coordinates, a daily mixing depth and ventilation coefficient was calculated to account for the daily variation in air quality potential. When the atmosphere is stable, there is little vertical motion (rising or sinking air), and on these days, pollutants can become concentrated and air quality reduced, particularly when winds are light. Conversely, on unstable and windy days, pollutants are more easily diluted within a larger volume of air.

The afternoon (00:00 UTC; 16:00 PST) mixing depth was extracted from the NARR data set for the study time period for this purpose. The height of the mixing depth is often marked by a temperature inversion, where the atmospheric layer closest to the ground encounters a transition to warmer air aloft. This inversion layer is represents the top of the layer in which pollutants arising from near the surface would be concentrated. The mixing depth is important for the determination of exposure because it is related the extent to which pollutants can mix: a lower mixing depth indicates a smaller volume of air for the diffusion of pollutants and, therefore, more concentrated pollutant levels.

The mixing depth was multiplied by the daily mean wind speed averaged over all grid nodes in the study area from the NARR data set to calculate the ventilation coefficient for each day in the study period. As a ventilation coefficient of less than 6,000m^2/s is generally accepted to indicate a potential for pollution exposure (Madany, 1974), trajectory events from the spatial points data frame that qualified as exposure days based on latitude and longitude were filtered out if the ventilation coefficient for that day was over 6,000 m^2/s. This adjustment ensured that only those days when the atmospheric stability in the region could have allowed for particulate matter from the origin point to reach the population were classified as potential exposure days. All days that did not fit this criterion for exposure were classified as non-exposure days.

Use of Trajectories with Hospital Admission Data Set

The established environmental data are next combined with the relevant health or hospital admissions data. By pairing health data with environmental information, analyses may be performed to explore the effect of pollution exposures on human health. In the current data set, hospital admission data were provided at the ZIP code level, and therefore, exposure and non-exposure days were also established at this level of spatial granularity. The resulting data set provides information for each day with a hospital admission from a particular ZIP code and whether a trajectory or dispersion point has crossed the buffer for that ZIP code on that day.

Results

Population Buffers and Exposure

The elliptical population buffers allowed for the inclusion of geographic areas that likely encompassed one standard deviation, or approximately 68%, of the population of each ZIP code. This was an important step when addressing this particular geographic region, as most of the population of Imperial County is located south of the Salton Sea (Figure 1), with large unpopulated or sparsely populated areas in ZIP codes to the east and west. Therefore, although it was necessary to exclude large geographic areas of this county because of a lack of population density, the application of this methodology to a different study area may warrant an adjustment of these considerations for that area's population distribution.

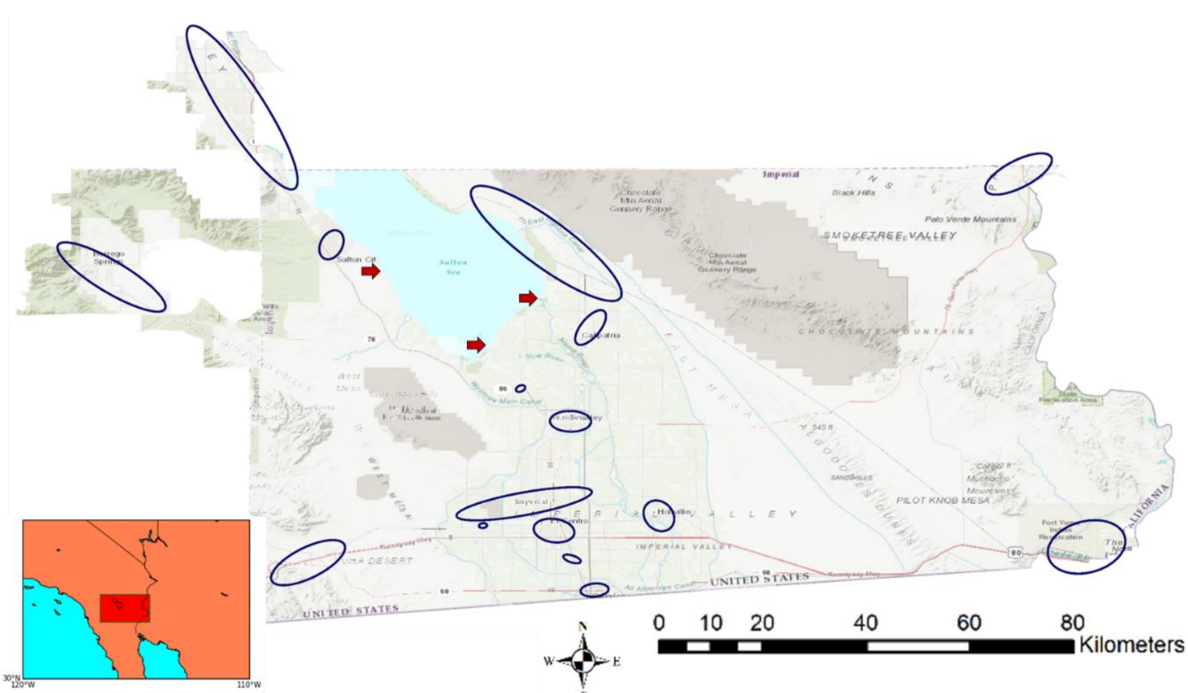

Figure 1. Map of the Imperial Valley within Imperial County, California, with reference map indicating the region used for meteorological data, HYSPLIT air parcel trajectory origin points (indicated with arrows), and elliptical buffers, weighted by population, for each ZIP code.

Trajectory Generation

Figure 2 is an example of the air parcel trajectory data that originate from an origin point near the Salton Sea for each twelve-hour increment in the month of April, 2012. In this case, a new trajectory is begun every six hours. Each line represents one air parcel trajectory, and each trajectory line contains hourly locations. These points represent the hourly positions (from hour zero to hour twelve) of each trajectory, as derived from the model gridded weather data for those dates and times. For example, for the time period shown in Figure 2, there was a tendency for both southerly and southwesterly winds transporting Salton Sea air toward the north and northwest. Less often, there were winds from the north and northwest, moving air from the Salton Sea over the population centers to its south and southeast toward Mexico.

Dispersion Modeling and Trajectory Classification

A total of 621,972 independent trajectories from three origin points were classified into 12 trajectory groupings, which includes an "Unclassified" category that accounts for 0.56% of the total trajectories. Each group's wind pattern, hourly position, overall frequency, and seasonality are shown in Figure 3. The Strong Southerly category (with winds originating from the South) was the most common type overall and most frequently occurred during the summer and winter months. In fact, winds from the west or southwest are quite common in this region in most seasons. Anticyclonic flow (or winds associated with high pressure systems, clear skies, and generally light, counterclockwise winds) is rare and represents the category most typically associated with poor air quality. Cases with northerly or northeasterly winds are particularly relevant to this research, as these situations represent cases when air originating over the Salton Sea is transported over the most heavily populated parts of Imperial County. While occurring less frequently, the Moderate Westerly, Weak Cyclonic (counterclockwise), and Strong Anticyclonic (clockwise) groups are also those that are most common in the winter months. These groups are arguably of the most interest, as the fall and winter months are typically accompanied by a lower ventilation coefficient. Therefore, these groups are most indicative of the potential to facilitate pollutant exposure in the region.

Ventilation Coefficients

The ventilation coefficient is strongly seasonal in this region, with a summertime peak (Figure 4a). In summer, with higher temperatures, the mixed layer tends to be deeper and pollutants are less concentrated. The mean ventilation coefficient exceeds the 6000 m2/km threshold from April through September. In contrast, the 75% ventilation coefficent is below the thresold from November through January, when air quality will tend to be poor in this region. October, February, and March are transitional months, with a mix of good and poor air quality days. These results for the region are consistent with our findings that emergency department admissions tend to be more common in the fall and winter months (Doede et al., 2020).

Ventilation varies significantly across trajectory groups (Figure 4b). One-way ANOVA showed a significant difference in the mean ventilation coefficient across trajectory groups ($F=47.87$, $p<0.001$). At the $p<0.001$ level, post-hoc comparisons using the Tukey HSD test indicated that the mean ventilation coefficient was significantly differed across a variety of groups. Large ventilation values (and likely good air quality) are particularly evident in the Strong Southerly, Strong Westerly, and Strong Anticyclonic categories. In all of these cases, wind speeds are high and air parcels emanating from the Salton Sea region tend to be transported significant distances, especially toward the east. Normally, anticyclonic winds tend to be weaker and linked to poor air quality; but in this Strong Anticyclonic case, the combination of moderate winds and higher temperatures results in fairly strong ventilation. Conversely, the lowest ventilation values and thus poorest air quality potential is associated with the Weak Anticyclonic, Moderate Southerly, and Strong Southeasterly types. Note that in all of these cases (Figure 3), the trajectories are among the shortest of all groups, and the associated winds are not transporting air parcels out of the study region within the 12-hour trajectory time period.

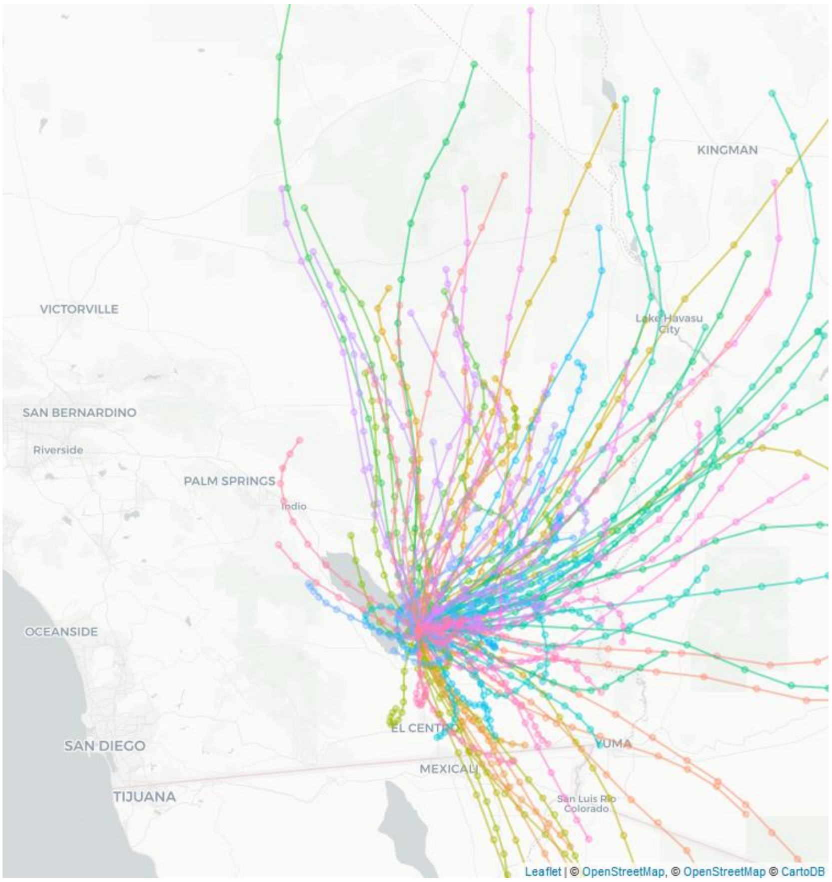

Figure 2. A demonstration of a trajectory output, produced from the SplitR package, for the month of April, 2012. Each line represents one air parcel trajectory. Points along each trajectory indicate hourly reports of the air parcels' positions in space, based on the NARR weather information at that time.

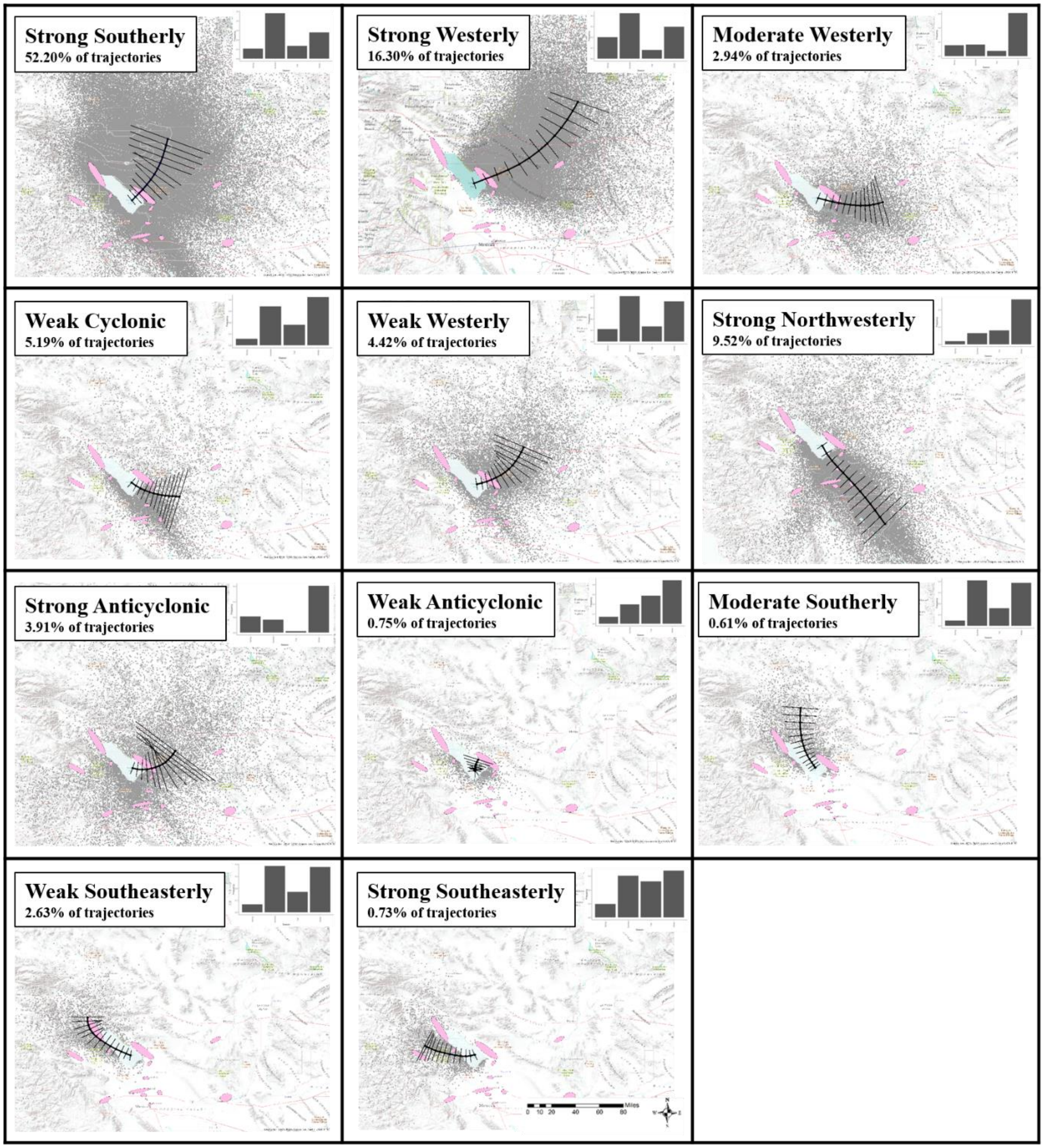

Figure 3. Dispersion points and mean hourly trajectory positions for each trajectory group originating from the Salton Sea with error bars of the mean hourly distance of all trajectories from the overall mean hourly positions. Histograms represent the relative within-group frequencies of each trajectory group by season, beginning with spring. Created with Google Earth and NOAA HYSPLIT-Web.

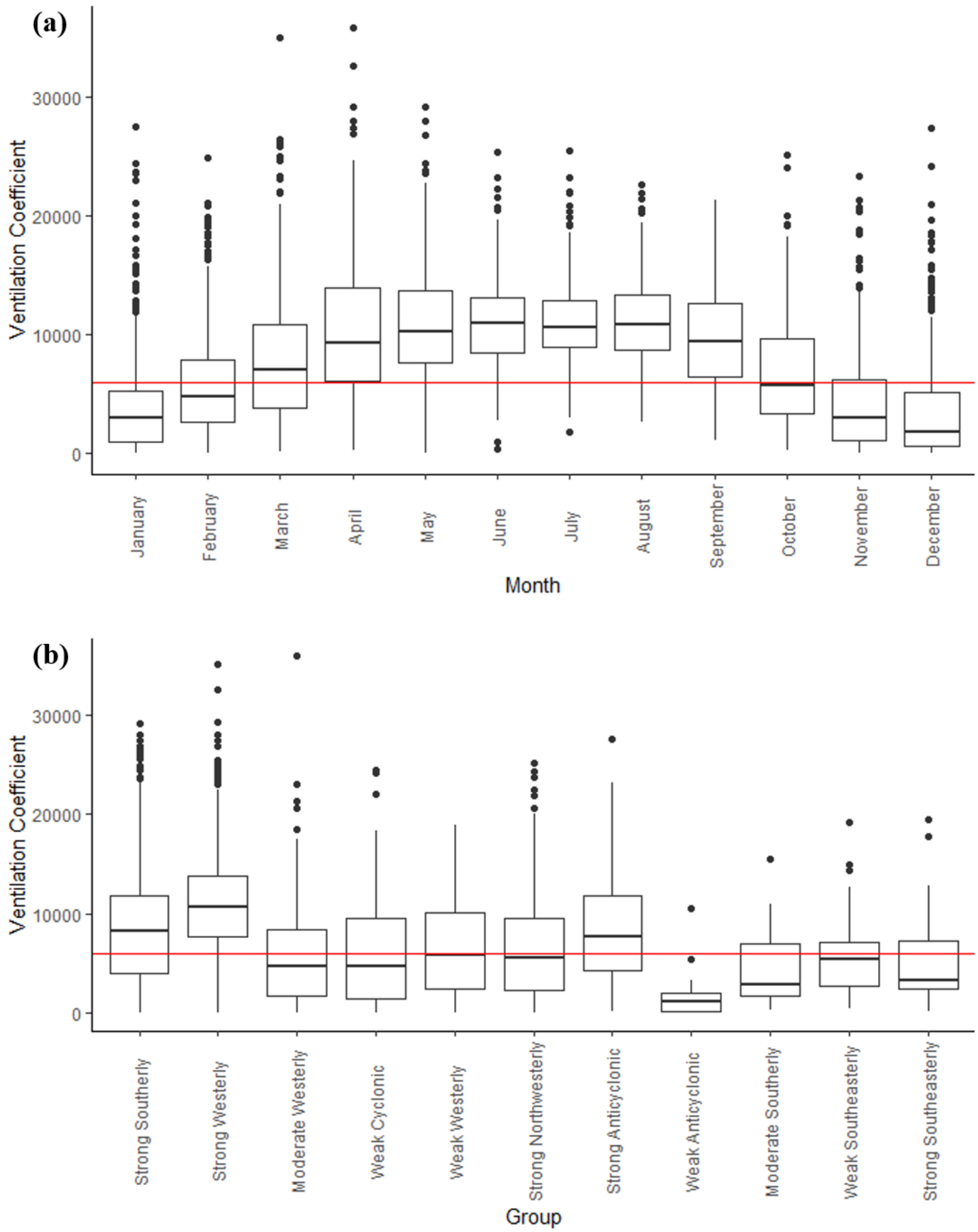

Figure 4. Mean and inter-quartile ranges of daily ventilation coefficients for the time period January 1, 2006 – December 31, 2016, by month (a) and trajectory group (b). The horizontal red line indicates 6,000 m^2/s.

Discussion

The purpose of this study was to use the Salton Sea in Imperial County, California, as a demonstration of environmental exposure analysis using air parcel trajectories as the key analytical tool. In this study, we demonstrate how to use trajectory-based methods, as the basis for determining the effect of airborne particulate matter from a single source on population health.

The utilization of the HYSPLIT model in conjunction with other meteorological and population data is a useful interdisciplinary strategy for determining risk to populations from environmental exposures. This is particularly helpful in regions that lack properly located air quality monitoring stations and may also provide some information about potential pollution sources. This paper describes the use of the HYSPLIT model in the context of health outcomes within Imperial County, California, where the Salton Sea is a possible source of particulate matter that could be detrimental to respiratory health. The concepts and methods outlined here may be applied to address other potential sources of poor air quality, in the current study area as well as others. In addition to the use of this methodology as it has been here for dust exposure, this health-centered approach to analyzing weather data and air trajectories may be a useful tool in assessing other pollutant sources and exposures.

For this particular region, we found strong seasonal trends with respect to the climatological variables necessary to perform the analysis as well as the weather patterns observed, which may be linked to the likelihood of exposure from a potential pollutant source. While many of the trajectory groups described for this region do not demonstrate strong seasonal patterns, several tend to follow a tendency to be more or less common in the spring and summer months compared to the fall and winter months. For example, Strong Northwesterly, Moderate Westerly, and Strong Anticyclonic wind patterns in this region are more common in the fall and winter months, with Moderate Westerly and Strong Anticyclonic winds also being more common during days with a low ventilation coefficient. In addition, the trajectory groups that are more common in the summer, the Strong Southerly and Strong Westerly groups (both of which are associated with stronger winds), occur most frequently when the ventilation coefficients are higher and thus when pollution is less likely to cause a health hazard. This finding is consistent with the idea that moderate to weak winds, when coupled with cool conditions, are the more likely cause of pollution exposure, as opposed to strong winds on warm days that are capable of quickly transporting pollutants away from the region within a greater atmospheric volume.

In this paper and the study described (Doede et al., 2020), we used the ventilation coefficient of 6,000 m^2/s as a threshold to indicate the potential for pollution to have an effect on respiratory health. Given this criterion, the majority of pollution events in this region would have occurred during the fall and winter months. In the case of the current study, the majority of cases of respiratory disease also occur during the fall and winter months, with some overlap between the dispersion groups that are most common when the ventilation coefficient is low and those most common during respiratory events.

Conclusion

In the field of public health and nursing, there is a current need for the broadening of skills beyond the healthcare field. Environmental events related to anthropogenic climate change, including drought, are expected to rise in frequency and severity, disproportionately affecting those at highest risk for health disparities (Cook, Smerdon, Seager, & Cook, 2014; Costello et al., 2009; Griffin & Anchukaitis, 2014; O'Connor et al., 2014). Public health professionals and nurses are ideally positioned to think about environmental risk factors on a population scale, assessing the root causes of diseases so that prevention can be emphasized, and putting the most vulnerable communities at the center of our practice. As the future of health will require a more robust integration with environmental science research and policy, this paper provides a possible methodology for public health nurses to better understand and apply the described concepts in other at-risk regions.

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CHAPTER 5

Impact of Drought and Airborne Pollutants on Pediatric Asthma Emergency Department Visits in Imperial County, California, USA

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Abstract

The pediatric population is at a unique and increased risk of immediate and long-term negative health effects of asthma from air pollution. The years 2012-16 marked the worst drought in California, USA, in over a century. Imperial County's landlocked Salton Sea is almost entirely dependent on agricultural irrigation runoff, where the water level has receded with drought conditions. Lakebed soil exposure may cause increased airborne particulate matter (PM), exacerbating asthma. Emergency department admissions and diagnosis codes for asthma were obtained for children ages 2-18, alongside population data to create population-weighted ZIP code buffers. Trajectory analysis, dispersion modeling, and meteorological data were used to determine likely PM exposure days. Drought severity data were used to establish a relationship between drought, exposure, and admissions. Conditional Poisson regression was used to determine the risk of Salton Sea dust exposure to asthma and moderating effects of drought. There is a significant relationship between exposure from the Salton Sea and admissions on exposure days (ERR 18.70%, p=0.012, 95%CI=3.936–35.623). Moderation analysis for drought indicated no significant effect from two indicators (ERR 1.005%, 95%CI =-0.0.084–1.111, p=0.714; ERR 104.44%, 95%CI=8.44–285.426, p=0.316). These results point to the possibility that particulates originating from the Salton Sea influence pediatric asthma. The large confidence interval is notable, suggesting the influence of additional variables or pollutant sources, which is consistent with the study area, where a variety of factors may contribute to air quality. Drought severity was not a significant moderator in the relationship between exposure and admissions, possibly due to the slow-response impact of drought that could not be captured in this analysis.

Introduction

The pediatric population is at a unique and increased risk of negative health effects from asthma. Not only are children at an increased lifetime risk for lung health and related diseases; children who are unable to participate in school or physical activities due to asthma are also at increased risk for secondary health and developmental consequences related to mental health, education, and obesity and related illnesses (Kohen, 2010; Oland, Booster, & Bender, 2017). In children and adolescents with asthma, exposure to particulate matter (PM) in urban areas – in conjunction with ground heating, land degradation, and rising temperatures – has resulted in greater disease morbidity (Bayram et al., 2016; D'Amato & Cecchi, 2008; Ghio, Smith, & Madden, 2012), including increased emergency department (ED) admissions related to asthma and other cardiopulmonary diseases (Bayram et al., 2016). Compounding this exposure risk are the long-term health effects of poor air quality on lung development and function, which have been shown to continue into adulthood (Gauderman et al., 2004, 2002). Although there is a gap in current evidence that children in rural areas experience similar effects as their urban counterparts, there is evidence that the responsible compounds in urban pollutants also exist near agricultural areas (Gomez, Parker, Dosman, & McDuffie, 1992; O'Hara, Wiggs, Mamedov, Davidson, & Hubbard, 2000).

Given the relationship between asthma and PM, one might hypothesize a linkage between asthma and drought conditions. Drought in Southern California may increase asthma-related morbidity in children**.** California's most severe drought took place between 2012 and 2017 (Barreau et al., 2017; Griffin & Anchukaitis, 2014), of which four years were declared a government state of emergency. During a drought or other environmental event, individuals impacted by health inequities are disproportionately impacted due to health disparities and the financial burdens of health care. These inequities extend to the Imperial County, one of the most medically underserved counties in California (Arballo et al., 2014). In 2011-2012, while the California drought was approaching peak severity (Griffin & Anchukaitis, 2014), Imperial County's rate of asthma-related ED admissions for children was among the highest in California and twice the rate of emergency department visits for California overall (Arballo et al., 2014), putting nearly 52,000 children in the area at risk of health consequences from dry and dusty air (Bureau, 2015).

Economic inequities have long been a determining factor in individuals' abilities to seek and obtain health care. The 2013 median family income of Imperial County was over 25% below the median national family income, and 23.3% of families were below the federal poverty level, compared to 15.9% in the United States (Arballo et al., 2014). As a result, families may be unable to afford medication in order to adhere to asthma guidelines or move away from the area in order to reduce children's exposure to poor air quality (Bureau, 2015). Given the long-term respiratory complications in children as a result of air pollution, in addition to the area's substantial agricultural industry that has been affected by an abnormally dry climate, it is important to focus research efforts on the pediatric population, which is most at risk from a lifespan, geographic, and health-disparities perspective prior to the next environmental event.

The Imperial Valley region, contained within Southern California's Imperial County, includes the cities of El Centro and Calexico in addition to smaller, agriculturally-based towns (Figure 1). Imperial Valley's air quality is considered to be marginal with respect to ozone levels (O'Connor et al., 2014), a factor that, in addition to airborne particulate matter, previously has been found to be correlated with asthma-related hospital visits in urban areas (Moore et al., 2008). Additionally, the impact of anthropogenic climate change and drought on farmers in the Central Valley (north of Imperial Valley) has been mentioned in government reports (O'Connor et al., 2014), and a link has been suggested between asthma and agricultural chemicals such as pesticides (Nordgren & Bailey, 2016). However, there has yet to be any direct investigation into the impact of drought on respiratory disease in agricultural areas, and no academic studies have investigated the impact of this particular region's environmental exposures on human health.

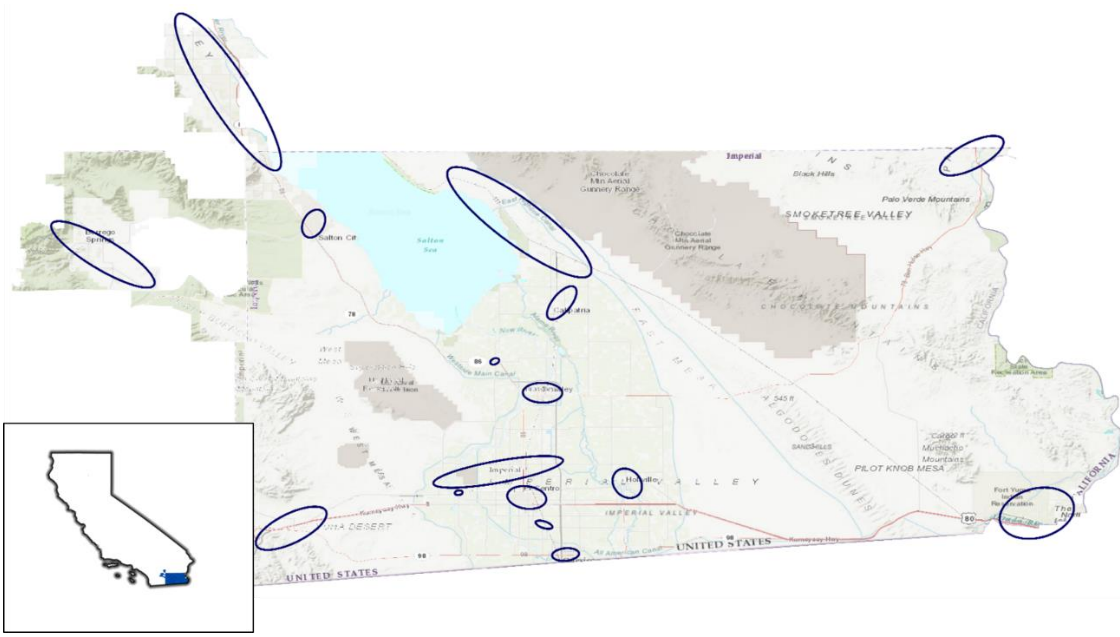

Figure 1. Imperial County, including the Salton Sea, surrounding cities and towns, and elliptical ZIP code population buffers. Created with ArcMap.

Despite its naturally arid climate, the Imperial Valley has become one of the most productive agricultural regions in California through the import of water for irrigation from the Colorado River [20]. A unique feature of this region is the Salton Sea, located near the center of the Imperial Valley, which is a landlocked geologic depression without natural feeding rivers. As a result of the arid climate, most water inflow originates from irrigation used for the 475,000 acres of farmland in Imperial Valley via two southern drainage streams within Imperial County and one northern stream, originating in Riverside County. Consequently, the water level of the Salton Sea is almost entirely dependent on agricultural irrigation runoff (Orlando, Smalling, & Kuivila, 2006), with 75% originating from agricultural drainage from Imperial Valley (Xu, Bui, Lamerdin, & Schlenk, 2016). Presently, the water level has been diminishing as a result of evaporation in the setting of decreased precipitation and river flow. Contamination with nitrogen compounds from farming, in addition to the increased area of exposed dry lake bed, have the potential to contribute to worsened asthma symptoms (Bloudoff-Indelicato, 2012).

The purpose of this research is to determine how exposure to wind patterns originating from the Salton Sea may impact rates of pediatric asthma emergency department visits in Imperial County. In addition, the mediating effect of drought conditions on this relationship is explored.

Methods

Ethical Considerations

Institutional Review Board protocols were approved by the University of Virginia Social and Behavioral Sciences and the California Office of Statewide Hospital Planning and Development (OSHPD).

Data Source

Daily de-identified ED admission data were obtained from the California OSHPD for children from ages two to 18 years old. Data were not collected for children under two because of documented difficulties in properly diagnosing asthma in infants (Wright, 2002). The impact of drought and pollutants on younger children versus older children and adolescents was assessed by dividing patient ages into categories of early childhood (age 2-5), middle childhood (age 6-11), and adolescence (age 12-18).

The data requested included all pediatric patients with a listed residency within Imperial County. This included ED admissions at hospitals outside the county, as emergent cases are transported via helicopter to San Diego. Data for each ED admission included age of the patient, ED admission diagnosis code(s), and the ZIP code of the patient's residency, assumed to be the location of exposure and onset of symptoms. As the purpose of this study was to evaluate the potential effects of drought on pediatric health, ED admission data were requested for the years 2006 through 2016 with the goal of encompassing the years during and surrounding the recent California drought.

Data Extraction

International Classification of Disease (ICD) diagnosis codes to be included in the study were taken from the most recent Agency for Healthcare Research and Quality (AHRQ) Pediatric Quality Indicator Specification for Asthma. An additional eight diagnosis codes were included as well, following the methods of Szyskowicz et al. (2018) to encompass other presentations or complications resulting from acute respiratory distress or disease, including acute bronchitis, allergic alveolitis, and acute respiratory failure. Diagnosis codes in ICD-9 format were used for entries before the fourth quarter of 2015, when the ICD-10 system came into use, after which point the ICD-10 codes reported were converted to ICD-9 format.

The data request from the California OSHPD returned 28,667 records for ED visits matching the diagnosis criteria. Secondary diagnosis codes present in the record were considered for inclusion; however, no secondary diagnosis codes for this patient population were relevant to the inclusion criteria for asthma and related respiratory disease. Therefore, only the primary diagnoses were applicable to the inclusion criteria.

Population Characteristics

The Imperial Valley region of Southern California has a primarily Hispanic population, and children and adolescents in this community who experience asthma and other respiratory disease may experience health disparities in the form of access to healthcare or heightened exposure to environmental triggers. Individuals who identify as Hispanic or Latino comprise the country's largest minority group, and the disproportionate number of childhood asthma cases in this population has contributed to health disparities, including a 21% increase in country-wide hospital charges due to asthma compared to any other ethnic group (Carter-Pokras, Zambrana, Poppell, Logie, & Guerrero-Preston, 2007).

However, due to established inconsistencies in self-reported race and ethnicity data and the known ethnic and genetic complexities of those who identify as Hispanic or Latino (Salari & Burchard, 2007), the decision has been made to omit the variable of race/ethnicity from data collection here. Patient age groups are the only demographic characteristic addressed in this research.

Population Distribution

This study was limited by the granularity of patient information, which contained only ZIP code-level information about a patient's residence. California's Imperial County contains some ZIP codes that are sparsely populated and portions of ZIP codes that are either sparsely populated or not inhabited. Therefore, the establishment of exposure by airborne particles required a more precise estimation of the likelihood of a child's location within the ZIP code. The 2010 US Census Block population data were used to create a population-weighted geographic buffer for each of the county's ZIP codes using the Directional Distribution (Standard Deviational Ellipse) tool in ESRI's ArcMap (Environmental Systems Research Institute, Inc., Redlands, California). This allowed the central tendency and dispersion of the population to be mapped as a one standard deviation ellipse polygon. Due to the concentration of population centers in cities and towns within the county and the lack of populated areas in the surrounding desert areas, it is believed that the majority of the population's likely location was accounted for within these buffers without including sparsely or non-populated areas as areas of exposure. Because of the small population sizes of some ZIP codes and consequent lack of statistical power, no differentiation was made between ZIP codes in the final analysis.

Exposure Model for Airborne Pollutants

The methods used to model exposure from airborne pollutant trajectories have been described at length in a separate publication (Doede, Davis, & DeGuzman, 2020) and therefore are only summarized here. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used in conjunction with dispersion modeling and meteorological data to determine the days on which exposure from wind-blown particles, originating from the Salton Sea, were likely to occur. This allowed the tracking of a theoretical parcel of air from its origin point over the course of a twelve-hour period. Trajectory runs were repeated every six hours for each day in the study period. When the plume associated with a modeled trajectory crossed an established geographic population buffer in the area, the day on which the 12-hour trajectory began was recorded as an exposure day for that ZIP code and was matched to ED admissions for that ZIP code.

Using methods previously described (Doede et al., 2020), each trajectory for the study period was assigned to one of eleven categories, each of which describes the shape, direction, and strength of the wind pattern, using a classification and discrimination approach (Figure 2). The resulting daily patterns were then linked to ED admissions to determine if certain climatological conditions were associated with days of high ED admissions. The presence of a dispersion plume within a ZIP code buffer was noted to account for the likely presence of particles around each HYSPLIT trajectory: if a point along a trajectory did not qualify as an exposure but the average plume for the assigned trajectory group was, in fact, shown to cross a ZIP code buffer, the associated day was counted as an exposure day.

In addition to the establishment of exposure vs. non-exposure days using latitude and longitude coordinates, a daily mixing depth and ventilation coefficient was calculated to take into account regional atmospheric stability. The afternoon mixing depth, or the extent of the atmospheric layer to which turbulence and convection lead to the mixing of air pollutants, was extracted from the North American Regional Reanalysis data set for the study time period. The mixing depth was multiplied by the daily mean wind speed to calculate the ventilation coefficient for each day in the study period. As a ventilation coefficient of less than 6,000m^2/s is generally accepted to indicate a potential for pollution exposure (Madany, 1974), trajectory events from the spatial points data frame that qualified as exposure days based on latitude and longitude were filtered out if the ventilation coefficient for that day was over 6,000m^2/s. This adjustment ensured that only those days when the atmospheric stability in the region could have allowed for particulate matter from the origin point to reach the population were classified as potential exposure days. All days that did not fit this criterion for exposure were classified as non-exposure days.

Drought Intensity Measures

Drought severity data were used to establish a relationship between drought, air trajectory exposure, and the effect of these factors on lung health and healthcare utilization. The United States Drought Monitor (USDM) is widely used and accepted within the field of environmental science as well as public health (Berman, Ebisu, Peng, Dominici, & Bell, 2017). The USDM is an amalgam of several established drought indices, each of which incorporate various drought severity indicators (National Drought

Mitigation Center, 2017b). Drought severity, characterized as a Drought Severity and Coverage Index (DSCI), was calculated weekly. Areas in the region of interest were categorized by drought severity, from D0 (abnormally dry) to D4 (exceptional drought). The DSCI was then calculated as the weighted sum of the percent of an area that has been categorized as equal to or worse than one of the five categories (National Drought Mitigation Center, 2017a).

In addition to the DSCI as a regional measure of drought severity, the elevation of the Salton Sea water level was used in the analysis. It is known that the water level of the Salton Sea has been diminishing, and as the Salton Sea is a water body with no natural feeding rivers and depends solely on agricultural runoff, this measure was used to create a more proximal indicator for drought severity in Imperial County that might better reflect the impact of drought on the population's exposure to dust from the Salton Sea. The USGS Water Resources data set (USGS, 2020) was used to obtain the Salton Sea daily mean lake surface elevation. Surface elevation values were used as an indicator of exposed lakebed that might be susceptible to becoming airborne.

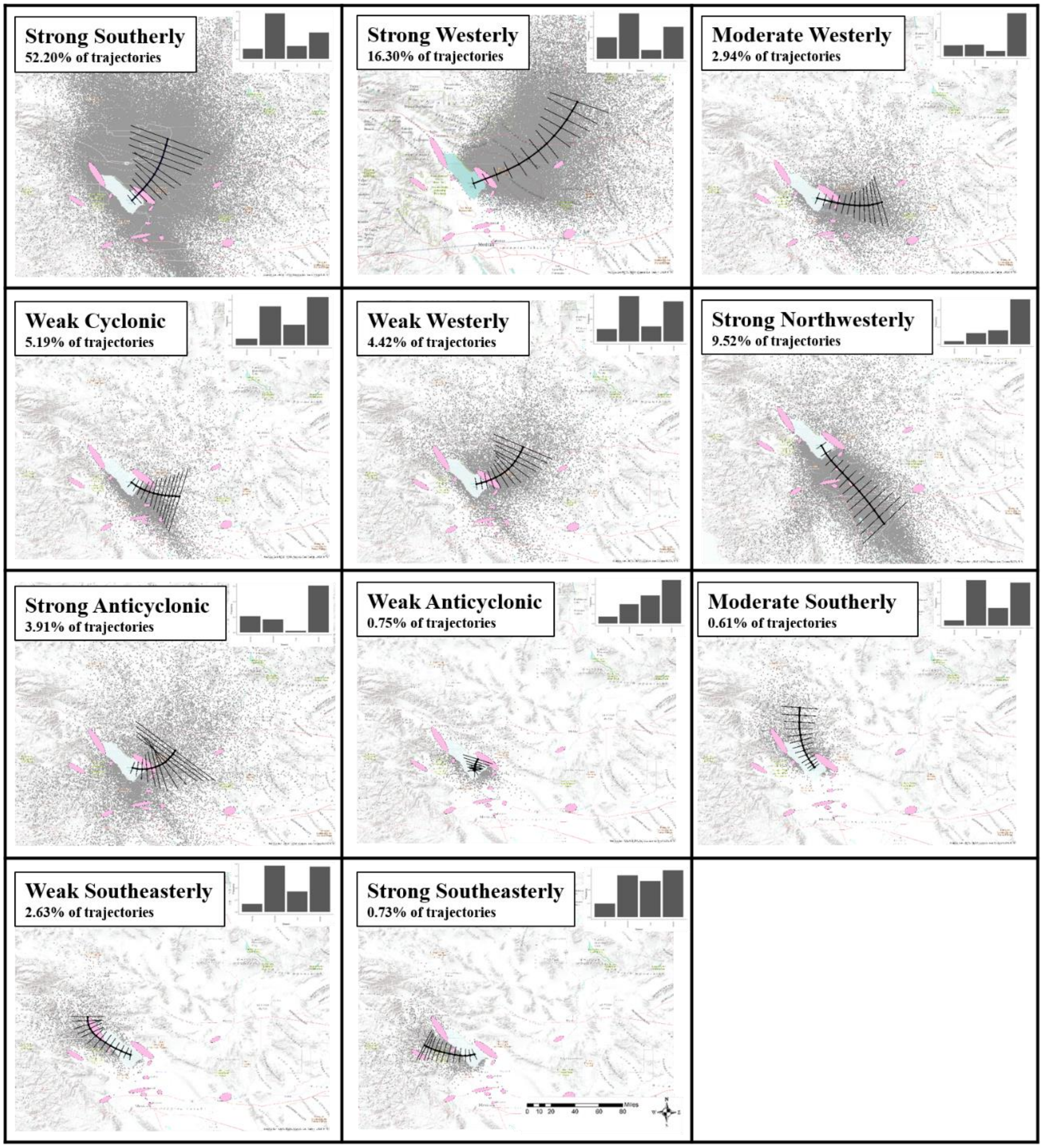

Figure 2. Dispersion points and mean hourly trajectory positions for each trajectory group originating from the Salton Sea with error bars of the mean hourly distance of all trajectories from the overall mean hourly positions. Histograms represent the relative frequencies of each trajectory group by season, beginning with spring. Created with Google Earth and NOAA HYSPLIT-Web.

Data Analysis

Data analysis was conducted using R Studio software version 1.1.383. Conditional Poisson regression was carried out to determine the risk of Salton Sea dust exposure to pediatric asthma. The daily count of ED admissions was measured against exposure from trajectory and dispersion runs crossing each ZIP code buffer in addition to the moderating effect of drought in this relationship. As is common in datasets of daily admissions, counts of zero or one are quite frequent. The conditional Poisson was chosen for its ability to handle the presence of over-dispersion and zero occurrences as well as the stratification of data across month, year, and day of week to account for time-dependent variations. The stratification aspect of the conditional Poisson model is also capable of adjusting for seasonality of the ED admission data (Armstrong, Gasparrini, & Tobias, 2014), which was an important consideration for this study region and patient population. Descriptive statistics were calculated to examine the presence of over-dispersion and zero occurrences. Results are reported in terms of excess relative risk (ERR), defined as the ratio of the excess incidence rate to the background incidence rate. A p-value of <0.05 with a 95% confidence interval (CI) was considered statistically significant. The frequency of ED admissions compared across trajectory groupings was also examined with a Kruskal-Wallis Chi-square test using ED admission frequency, adjusted for the overall frequency of each trajectory group.

Results

Descriptive Statistics

The analysis provided 133,967 individual trajectory observations from three origin points across eleven years and 16 ZIP codes. Of these, 50,070 qualified as a positive exposure by generating some concentration of particulates in one or more population buffers. ED admissions were cross-referenced with the ZIP codes over which these trajectory observations passed. This includes multiple counts for trajectories that were capable of crossing more than one ZIP code buffer (i.e., a single trajectory has the capability of causing an exposure event over multiple ZIP codes, and as exposures are measured based on a single ZIP code buffer crossing, one trajectory in this case will be counted multiple times).

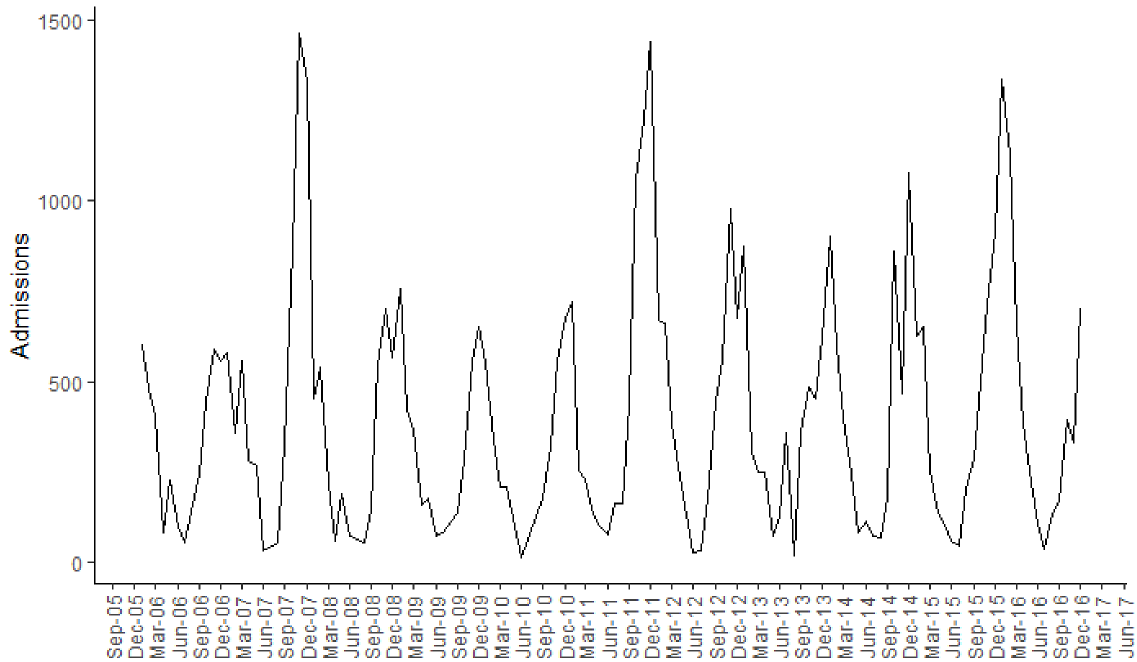

Figure 3. Time series of total monthly pediatric ED admissions for exposure days over the study area, 2006–2016.

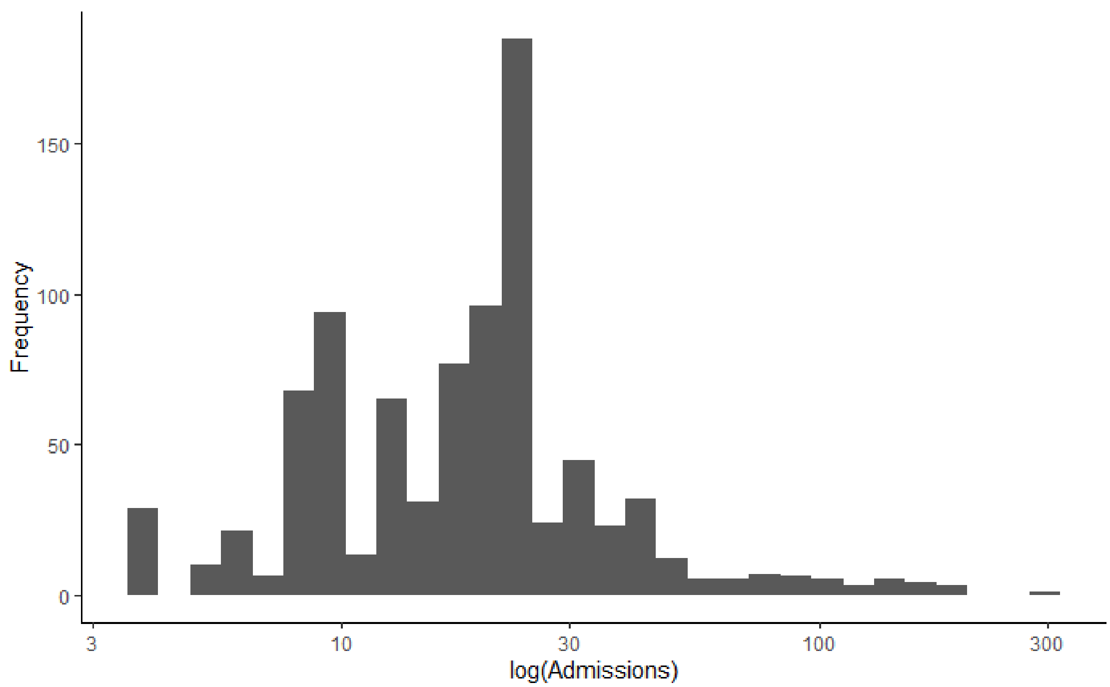

Figure 4. Log-transformed distribution of daily admission counts.

The ED admission data yielded 19,889 total admissions for the study period, with the majority of the days in the study period containing one or zero admissions per day, per ZIP code (Figure 4). The age (mean +/- std. dev.) of patients was 7.68 +/- 4.80. When stratified by age, a Kruskal-Wallis Chi-square test showed no significant difference in ED admission frequency between the age groups.

Table 1. Descriptive statistics of emergency department admissions, by age group.

	Admissions (n)	Percent of admissions	Mean (age, years)	Standard Deviation (age, years)
Early childhood (ages 2-5)	12,017	43.62	3.50	1.29
Middle childhood (ages 6-11)	8,914	32.36	8.50	1.87
Adolescent (ages 12-18)	6,618	24.02	15.00	2.16

Table 2. Descriptive statistics of emergency department admissions, by ICD-9 code (n=28,817). *=AHRQ Pediatric Quality Indicator Specification for Asthma.

Diagnosis and ICD-9 Code*	**Frequency (n)**	**Relative Frequency (%)**
465.0, Acute laryngopharyngitis	3	0.0104
465.8, Acute upper respiratory infections of other multiple sites	3795	13.169
465.9, Acute upper respiratory infections of unspecified site	13246	45.966
466.0, Acute bronchitis	4066	14.110
466.1, Acute bronchiolitis	0	0.000
493.00, Extrinsic asthma, unspecified	81	0.281
*493.01, Extrinsic asthma with status asthmaticus	5	0.0174
*493.02, Extrinsic asthma with acute exacerbation	99	0.344
493.10, Intrinsic asthma, unspecified	4	0.0139
*493.11, Intrinsic asthma with status asthmaticus	2	0.00694
*493.12, Intrinsic asthma with acute exacerbation	0	0.000
493.22, Chronic obstructive asthma with acute exacerbation	3	0.0104
*493.81, Exercise induced bronchospasm	19	0.0659
*493.82, Cough variant asthma	28	0.0972
*493.90, Asthma, unspecified type	2456	8.523
*493.91, Asthma, unspecified type, with status asthmaticus	124	0.430
*493.92, Asthma, unspecified type, with acute exacerbation	4860	16.865
495.0-9, Extrinsic allergic alveolitis	2	0.00694
506.0-9, Respiratory conditions from chemical fumes & vapors	5	0.0174
518.81, Acute respiratory failure	19	0.0659
518.84, Acute and chronic respiratory failure	0	0.000

Effect of Exposure from the Salton Sea on Pediatric Emergency Department Visits

There is a statistically significant relationship between exposure from wind or dust originating from the Salton Sea and the likelihood of pediatric ED admissions on days experiencing exposure (Table 3). Allowing for first-order autocorrelation of the conditional Poisson regression using Brumback's method, the estimated ERR for ED admission was 18.70% (p = 0.012, 95% CI = 3.936 – 35.623), i.e., there was an 18.70% higher risk of ED admission on days classified as exposure days compared with non-exposure days.

Moderating Effect of Drought on Pediatric Emergency Department Visits

The moderating effect of drought is summarized in Table 3. The addition of the DSCI drought indicator indicated that there is no statistically significant moderating effect of drought on the relationship between exposure and pediatric ED visits (ERR 1.005%, 95% CI = -0.0.084 – 1.111, p = 0.714). The substitution of Salton Sea water elevation as a proxy indicator for drought yielded a positive relationship between lakebed exposure and ED visits, though it was also a non-statistically significant modifier for this relationship (ERR 104.44 %, 95% 8.44 – 285.426, p = 0.316).

Table 3. Analysis of Salton Sea dust exposure and moderating effects of drought on emergency department visits for pediatric asthma. (ERR=excess relative risk; CI=confidence interval; ED=emergency department; DSCI=drought severity coverage index)

Model/outcome variable	Coefficient (exposure day)	Exponentiated coefficient	ERR (%)	Std. Error (%)	95% CI	p-value
Exposure vs. ED visits						
Exposure	0.171	1.187	18.696	7.023	3.911 – 35.584	0.0116
Moderating effect of drought						
DSCI	0.00510	1.005	0.512	0.414	-0.0.084 – 1.111	0.714
Water level	0.715	2.044	104.44	43.505	8.44 – 285.426	0.316

Effect of Meteorological Patterns on Pediatric Emergency Department Visits

A comparison of ED admissions across trajectory group assignments indicated that there were three trajectory types most strongly associated with ED admissions during exposure events. When stratifying ED admission counts by trajectory grouping, one-way ANOVA showed a significant difference between trajectory groupings and counts of ED admission frequency ($F=2128$, $p<0.001$). Most notably, while the Strong Southerly group was most common throughout the study period, the Strong Northwesterly and Weak Southeasterly groups were both among the most frequent groups and more common than would have been expected based on their climatological frequency (Figure 5). The Weak Southeasterly group is the pattern most likely to expose the majority of the study population to airborne contaminants from the Salton Sea, given the location of the largest population centers to its south and west.

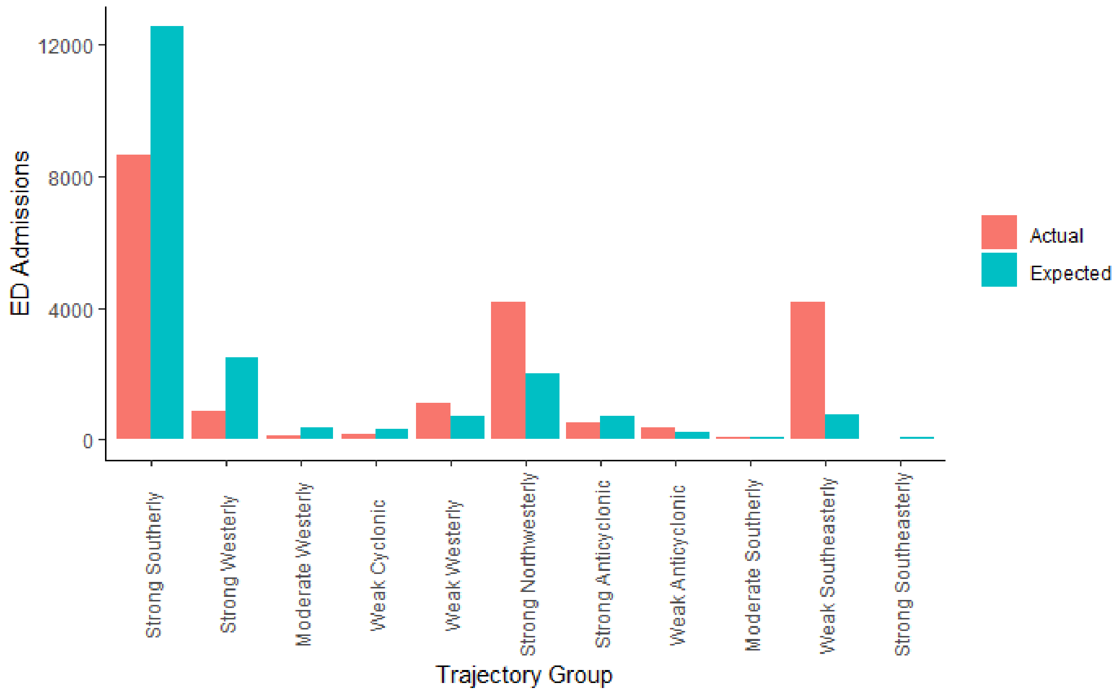

Figure 5. Comparison of emergency department visits for pediatric asthma across trajectory groups, adjusted for climatological frequency, compared to the expected number of visits.

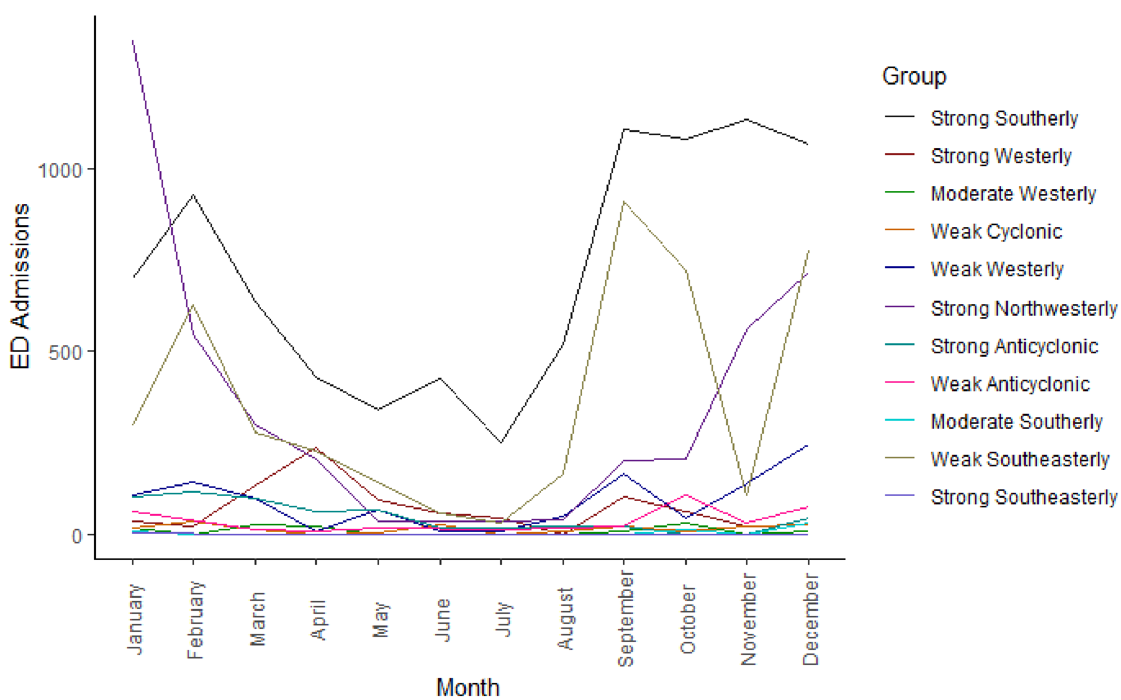

Figure 6. Monthly ED visit frequency by trajectory group.

Ventilation Coefficient

The ventilation coefficient, calculated as the maximum mixing depth multiplied by the mean daily wind speed, was used as an indication of atmospheric stability and the potential for the exposure of humans to airborne pollutants. In the analysis of the effect of pollution exposure on ED admissions, only days with a ventilation coefficient that was less than 6,000 m^2/s were included for this reason.

It has been previously established that the ventilation coefficient in this region carries a seasonal component, with ventilation coefficients tending to be most commonly below this threshold during the fall and winter months and higher during the spring and summer (Doede et al., 2020), facilitating human exposure to pollutants. To verify the ventilation coefficient's effect on ED admissions at the chosen threshold, a one-way ANOVA demonstrated a statistically significant difference in the mean daily admissions between days with a high compared with a low ventilation coefficient. ($F=2064.7$, $p<0.001$) with a significant difference between seasons. At the $p<0.001$ level, post-hoc comparisons with Tukey HSD indicated that the mean daily admission rate was significantly different between all seasons, with the exception of spring vs. summer, with ED admissions peaking in the fall and winter months.

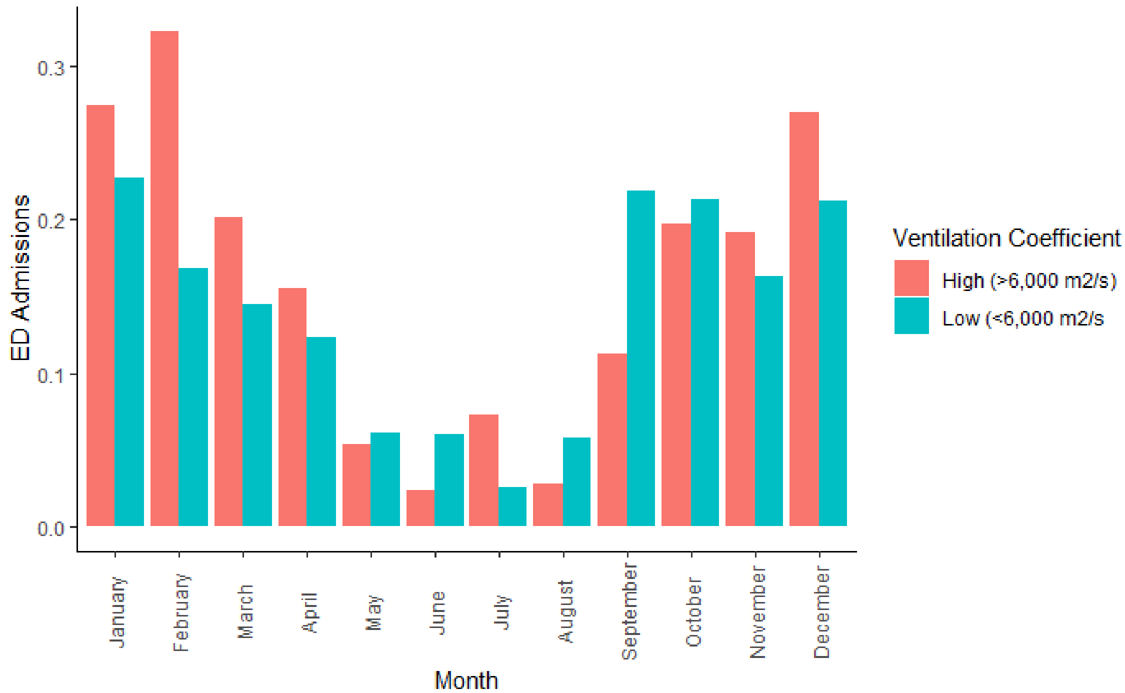

Figure 7. Mean daily ED admissions, by ventilation coefficient and month.

Discussion

The presence of a statistically significant excess relative risk of ED admissions on days with exposure events indicates the strong possibility that airborne particles originating from the Salton Sea contribute to pediatric asthma in the area. The ERR for ED admissions vs. exposure indicates that on days with exposure events from the Salton Sea, there is an 18.70% increased risk of a child visiting the hospital for asthma or other respiratory disease compared with days with no exposure event. The width of the 95% confidence interval (3.936% - 35.623%), however, is notable, suggesting that in addition to small daily sample sizes, other, unmeasured variables or pollutant sources may be involved. Although future studies may benefit from increasing the study time period or extending the sample population to include adults, the current findings are consistent with the study area, where several factors may contribute to poor air quality. This may indicate, for example, the local pollutants from the agriculture industry or factory pollution to the south of the United States-Mexico border are contributing to ED admissions as well.

The seasonality of these variable is important, with many more ED admissions occurring in the fall and winter months when the area's ventilation coefficient was lower and the atmosphere more stable. There are almost no exposures from April through September, which is also consistent with observed declines in ED admissions during this time of year.

Effect of Trajectory Groupings

While one of the most common trajectory grouping includes a dispersion pattern that would both cause exposure to the population centers in the study area and originate from the Salton Sea, two trajectory groupings, including the most common Weak Southeasterly type, indicate a contribution to asthma cases originating from the south. This is consistent with the uncertainty surrounding the excess relative risk of ED admissions associated with exposures and the suggestion that more than one exposure source may contribute to ED admissions.

As with the overall effect of exposure on ED admissions, the physical attributes of the study area may explain the presence of more than one trajectory group that contribute more frequently to ED admissions. When adjusting for trajectory frequency, the Strong Northwesterly current, which is theoretically most associated with exposure from the Salton Sea, is among the trajectory groups most likely to be associated with elevated risk of ED admissions. However, the group most commonly associated with high admissions is the Weak Southeasterly type. Although the Kruskal-Wallis test indicated no statistically significant difference between trajectory groups in relation to ED admissions, it is notable that visually, the most common trajectory group might be associated with pollutants from south of the Imperial Valley, for example, possibly emanating from south of the US-Mexico border.

In addition, it is notable that the Weak Southeasterly type occurs most frequently during the summer months, when ED admissions are least common. On the other hand, the Strong Northwesterly wind, which would be most associated with wind originating from or near the Salton Sea, occurs most commonly during the fall and winter months, during which time ED admissions are more common. Nevertheless, these results indicate a possibility of the Salton Sea's influence on pediatric respiratory health or, potentially, desert dust originating from north of the Salton Sea. There are, however, no large cities north of the Salton Sea, though desert dust may play a role.

Moderating Effect of Drought

Drought severity using the DSCI as an indicator was not a statistically significant moderator in the relationship between exposure from the Salton Sea and ED visits. This may be due to the fact that this drought index covers a large area and may not be indicative of the local conditions that may affect patients in the study area. This led to the introduction of the Salton Sea water level, with the idea that previously submerged particles would become increasingly exposed to the air as drought severity, and therefore the area of exposed lake bed, increased. However, the Salton Sea's water level also did not show any statistically significant impact on the relationship between exposures and ED admissions. While this may indicate that drought does not significantly contribute to ED admissions or moderate the relationships examined in this study, the possibility also remains that any impact of drought has a slow-response effect, which could not be captured using our approach and should be further examined in the future.

Study Limitations

A known obstacle in calculating community-level characteristics such as environmental exposures or individual health is the obligation to use area-level estimations as proxies for the individual while controlling for known information about the patient or family (Barry & Breen, 2005). The ecological model also introduces the possibility that confounding variables, known or unknown, may exist in the surrounding environment. The current study only analyzes data that reflects the potential for outdoor air pollution. Therefore, effects of indoor air pollution, such as household dust and tobacco smoke, are not considered in this research.

In addition, the purpose of this study was to assess the influence of the Salton Sea on airborne pollutants and respiratory health. Therefore, other outdoor pollutant sources are possible in this area but are not explored here. For example, particularly for a retrospective study, it is not possible to ascertain whether local sources of air pollution, such as chemical fumes from agricultural activity, may contribute to exposure and health outcomes. Finally, the factories in Mexicali, Mexico, immediately south of the United States-Mexico border, are a source of air pollution that may partially account for Imperial County’s air quality issues.

Finally, additional measures of pollution such as air quality data from local monitoring stations, should be included in the analysis. However, the location of air quality monitoring stations in the study area were not conducive to assessing whether distant sources, such as the Salton Sea or Mexicali, Mexico, had the potential to cause poor air quality at the locations of the monitoring stations. Air quality monitors tend to be located for regulatory purposes near local sources of air pollution, such as highways and factories.

From the perspective of available patient records from emergency departments, it should be noted that only those patients included in the analysis were those associated with a ZIP code of residence within Imperial County, California. It is commonly known that residents of Mexico commute to Imperial County, and these individuals are not be included in these data.

Conclusion

To our knowledge, this is the first study to address the possible source of pediatric respiratory disease in Imperial County. Despite some unavoidable data limitations inherent to this study, the results described here offer a model for determining and differentiating between the possible environmental factors that contribute to respiratory disease. Although other sources must be examined as well, such as local farming and pollution from nearby Mexicali, Mexico, our results suggest that the Salton Sea may be a significant contributor to ED visits in pediatric patients for respiratory complications such as asthma.

Further research into the impacts of poor respiratory health in drought areas will provide a perspective on environmental challenges in a region not previously studied at the local and regional levels. Not only are children at an increased lifetime risk for lung health and related diseases; children who are unable to participate in school or physical activities due to asthma are also at increased risk for secondary health and developmental consequences related to mental health, education, and obesity and related illnesses (Kohen, 2010; Oland et al., 2017). As airborne PM has the ability to cause systemic as well as local inflammation (Ghio et al., 2012), findings from this study may have implications for other health issues, such as cardiovascular disease (Berman et al., 2017; Powell, Krall, Wang, Bell, & Peng, 2015) and cancer (Nelson et al., 2017). The future of health will require a more robust integration with environmental science research and policy (Cook, Smerdon, Seager, & Cook, 2014).

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CHAPTER 6: SYNTHESIS AND IMPACT WITHIN PUBLIC HEALTH NURSING

The purpose of this research was to study the Salton Sea in Imperial County, California, as a potential source of airborne pollutant exposure that may explain the increased rate of asthma in pediatric patients in this county, compared with other counties in California. As the state of California recently underwent and recovered from a drought, and because the most prominent drought years also coincided with an increase in emergency department visits for pediatric asthma, it was hypothesized that the effects of drought on the Salton Sea were a moderating factor in the impact of wind-blown particles from the Salton Sea's shoreline on childhood asthma.

The driving framework behind this research is that of planetary health, which, by its nature, is a framework and field that cannot exist when based solely on one discipline. This dissertation, therefore, draws heavily from both the environmental sciences as well as the public health disciplines in order to explain the interactions between the health of human civilizations and the natural systems on which they depend. Therefore, it is critical to future research to accelerate and support interdisciplinary teams seeking to investigate issues at the intersection of environmental and human health. Nurses, and public health nurses in particular, are uniquely positioned to study this intersection. As the effects of anthropogenic climate change become more common and pronounced, vulnerable communities with existing health disparities will be affected first and most often. Public health nursing, therefore, is primed to partner with these communities and to lead evidence-based studies that target the root causes of disease so that prevention can be emphasized while maintaining a focus on the social and environmental determinants of health.

While this research did not find a strong relationship between drought and pediatric respiratory health, there is promising preliminary evidence that certain weather patterns, possibly originating from the Salton Sea, are responsible for increased emergency department visits in Imperial County. While the question of specific sources of pollution must be addressed in more detail in the future, the rate of pediatric asthma in Imperial County remains high. Therefore, other potential sources must also be investigated, and it is likely that this hazard to respiratory health does not originate from only one source. For this reason, it is important for public health nurses to have a guide to conduct these investigations. Such a research model will help to form more meaningful models about a population or region in question and, in the future, will include community research partners as well as inter-professional collaborations.