Impact of drought and airborne pollutants on pediatric asthma emergency department visits in Imperial County, California, USA

Aubrey L Doede[1], Robert E. Davis[2], and Pam DeGuzman[1]

[1]University of Virginia
[2]U. Virginia

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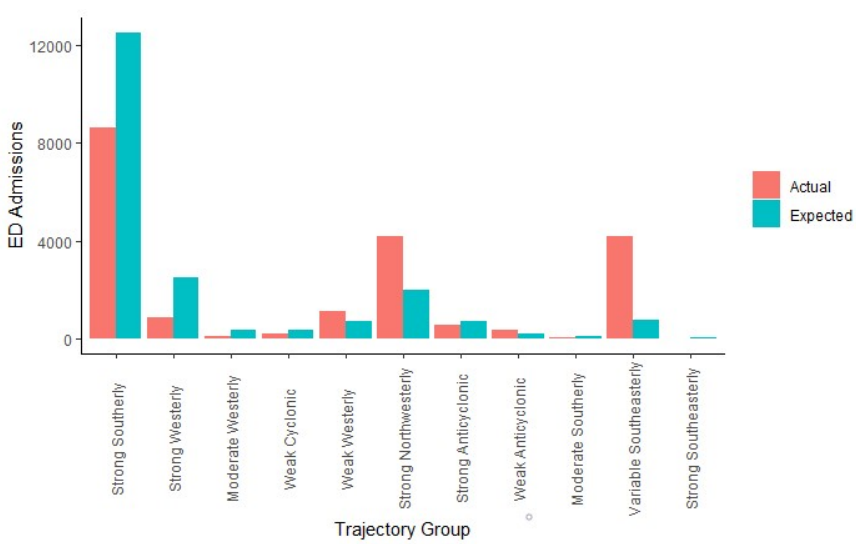
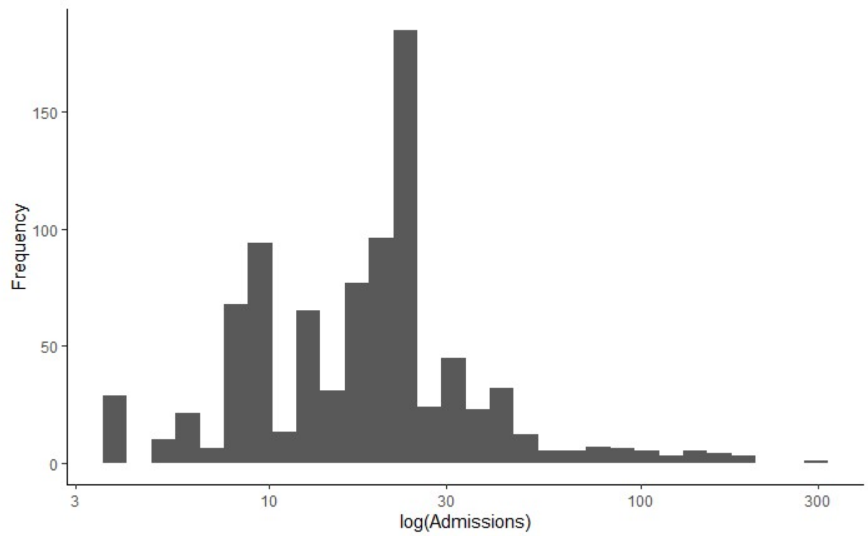
Abstract

The pediatric population is at a unique and increased risk of immediate and long-term 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 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), pointing to the possibility that particulates from the Salton Sea influence pediatric asthma. The large confidence interval is notable, suggesting the influence of additional 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 between exposure and admissions, possibly due to the slow-response impact of drought that was not captured.





Frequency
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100
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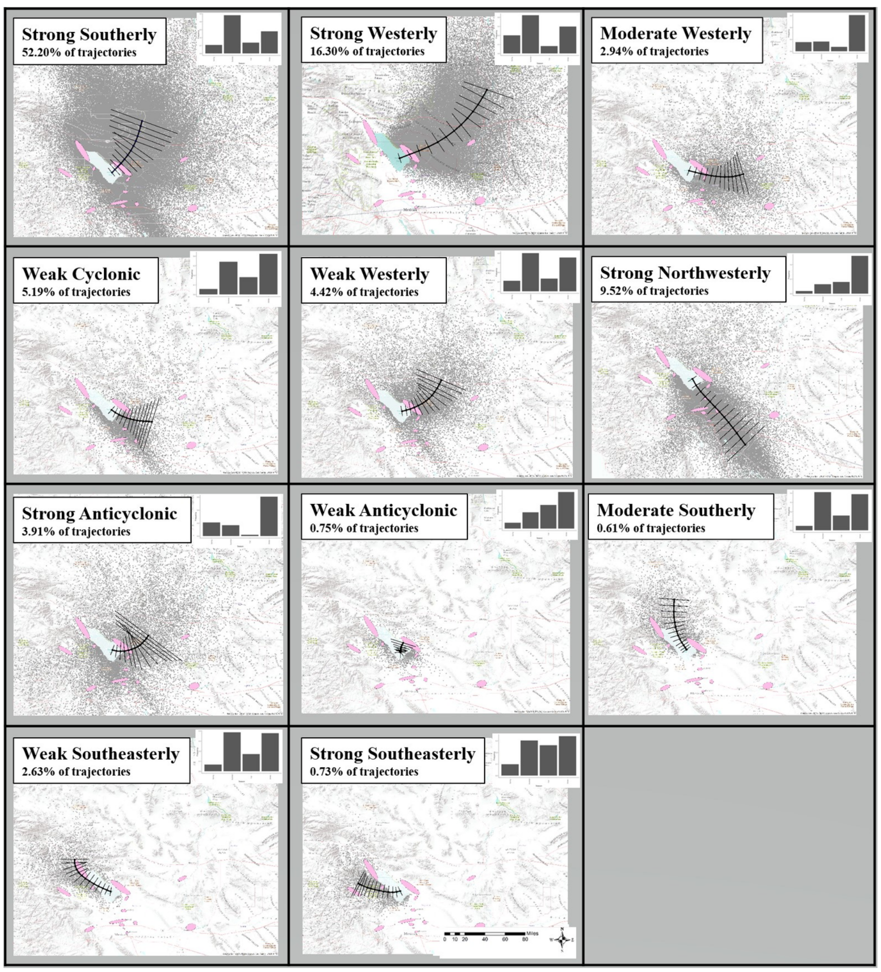
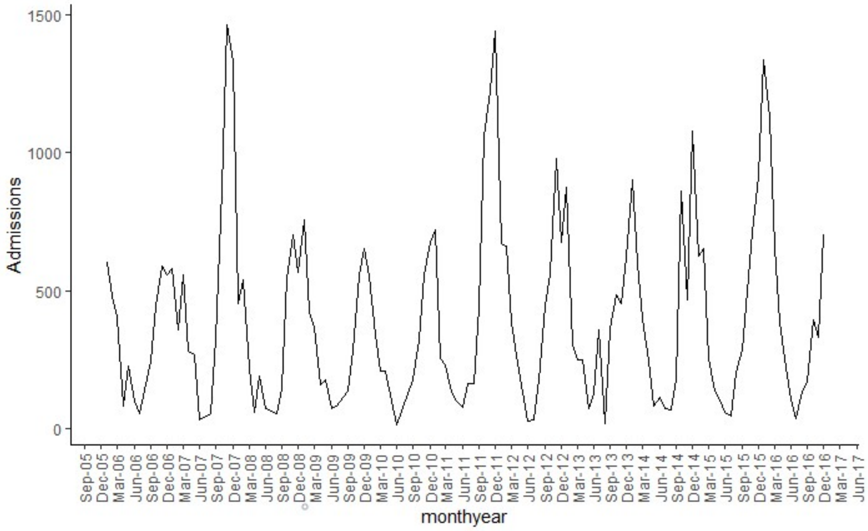
log(Admissions)



Strong Southerly
52.20% of trajectories
Strong Westerly
16.30% of trajectories
Moderate Westerly
2.94% of trajectories
Weak Cyclonic
5.19% of trajectories
Weak Westerly
4.42% of trajectories
Strong Northwesterly
9.52% of trajectories
Strong Anticyclonic
3.91% of trajectories
Weak Anticyclonic
0.75% of trajectories
Moderate Southerly
0.61% of trajectories
Weak Southeasterly
2.63% of trajectories
Strong Southeasterly
0.73% of trajectories


Admissions
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1000
500
0
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Dec-05
Mar-06
Jun-06
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Jun-07
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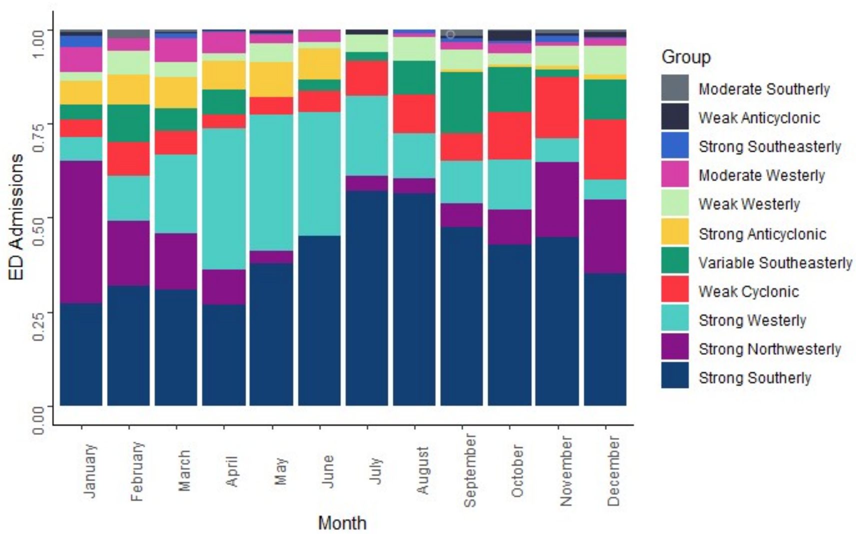
monthyear


ED Admissions
1.00
0.75
0.50
0.25
0.00
January
February
March
April
May
June
July
August
September
October
November
December
Month
Group
Moderate Southerly
Weak Anticyclonic
Strong Southeasterly
Moderate Westerly
Weak Westerly
Strong Anticyclonic
Variable Southeasterly
Weak Cyclonic
Strong Westerly
Strong Northwesterly
Strong Southerly

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

Aubrey L. Doede, [1,2*] Robert Davis, [3] Pamela B. DeGuzman [1]

[a] University of Virginia School of Nursing
225 Jeanette Lancaster Way
Charlottesville, VA 22903

[b] Present address
University of California San Diego School of Medicine
Department of Family Medicine and Public Health
9500 Gilman Drive M/C 0965
La Jolla, CA 92093-0965

[c] University of Virginia
Department of Environmental Sciences
291 McCormick Road
Charlottesville, VA 22904

*Corresponding author contact information:
aubrey.doede@gmail.com
+1 619-980-3749

Abstract

The pediatric population is at a unique and increased risk of immediate and long-term 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 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), pointing to the possibility that particulates from the Salton Sea influence pediatric asthma. The large confidence interval is notable, suggesting the influence of additional 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 between exposure and admissions, possibly due to the slow-response impact of drought that was not captured.

Keywords: Pollution; exposure; asthma; respiratory disease; pediatric

Key Points

- Imperial County, CA, has a disproportionately high pediatric asthma rate, possibly exacerbated by airborne particulates from the Salton Sea.
- A significant relationship was found between exposure to wind from the Salton Sea and pediatric asthma, compared to day with no exposure.
- Drought severity was not a significant moderator between exposure and admissions.

Abbreviations

AHRQ – Agency for Healthcare Research and Quality

DSCI – Drought Severity and Coverage Index

ED – Emergency Department

HYSPLIT – Hybrid Single-Particle Lagrangian Integrated Trajectory

ICD – International Classification of Disease

OSHPD – California Office of Statewide Hospital Planning and Development

USDM – United States Drought Monitor

PM – Particulate Matter

Funding

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Human Subjects Research

Institutional Review Board protocols were approved by the University of Virginia Social and Behavioral Sciences IRB (Project # 2018-0334-00) and the California Office of Statewide Hospital Planning and Development (Protocol ID 2018-278).

1.1. 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.

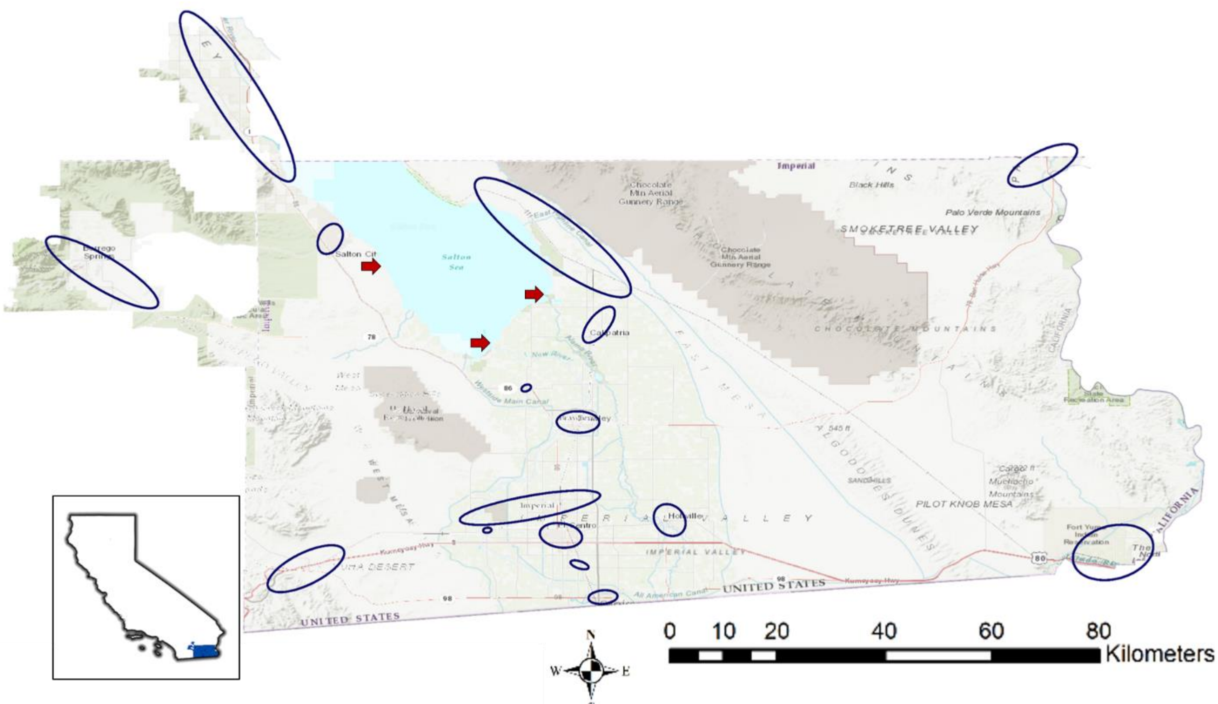

Figure 1. Imperial County, including the Salton Sea, surrounding cities and towns, and elliptical ZIP code population buffers. Created with ArcMap.

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.

2.1. Methods

2.2. Ethical Considerations

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

2.3. 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.

2.4. 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.

2.5. 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.

2.6. 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.

2.7. 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 (Figure 2). 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 3). 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.

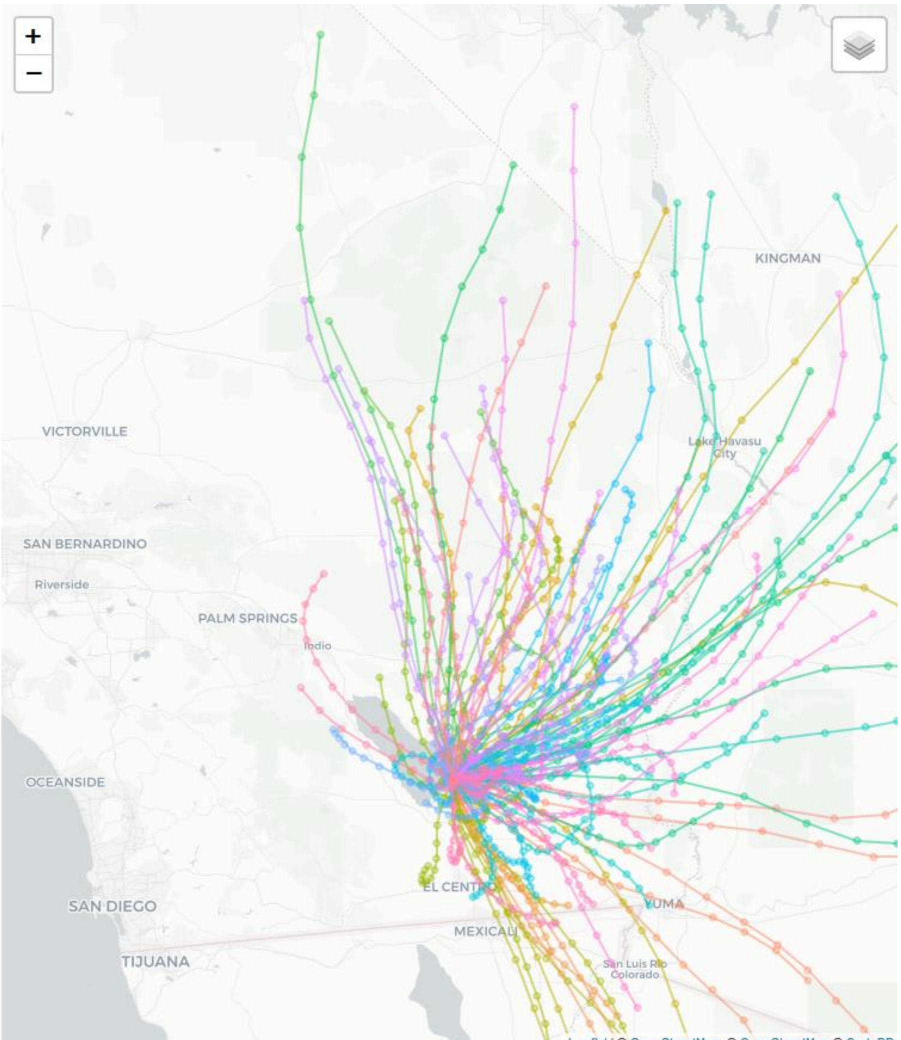

Figure 2. Example trajectory output representing air parcel movement from the Salton Sea during April, 2012. Each individual trajectory contains points indicating hourly positions of air parcels. Created using the SplitR package for R.

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.

2.8. 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)

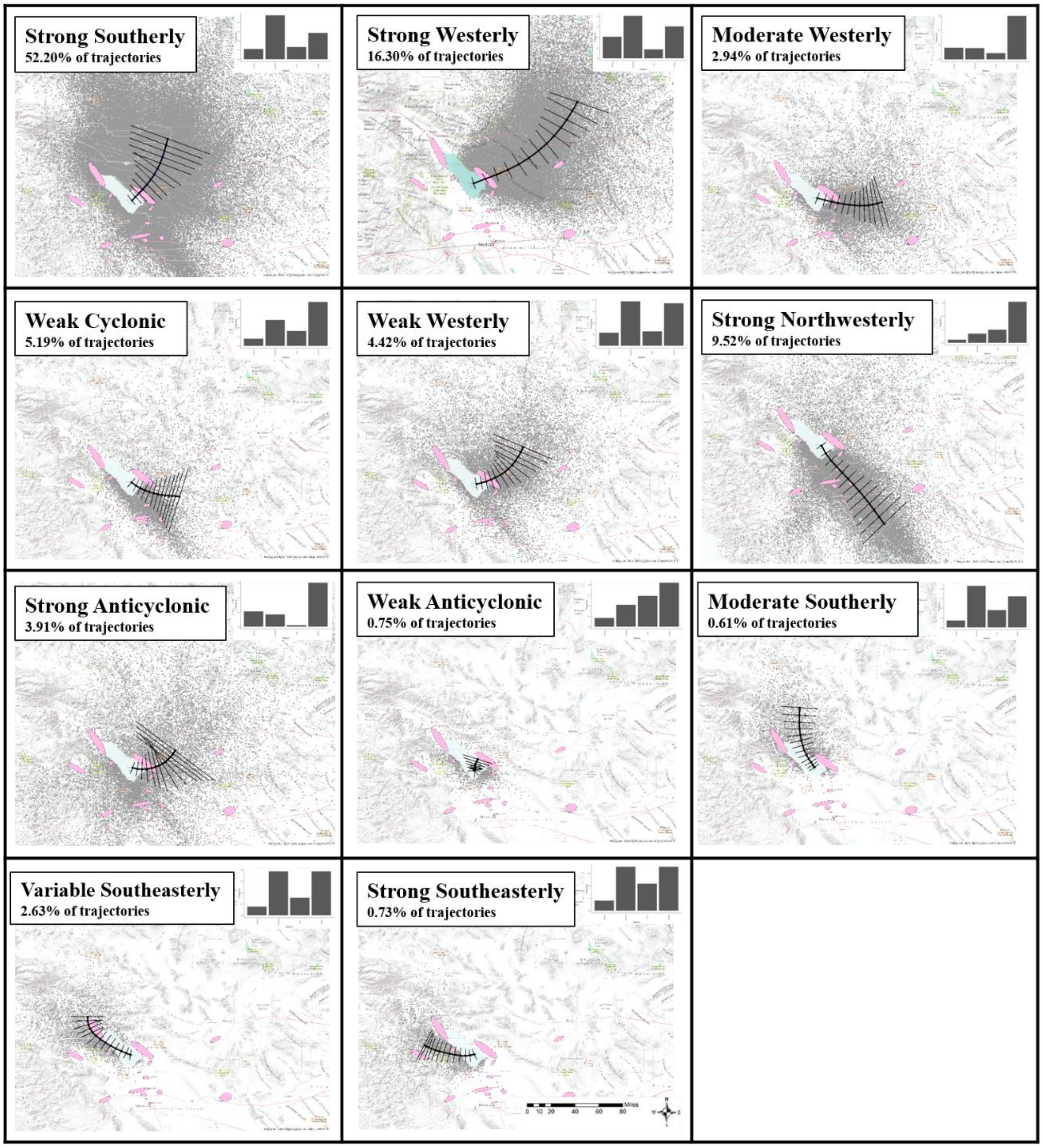

Figure 3. Dispersion points and mean hourly trajectory positions for each trajectory group originating from the Salton Sea with error bars of the mean hourly distance of all trajectories from the overall mean hourly positions. Histograms represent the relative frequencies of each trajectory group by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

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.

2.9. 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 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.

3.1. Results

3.2. 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).

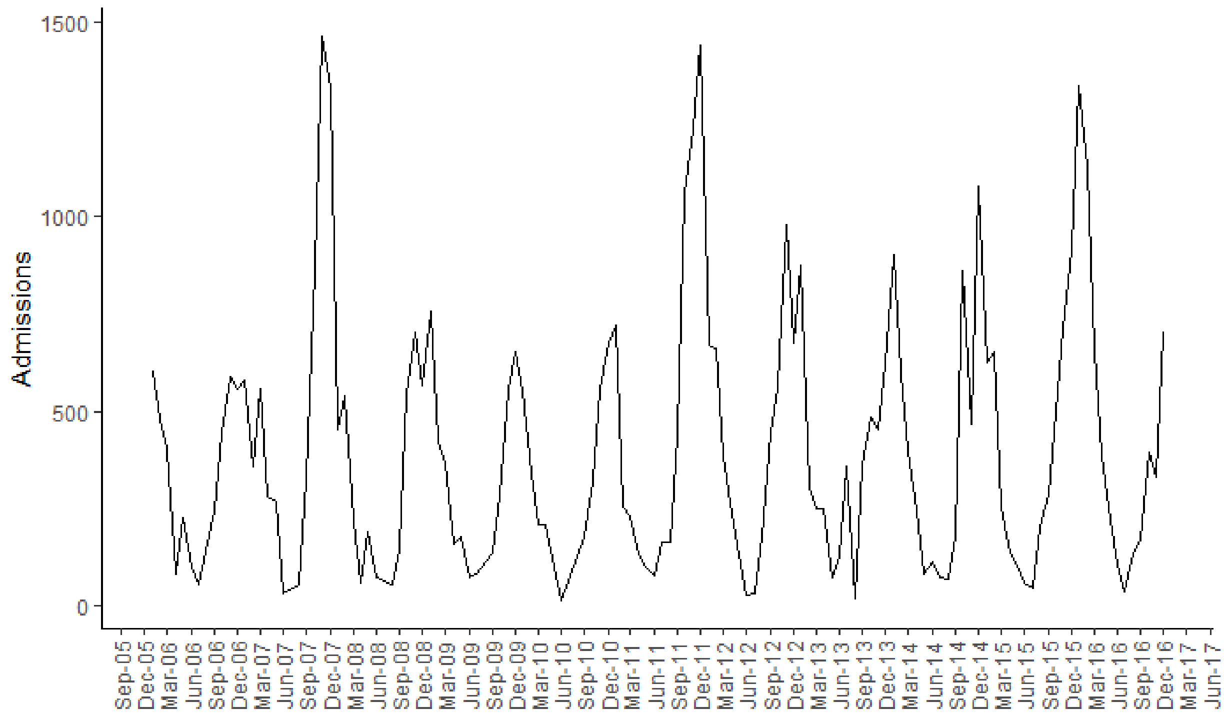

Figure 4. Time series of total monthly pediatric ED admissions for exposure days over the study area, 2006–2016.

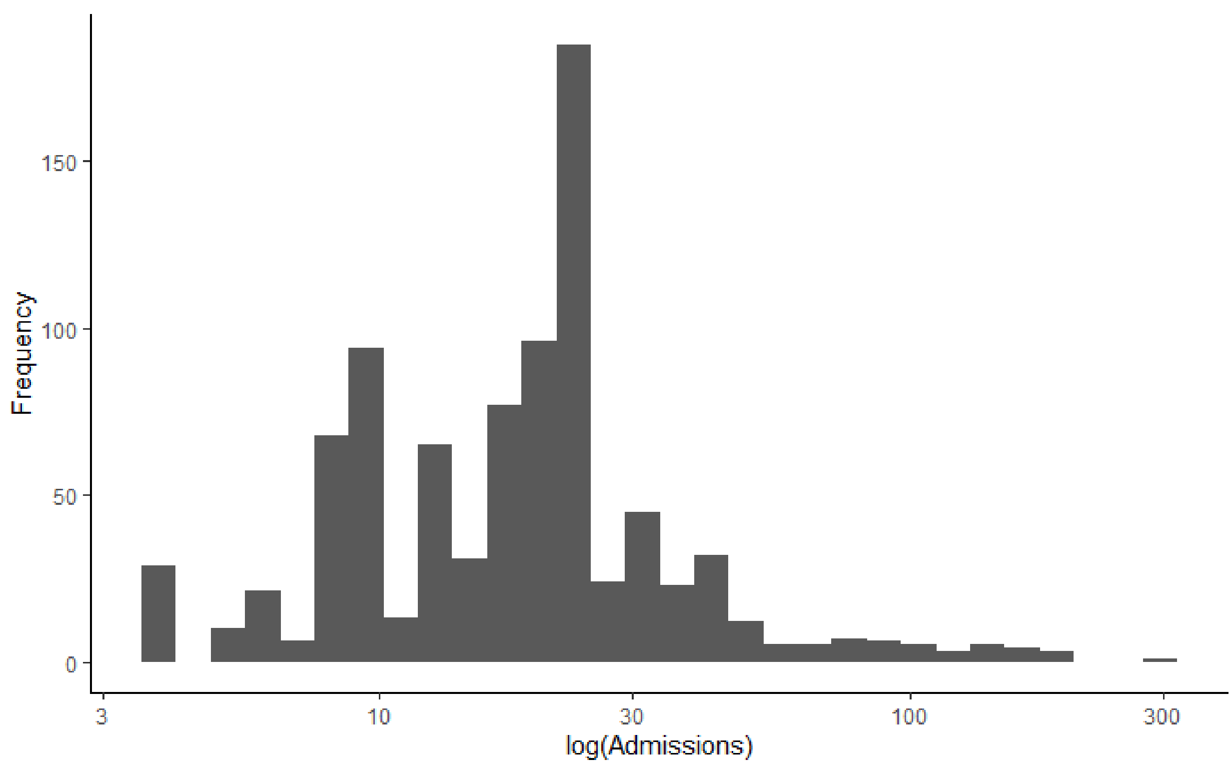

Figure 5. Log-transformed distribution of daily admission counts.

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 5). 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

3.3. 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.

3.4. 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	0.012
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

3.5. 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 Variable Southeasterly groups were both among the most frequent groups and more common than would have been expected based on their climatological frequency (Figure 6). The Variable 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 6. Comparison of emergency department visits for pediatric asthma across trajectory groups, adjusted for climatological frequency, compared to the expected number of visits.

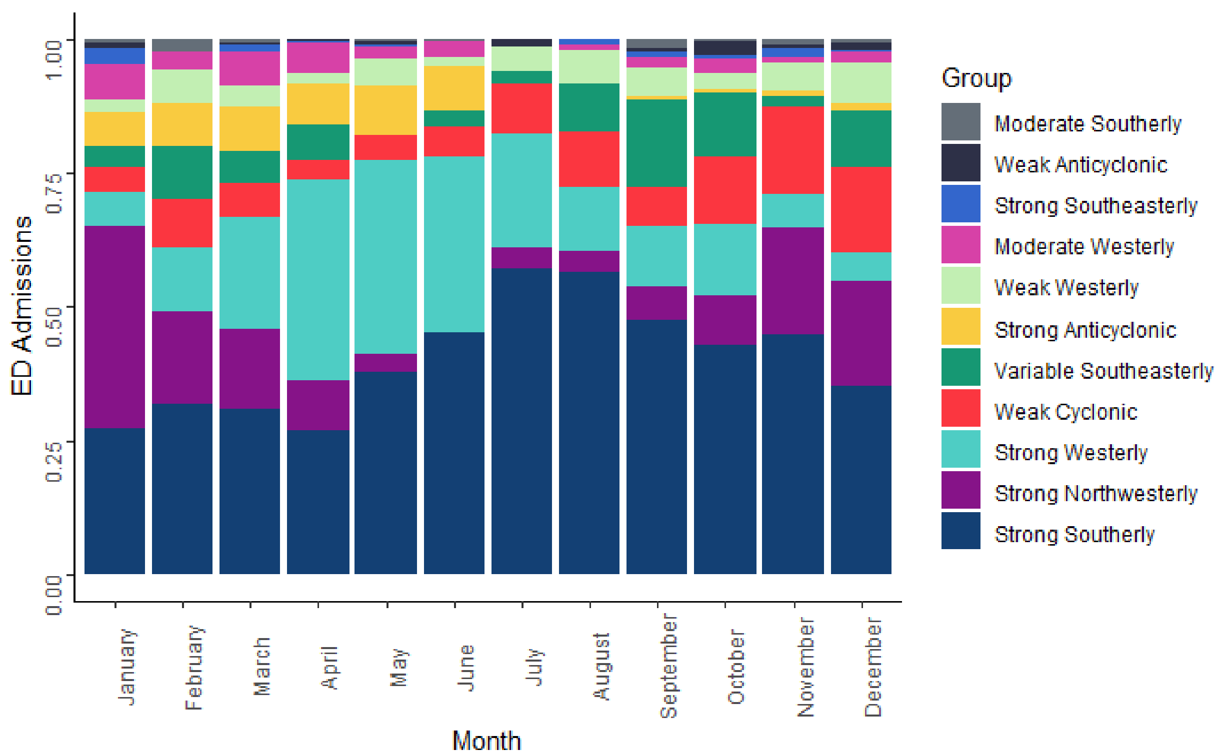

Figure 7. Monthly ED visit frequency by trajectory group.

3.6. 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.

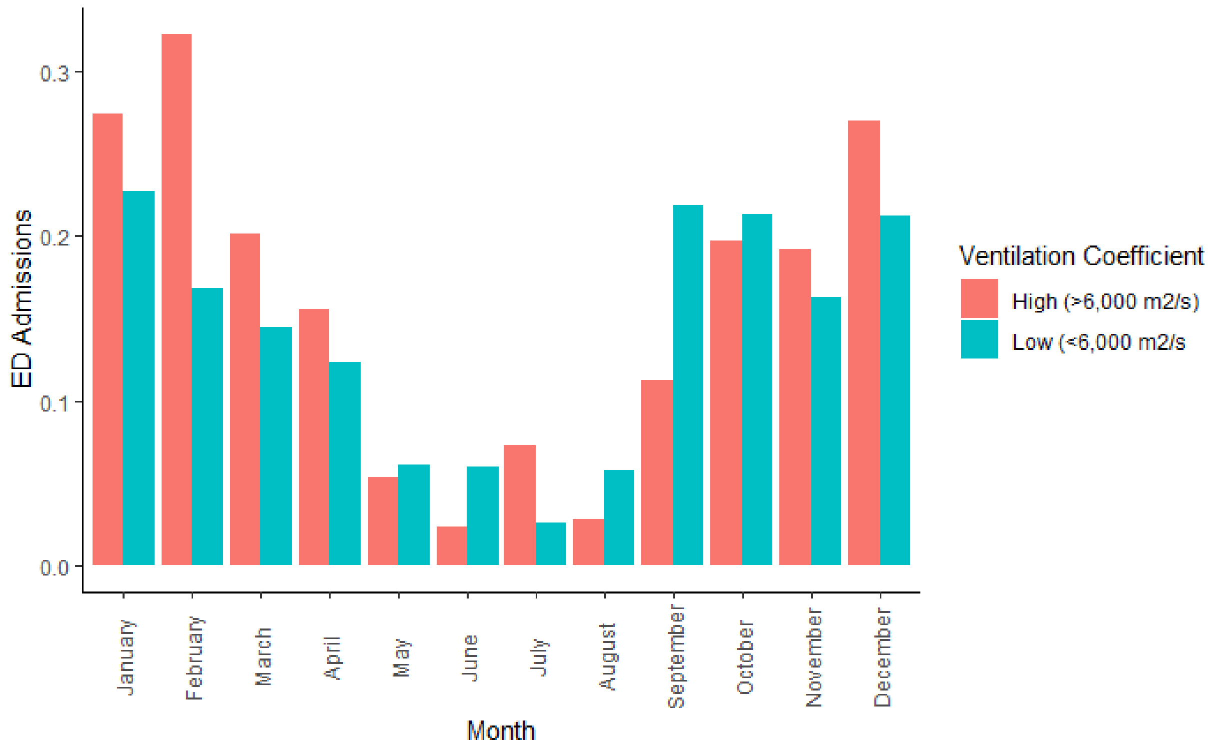

Figure 8. Mean daily ED admissions, by ventilation coefficient and month.

4.1. 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.

4.2. 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 Variable 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 Variable 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 Variable 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.

4.3. 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.

4.4. 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.

5.1. 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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All data, with the exception of protected health data, is publicly available and downloadable. These datasets are the North American Regional Reanalysis (climatological data), provided by the National Oceanic and Atmospheric Adminstration; the United States Drought Monitor (drought severity data), jointly produced by the United States Department of Agriculture, The National Drought Mitigation Center, The

United States Department of Commerce, and the National Oceanic and Atmospheric Administration; and the United States Geological Survey (Salton Sea water level data). These datasets may be publicly accessed from the resources below:

North American Regional Reanalysis:

https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr

United States Drought Monitor:

https://droughtmonitor.unl.edu/Data.aspx

United States Geological Survey:

https://waterdata.usgs.gov/ca/nwis/dv?referred_module=sw&site_no=10254005

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Imperial
Chocolate Mtn Aerial Gunnery Range
Black Hills
Palo Verde Mountains
SMOKETREE VALLEY
Salton City
Salton Sea
East Highline Canal
Chocolate Mtn Aerial Gunnery Range
CHOCOLATE MOUNTAINS
Borrego Springs
Calipatria
New River
EAST MESA
Westside Main Canal
Brawley
545 ft
ALGODONES DUNES
SANDHILLS
Muchacho Mountains
PILOT KNOB MESA
Imperial
IMPERIAL VALLEY
Holtville
El Centro
Fort Yuma Indian Reservation
Kumeyaay Hwy
IMPERIAL VALLEY
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CALIFORNIA
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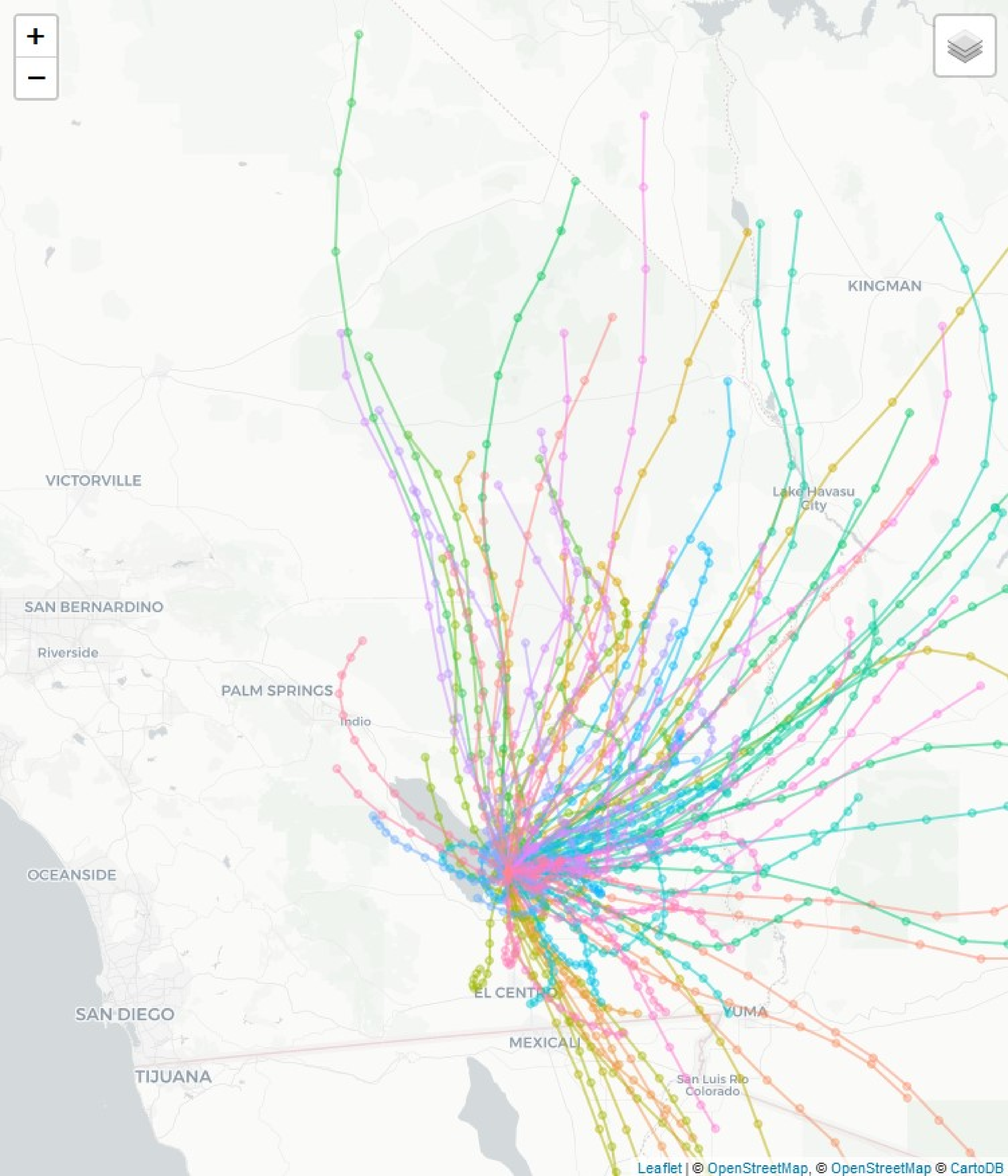

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Riverside
PALM SPRINGS
Indio
OCEANSIDE
EL CENTRO
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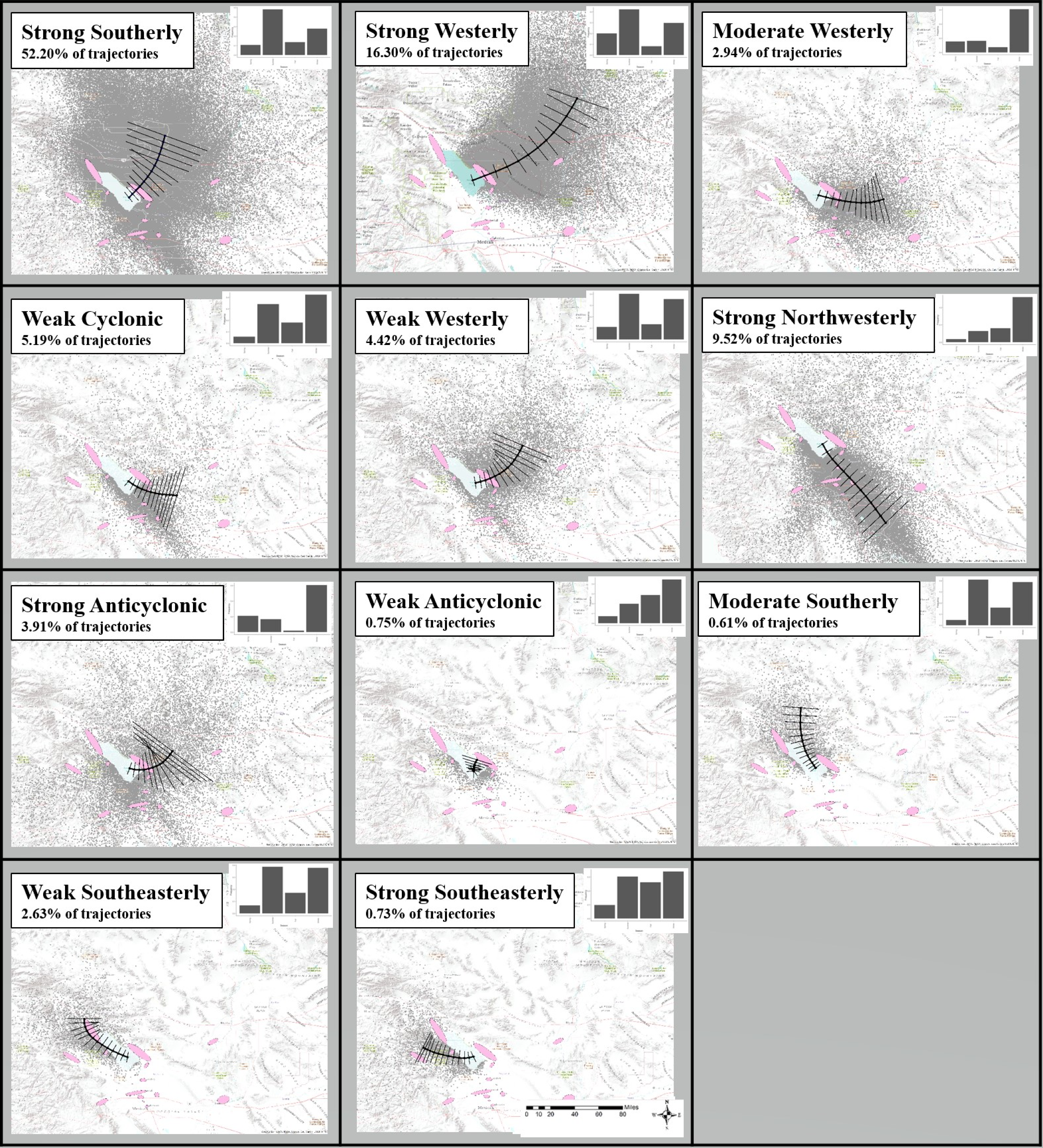
SAN DIEGO
MEXICALI
TIJUANA
San Luis Rio Colorado
Leaflet | © OpenStreetMap, © OpenStreetMap © CartoDB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Strong Westerly
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Moderate Westerly
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Weak Cyclonic
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4.42% of trajectories
Strong Northwesterly
9.52% of trajectories
Strong Anticyclonic
3.91% of trajectories
Weak Anticyclonic
0.75% of trajectories
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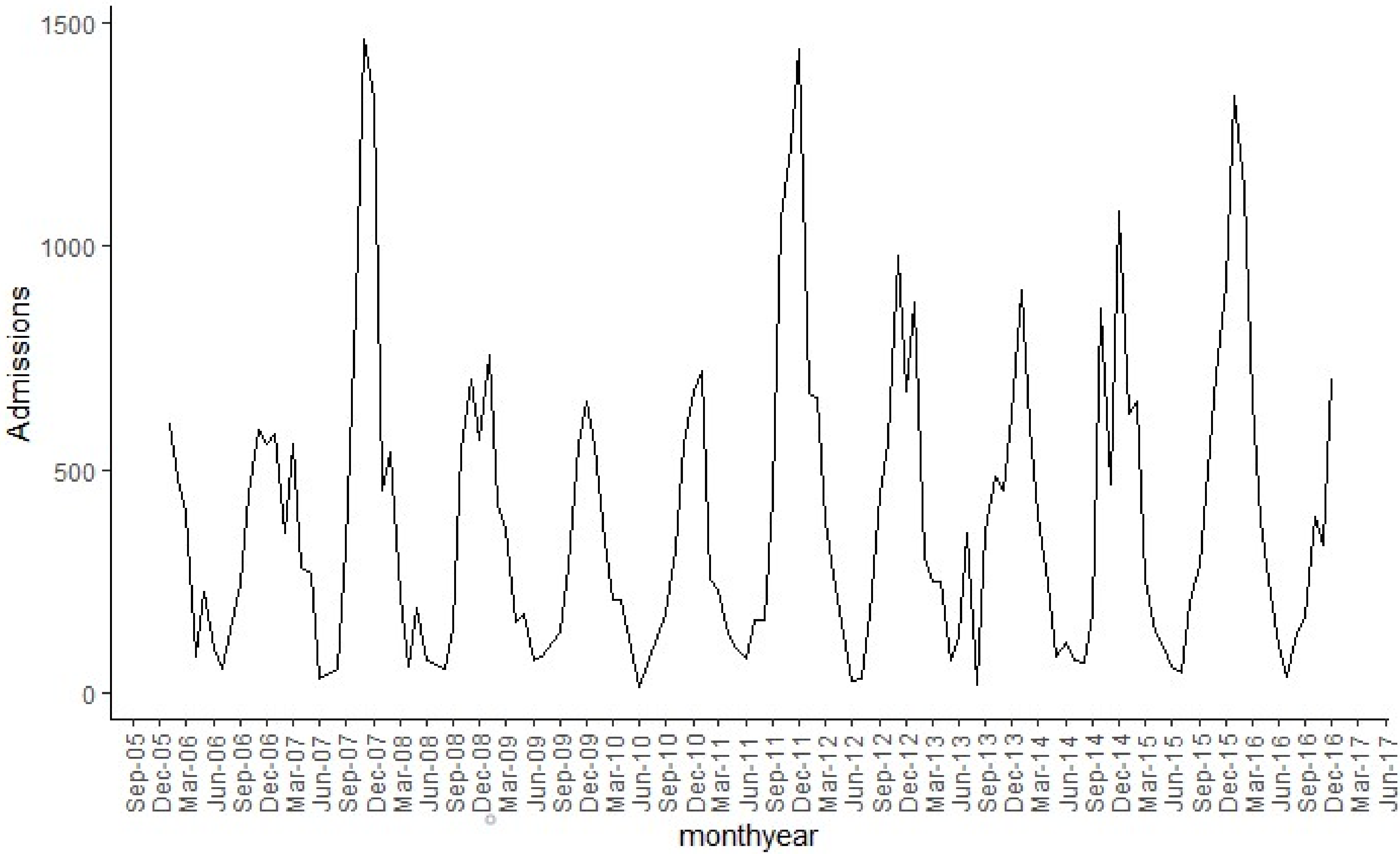

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1000
500
0
Admissions
Sep-05
Dec-05
Mar-06
Jun-06
Sep-06
Dec-06
Mar-07
Jun-07
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Dec-07
Mar-08
Jun-08
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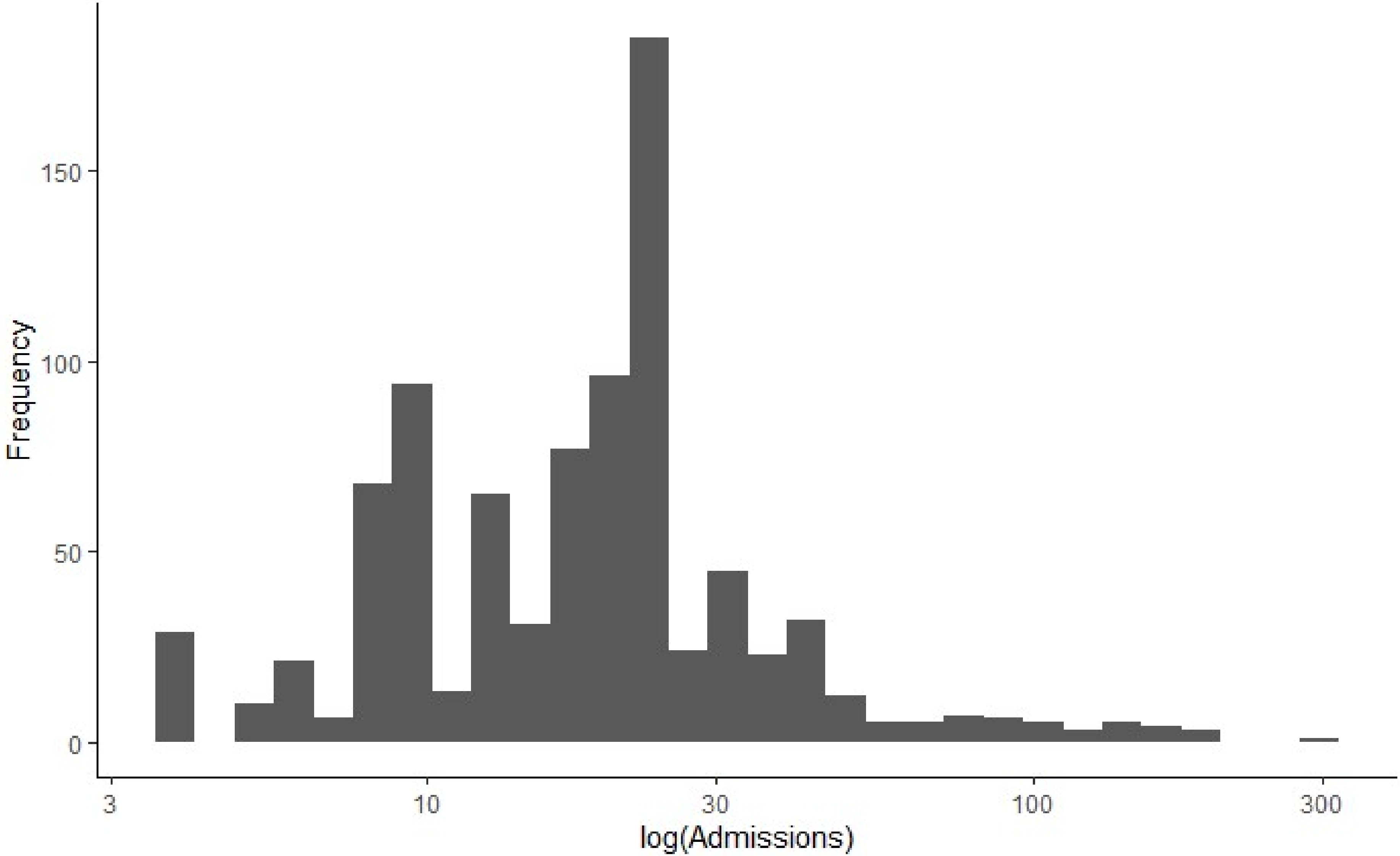
monthyear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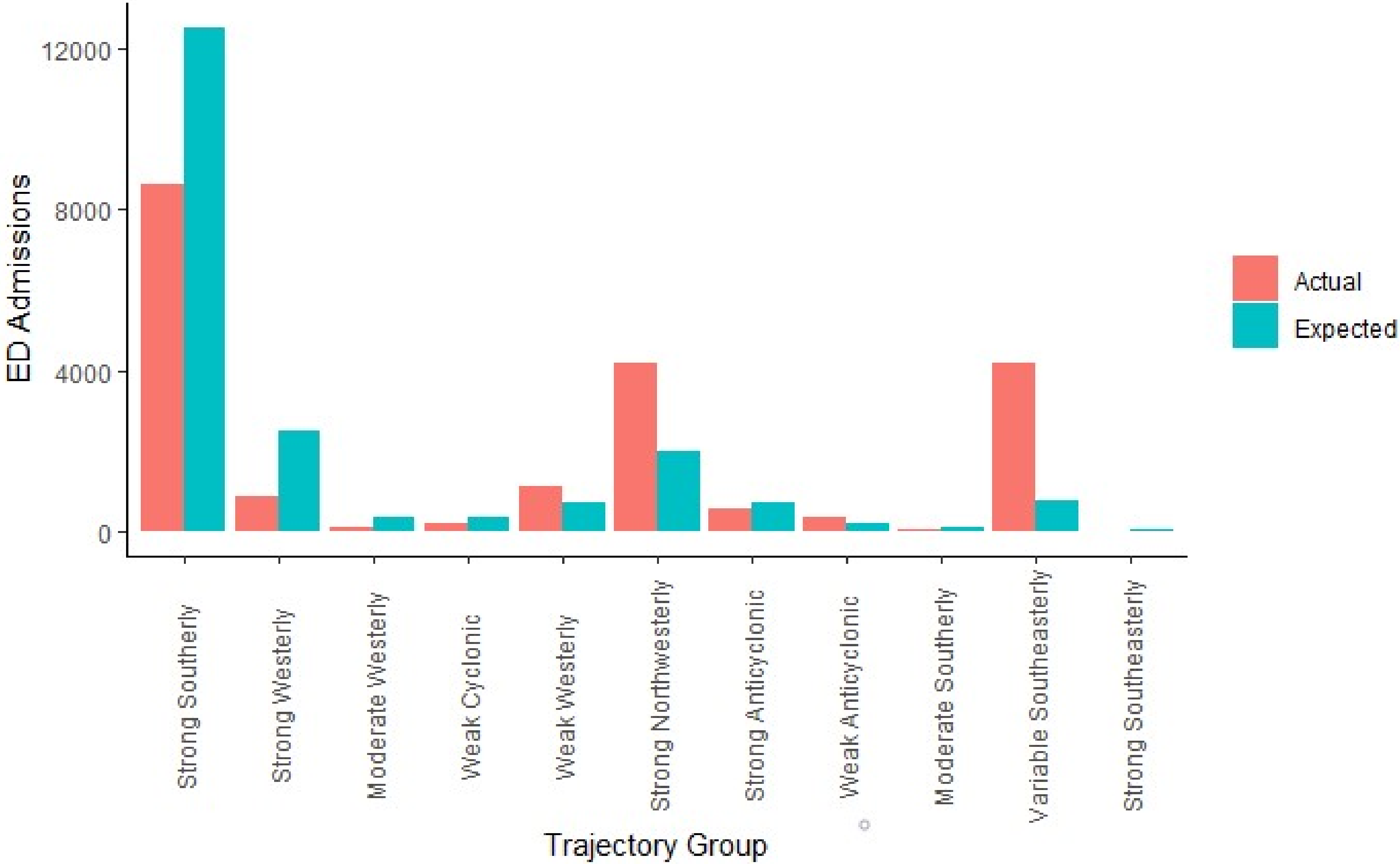
ED Admissions
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4000
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Actual
Expected
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Strong Westerly
Moderate Westerly
Weak Cyclonic
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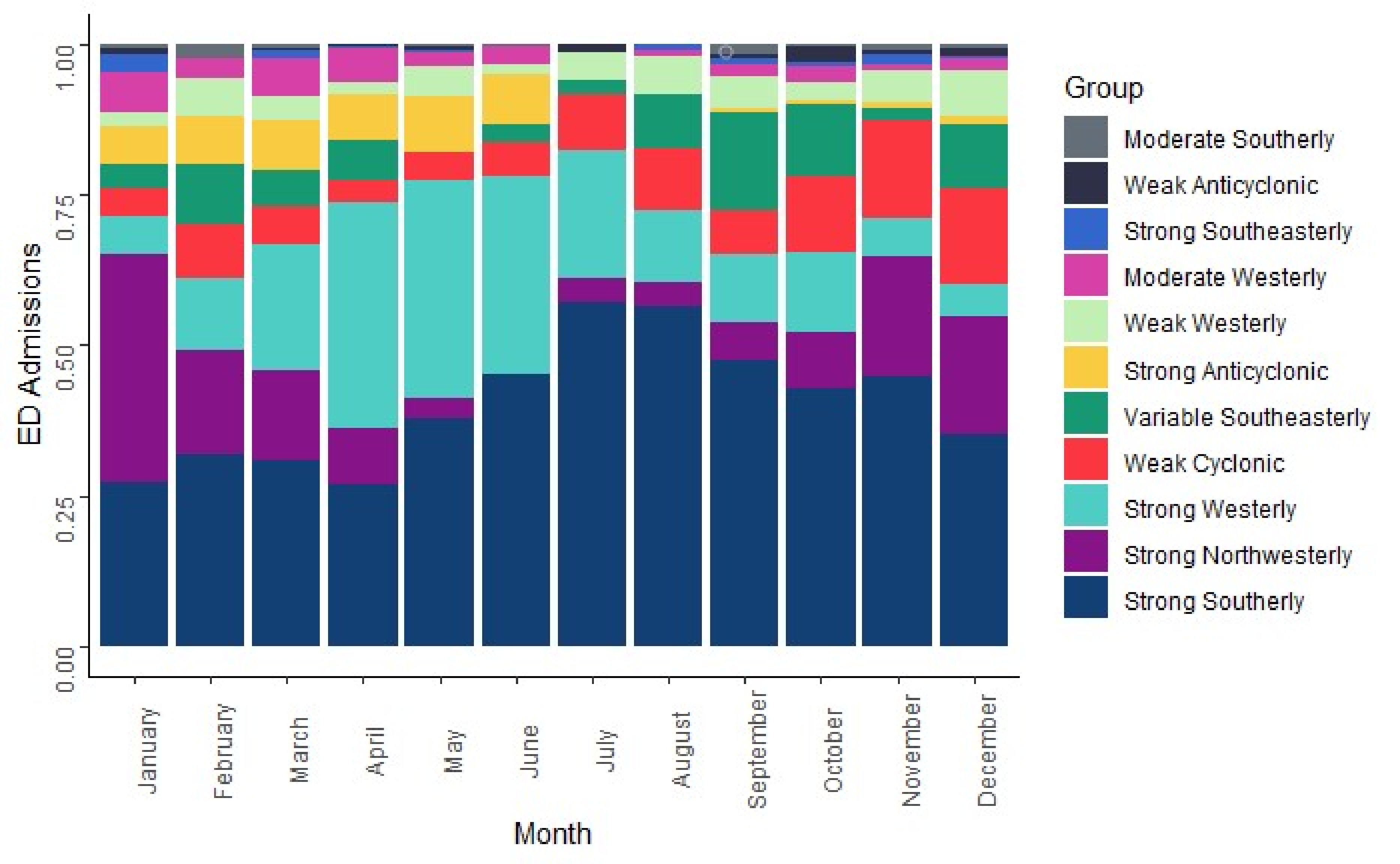
Moderate Southerly
Variable Southeasterly
Strong Southeasterly
Trajectory Group



ED Admissions
0.00
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0.75
1.00
Month
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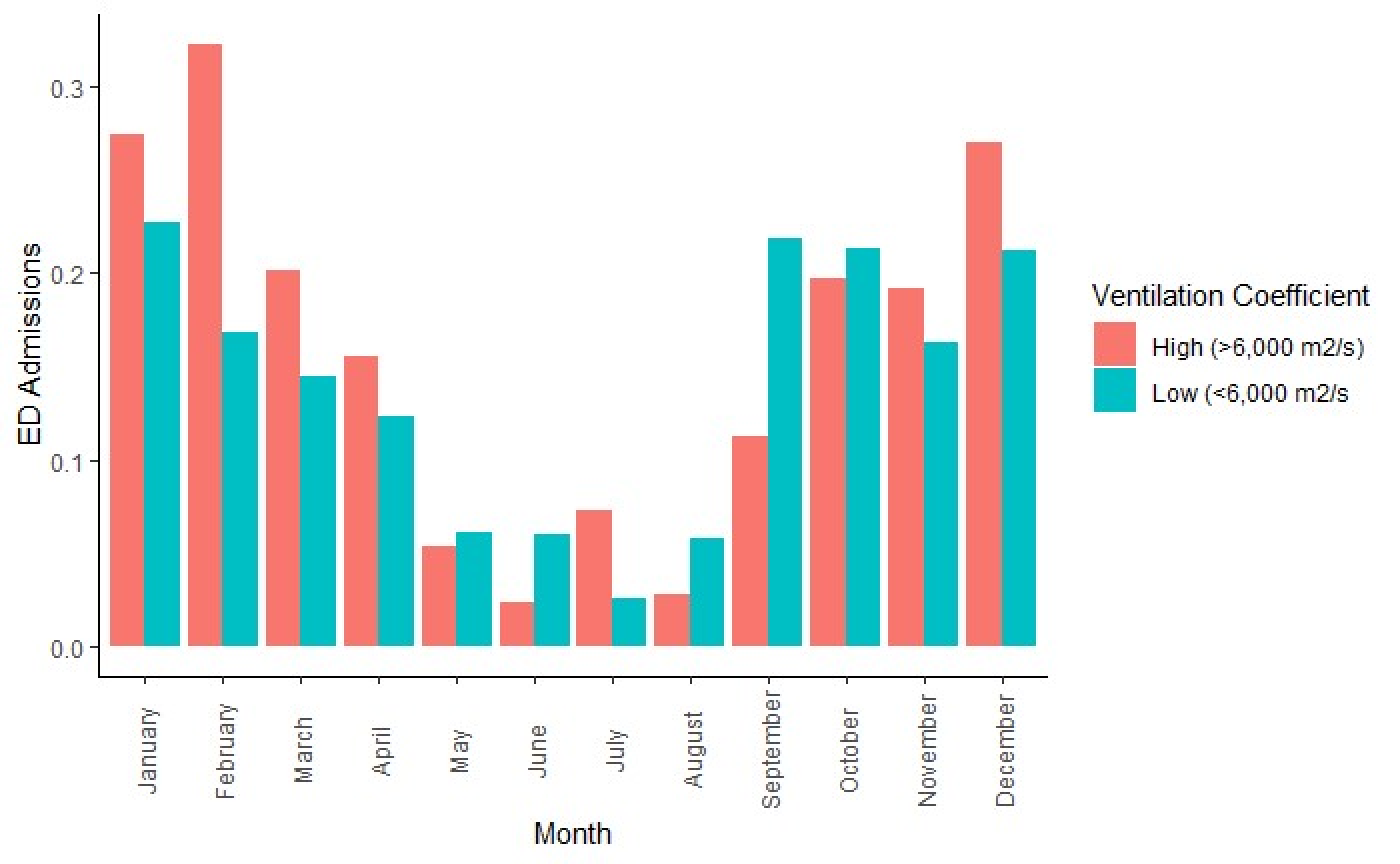
April
May
June
July
August
September
October
November
December
Group
Moderate Southerly
Weak Anticyclonic
Strong Southeasterly
Moderate Westerly
Weak Westerly
Strong Anticyclonic
Variable Southeasterly
Weak Cyclonic
Strong Westerly
Strong Northwesterly
Strong Southerly



ED Admissions
0.0
0.1
0.2
0.3
January
February
March
April
May
June
July
August
September
October
November
December
Month
Ventilation Coefficient
High (>6,000 m2/s)
Low (<6,000 m2/s