Environmental Temperature Extremes: Feasibility Study of Effect on Pediatric Health

Marcelo R Malakooti, MD[1,2,3], Tricia R Pendergrast, BA[1,2], Russ Horowitz, MD[2,4], John R Hummel, PhD[5], Ryne Estabrook, PhD[6], Debra E Weese-Mayer, MD[2,3,7]

[1]Division of Critical Care Medicine, Ann & Robert H. Lurie Children's Hospital of Chicago
[2]Department of Pediatrics, Northwestern University Feinberg School of Medicine
[3]Stanley Manne Children's Research Institute
[4]Division of Emergency Medicine, Ann & Robert H. Lurie Children's Hospital of Chicago
[5]Decision & Infrastructure Sciences Division, Argonne National Laboratory and Northwestern Argonne Institute of Science and Engineering
[6]Department of Psychology, University of Illinois at Chicago
[7]Division of Autonomic Medicine, Ann & Robert H. Lurie Children's Hospital of Chicago

Corresponding author: Marcelo Malakooti, MD, m-malakooti@northwestern.edu

Key Points:

- Infants and children are minimally represented in climate change literature.
- Daily environmental temperatures increased over time while Emergency Department and Pediatric Intensive Care Unit admissions decreased.
- Partnerships with research and healthcare organizations can provide synergies for studies of climate change impacts on human health.

Abstract

Despite consensus that projected climate changes may result in significant threats to human health, and considerable research on extreme temperature-health risks in adults, there is a paucity of information on pediatric health impacts from extreme temperature conditions. Weather data from Chicago's O'Hare Airport measured at multiple times/hour were collected for January 1, 2009 to August 1, 2018. Generalized Additive Models (GAMs) were used to investigate the relationships between air temperature and electronic health record data for emergency department (ED) and pediatric intensive care unit (PICU) admissions at a quaternary-pediatric medical center, for the same period. Daily environmental temperatures increased over time as expected, while unexpectedly ED and PICU admissions decreased. Even when temporal trends in each admission-high risk condition variable were accounted for, a consistent negative relationship was found with 0.406 fewer total (0.038 fewer high risk) ED encounters and 0.012 fewer total (0.010 fewer high risk) PICU admissions per 1°F increase in daily environmental temperature using both regression and GAMs. Our results for the ED and PICU admissions are not consistent with previously reported studies. Many of the previous studies were from under-resourced countries in which factors not considered in this study (e.g., food insecurity, other diseases, air quality, natural disasters) existed. These differences point to the need for further clarification of the relationship between environmental temperature and child health.

Plain Language Summary

This manuscript explores the relationship between climate change and pediatric health, specifically via temperature patterns and emergency department/pediatric intensive care unit admissions to our academic children's hospital in Chicago, over the past decade. This was made possible via a partnership between our institution and Argonne National Laboratory, delivering the first ever study to describe a multi-industry method elucidating the impact of climate change on pediatric hospitalizations, while exploring particularly vulnerable patient groups. The results for this study are not consistent with previously reported studies. Many of the previous studies were from under-resourced countries in which factors not considered in this study (e.g., food insecurity, other diseases, air quality, natural disasters) existed. These differences point to the need for further clarification of the relationship between environmental temperature and child health.

1 Introduction

There is consensus among scientific organizations and climatologists that the recent physical, chemical, biogeochemical, and ecological changes to planet Earth, collectively known as "climate change", present a catastrophic threat to human health, safety, and security (Anderegg et al., 2010; Doran & Zimmerman, 2009; Oreskes, 2004; and Vitousek et al., 1997). In 2000, over 150,000 deaths worldwide were attributed to climate change, and 88% were child deaths (Sheffield and Landrigan, 2010). Tens of thousands of additional deaths are predicted by the World Health Organization (WHO) as early as 2030, compared to a future with no climate change (Hales et al., 2014), and the expectation is that infants and children will be over-represented due to their immature physiology and metabolism, increased oxygen, caloric, and water needs relative to unit body weight, unique behavior patterns, and dependence on caregivers for sustenance and protection (Sheffield et al., 2011). Collectively, these factors render them at higher risk of climate-related health burdens (compared to adults). The projected clinical sequelae of climate change in children are varied and numerous, including expanded ranges of vector-borne diseases such as malaria and dengue fever, increased severity of diarrheal and respiratory disease, increased morbidity and mortality from extreme weather, worsened poverty, food and physical insecurity, and threats to habitation (Akachi et al., 2009; Bunyavanich, 2003; Ebi & Paulson, 2007; and Shea, 2007). These clinical effects are associated with elevated environmental temperatures, ecosystem disruption, extreme weather events including flooding and drought, and increased humidity and rainfall (Ahdoot & Pacheco, 2015).

The impact of longitudinal climate changes evolving over thousands of years is difficult to gauge over smaller units of more contemporary time (Fouillet et al., 2008; Golden et al., 2008; and Semenza et al., 1999). Thus, climate change presents a unique challenge to researchers. Instead of relying on a lack of longitudinal prospective or retrospective data, researchers often must theorize, model, or estimate the potentially catastrophic effects of climate change (Honda et al, 2014; Smith & Myers, 2018; Springmann et al., 2017). Our study diverges from this paradigm by 1) evaluating the feasibility of a partnership between Argonne National Laboratory and a quaternary-level pediatric hospital-academic medical center, and 2) utilizing contemporary analysis of historical temperature extremes in the geographic vicinity of the hospital as a proxy for global warming and retrospective electronic health records (EHR) of emergency department (ED) encounters and pediatric intensive care unit (PICU) admissions as a measure of overall pediatric health and specific health conditions expected to have a heightened risk of illness and hospitalization among infants and children, over nearly a decade (Boonstra et al., 2014).

2 Materials and Methods

2.1 Climate Data

Argonne National Laboratory provided access to the National Centers for Environmental Information (NCEI) archives (https://www.ncei.noaa.gov/) of data from weather stations and assessment of the state of the Earth's climate in near real-time. The NCEI open-access datasets include temperature, dew point, relative humidity, precipitation, wind speed and direction, and other variables, and are accessible from the NCEI website. NCEI data were obtained from January 1, 2009 to August 1, 2018. The download portal allows researchers to specify the increments and time frame of interest, as well as choose the closest land-based measurement station. Chicago, located in the mid-latitude temperate regime where *normal* temperatures can range from a low of 15°F in winter to a high of 85°F in summer, experiences *extreme* temperatures as low as -25°F and as high as 105°F. The weather station at the Chicago O'Hare International Airport, fewer than fifteen miles away from Ann & Robert H. Lurie Children's Hospital of Chicago (Lurie Children's Hospital; LCH), was selected as the source of the weather data for this study. This weather station is part of the international reporting network that provides weather data for aviation operations and is the site for official Chicago-area weather data. The complete record of weather data recorded at O'Hare includes multiple measurements per hour and hourly, daily, and monthly averages and the deviations of these averages from the historical climate record.

2.2 Lurie Children's Hospital

LCH is a 364 bed, free-standing children's hospital that serves racially and ethnically diverse pediatric patients, located within Cook County, the second largest county in the United States and home to 40% of the population of Illinois based on census data (U. S. Department of Commerce, 2019). LCH electronic health records (EHR) for all patients evaluated in the ED or admitted to the PICU between January 1, 2009 and August 1, 2018 in total and secondarily those with the most pertinent and frequent pediatric health conditions identified in the Cook County Department of Public Health annual reports of the top causes of death by age group and race were targeted for data extraction (Cook County Department of Public Health, 2013). These 'high risk' conditions include acute respiratory distress, chronic persistent respiratory distress, circulatory system disease, influenza, meningococcal infection, pneumonia, and sepsis. Preliminary analyses of frequency for health conditions of interest were conducted to ensure sufficient year-to-year variability in ED encounters and PICU admission numbers for planned analyses. Among the aforementioned conditions, the following had sufficient prevalence and variability for inclusion in analysis: acute respiratory distress, chronic persistent respiratory distress (tracheostomy status upon admission and/or ICD code corresponding to chronic respiratory distress), circulatory system disease (hypertension, heart disease, valve diseases, chronic kidney disease), pneumonia, and sepsis. The starting date for this study was selected because it corresponded with the introduction of EHR at LCH.

2.3 Statistical Analysis

A daily temperature measure was created as the mean of daily maximum and mean of daily minimum temperatures and used in all presented analyses. Analyses are provided in two parts. First, descriptive analyses show the general relationships between environmental temperature data with ED encounters and PICU admissions, featuring graphical displays and simple regressions to show trends over time. These models include several regression analyses to separate time trends into seasonal effects and year-over-year change. Second, we employed Generalized Additive Models (GAMs) (Wood, 2017 and Hastie, 2017) in keeping with existing literature on global warming (Hastie, 2017; Panagiotakos et al., 2004; and Schwartz, 1996), with aim to investigate the relationships between daily temperature and ED encounters and PICU admissions. All GAMs were fit using the mgcv library in R (Wood, 2011). These analyses were completed for the total ED encounters and PICU admissions, as well as for the subset with the above-described high-risk conditions.

This study received approval from the Institutional Review Board at LCH (IRB 2018-2183) as exempt from requirement of informed consent. Members of Lurie Children's Data Analytics and Reporting (DAR) group, analysts who specialize in the extraction of data from EHR, were consulted in the design of the project.

3 Results

3.1 Fluctuations in temperature, ED encounters and PICU admissions

Analyses of temperature patterns over the study interval show a strong and expected seasonal effect of temperature (Figure 1). Both daily maximum and daily minimum temperatures are very highly correlated ($r=0.949$, CI=[0.945, 0.952], $p<0.001$). Results of ED encounter- and PICU admission-temperature relationships do not vary as a function of which measure is used, due to the very high correlation between these maximum/minimum temperature variables. For subsequent analyses, we used the midpoint of these two temperatures as a predictor. A simple regression analysis with year as the only predictor shows an annual increase in midpoint temperature of 0.298°F per year ($R^2=0.002$, $p=0.015$).

During the analyzed study period, there were overall a total of 546,627 ED encounters and 17,067 PICU admissions. ED encounters (Figure 2) and PICU admissions (Figure 3) show a similar oscillatory pattern. Regression models predicted 173.99 ED encounters per day in 2009 and a decrease of 3.720 admissions per year (partial R^2=0.115, p<0.001). Of those, 6.03 admissions per day were deemed 'high risk' in 2009, dropping by -0.13 per year (R^2=0.018, p<0.001). PICU admissions began at 5.09 per day in 2009 and decreased by 0.044 admissions per year (partial R^2=0.003, p=0.002). Of those, 1.05 per day were 'high risk', dropping by 0.08 per year (partial R^2=0.023, p<0.001). Daily ED encounters were highly variable. Three dates showed more than 300 ED encounters, including two on consecutive days (373 on 4/29/09, 343 on 4/30/09, and 302 on 11/8/09): these dates are excluded from regression analyses due to their extreme influence and lack of impact on results. The seven dates with the most admissions all occurred in 2009. Excepting 2/2/11 (n=63) and 2/1/15 (n=78), all dates had more than 80 ED encounters. The relatively small number of PICU admissions make it more difficult to test for outliers in this manner.

3.2 Regression analyses

We tested the impact of temperature on total ED encounters and PICU admissions via multiple regression as well as a simple correlation. The regression allows us to control for other factors, while the correlation provides a simple-to-understand check on our results. Results for these models are shown in Table 1. Midpoint daily temperature was negatively correlated with both the total number of ED encounters (r=-0.282, p<0.001) and the number of 'high risk' encounters (r=-0.197, p<0.001), meaning that ED encounters increased as temperature declined. Multiple regression estimates a decrease of 0.406 total ED encounters and 0.025 'high risk' encounters per day for every degree Fahrenheit increase in temperature. Adding an interaction term showed that the weather-admission relationship grew stronger in recent years (B_{int}=-0.038, p<0.001), but this did not replicate for 'high risk' admissions (B_{int}=0.000, p=0.330). Temperature, time in years, and their interaction combine to explain 18.8% of the variance in ED encounters, but only 5.4% of variance in 'high-risk' encounters. Comparable analyses for PICU admission data showed a small but significant relationship between PICU admissions and temperature, with -0.012 additional admissions per degree Fahrenheit increase in temperature (p<0.001) and -0.010 additional 'high risk' admissions per degree increase. Despite the high significance level, daily temperature and timing data explain approximately 1.3% of the variance in PICU admissions and 4.2% of variance in 'high risk' PICU admissions.

3.3 Generalized additive models (GAMs)

Results for GAMs replicated the results of the simpler regression approaches. As expected, there were strong significant associations between smoothed time and temperature (F(3.824, 3.981)=498.9, p<0.001, R2adj=0.845). There was a weaker relationship between smoothed time and both total ED encounters (F(8.663, 8.967)=100.1, p<0.001, R2adj=0.204) and 'high risk' ED encounters (F(6.924, 8.010)=12.080, p<0.001, R2adj=0.026). Controlling for smoothed time, there was a negative association between daily temperature and ED admissions that closely mirrored the regression results for both total (B=-0.419, t=-18.63, p<0.001) and 'high-risk' encounters (B=-0.012, t=-3.39, p<0.001). Taken together smoothed time and temperature explain 27.6% of variance in ED admissions (7.3% of 'high risk'), with the improved fit relative to the regression approaches due to improved fit of smoothed time under the GAM approach.

GAMs fit to PICU admissions showed similar trends. Smoothed time and PICU admissions showed a weak but significant relationship between both total ($F(8.421, 8.906)=9.990$, $p<0.001$, $R2adj=0.023$) and 'high risk' encounters ($F(18.750, 18.990)=10.51$, $p<0.001$, $R2adj=0.050$). Controlling for the effect of time, PICU admissions decreased with increasing temperature with -0.012 total admissions (-0.010 'high risk') per additional degree Fahrenheit ($p<0.001$), closely mirroring the regression results.

Clinical condition occurrences were relative to temperature extremes. Among the pediatric health conditions with higher risk of death based on inclusion criteria, only chronic respiratory distress had consistently increased representation for ED encounters and PICU admissions during the January to March window and for the July to September window over the nearly decade of evaluation.

4 Discussion

In this study, we examined the relationship between temperature extremes (as a proxy for global warming) and electronic health records for ED and PICU patients overall and for those with the highest risk diagnoses for death, using nearly a decade of daily data. Overall, we found that daily environmental temperatures increased over time as expected, while unexpectedly ED encounters and PICU admissions decreased over this time period. Considered overall, we found a consistent negative relationship with approximately 0.4 fewer ED admissions (0.038 of which are 'high risk') and 0.012 fewer PICU admissions (0.010 'high risk') per 1°F increase in daily environmental temperature using both regression and GAMs. Both regression and GAM approaches identified the same negative relationship between temperature and admissions, with GAMs fitting slightly better due to their more flexible approach to modeling time.

Despite notable temperature change over the nearly decade of study, our analysis did not demonstrate the expected surge in ED evaluations and PICU admissions. These results are in keeping with the work of O'Lenick et al. (2017) who similarly did not identify a significant effect of high ambient temperature on pediatric respiratory disease ED encounters. However, a relationship between high ambient temperatures and asthma has been consistently documented (O'Lenick et al., 2017; Anderson et al., 2013; Li et al., 2014; and Winquist et al., 2016). Because in our study respiratory diseases, aside from pneumonia, were studied grouped as acute or chronic, we are unable to compare asthma results specifically to the published literature. Xu et al. (2014) identified an increase in pneumonia in both low and high temperatures, in contrast to our results wherein pneumonia as a solitary condition did not have a consistent relationship to environmental temperature. Mixed results have been found when investigating change in hospital visits and mortality with higher ambient temperatures (Basu & Ostro, 2008; Kysely & Kim, 2009; Huang et al, 2010; Nitschke et al, 2011; Basagaña et al., 2011; Ye et al., 2007; and Nastos et al., 2008), and in some reports a significant effect was only identified for young children or certain medical conditions (Knowlton et al., 2009; Lam, 2007; Checkley et al., 2000; and Hashizume et al., 2007). Because we did not focus on mortality we are unable to make comparison between our cohort and this literature. Another key comparison is recognition that most studies, including our research, have gathered ambient temperature and other meteorological information using ground monitors, rather than satellite sensing technology that is proposed to be more accurate for environmental variable measurements than ground monitors (Xu et al., 2014).

While the results of our study are compelling and unexpected, they must be interpreted in the context of several important identified limitations. The clinical information was derived from a single-center retrospective EHR review that did not begin until EHR introduction to our medical center, limiting the number of years of study and the volume of the patients in each diagnostic group for the 'high risk' patient condition analysis. Second, ED encounter and PICU admission diagnosis data were extracted from the EHR record on a large scale, which prevented review of each patient's chart. This may have allowed for risk of an erroneous diagnosis, or omission of multiple significant diagnoses, when the primary admission diagnosis that auto-populated in the EHR might not encapsulate all conditions potentially impacted by temperature extremes. As such, the true impact of temperature change in 'high risk' pediatric populations may have been underestimated in this study population. Third, variance in admission trends may be confounded by non-environmental causes unaccounted for in our analysis, such as demographic changes, market/consumer behavior influences, changes in population-specific service delivery at our institution over time, and seasonal variation of common infectious diseases contributory to cyclical admissions. Fourth, though we were strategic in looking at total ED encounters/PICU admissions and secondarily selecting 'high risk' health conditions that were most often associated with death, we may have inadvertently selected diagnoses that were not impacted by temperature extremes. Fifth, our study design used environmental air temperature as the assumed driver for the physiological conditions that would result in a need for hospital care. Temperature can be a contributing factor but there are other environmental conditions, such air quality, that were not considered in this initial study. Inclusion of composite measures as a proxy for climate change and inclusion of several geographically diverse quaternary medical centers might allow for a more definitively determined relationship between such measures and ED encounters/PICU admissions than we studied in our pilot analysis. Finally, the observation of an increase in chronic respiratory failure for ED encounters/PICU admissions over time may be indicative of evolution in caring for more medically complex/technologically-dependent children in the outpatient setting; with advances in modern medicine, they are being increasingly successfully supported beyond the hospital walls with mechanical ventilation, yet contributing to relatively increased frequency of admissions due to their heightened vulnerability to critical illness. This trend is likely unrelated to the consequences of extreme temperature, but to the ability to manage patients in an outpatient setting for longer durations without needing hospitalization. Despite these limitations, the success of the partnership between Argonne National Laboratory and a large academic and clinical pediatric medical center lays the foundation for expanded study of the impact of global warming on the health of infants and children, and similar multi-industry research partnerships.

The impact of rising temperature and other sequelae of climate change hold a critical influence on human health, with unknowns that necessitate further exploration by the medical and science communities. Pediatric health is unique in its sensitive response to changes in our planet's environment, especially that of the medically complex and critically ill infants and children. Partnerships among multi-industry agencies and healthcare delivery organizations have the potential to build synergies for system readiness to protect this vulnerable population as the effects of climate change continue to manifest over time. Future analyses will broaden temperature data evaluation to focus on patients with the most common causes of acute and chronic respiratory distress in children, such as asthma and bronchiolitis, examine trends in exacerbating factors such as hazardous air particulate matter, and have the potential to alert at-risk populations on health precautions in anticipation of projected extreme temperature events.

Acknowledgements

The authors express their gratitude to Lauren C. Balmert, PhD for her statistical expertise in guiding development of this project and to Z. Leah Harris, MD for her overriding vision to marry Argonne National Laboratory with Lurie Children's Hospital/Northwestern University Critical Care, Emergency, and Autonomic Medicine. Data supporting this research are available in a password-protected, HIPAA compliant database secured by the authors per the study center's IRB approval process; the citation reference is this study's title as listed. These data are not accessible to the public or research community, unless as granted by the authors. John Hummel was supported through the U.S. Department of Energy contract DE-AC02-06CH11357.

- None of the authors have a conflict of interest to report.
- None of the authors have other affiliations that can result in a conflict of interest.
- Upon acceptance of the paper, the data will be assembled in an accessible archive.

References

Ahdoot, S., & Pacheco, S. E. (2015), Global climate change and children's health. *Pediatrics*, *136(5),* e1468-e1484. doi: 10.1542/peds.2015-3233.

Akachi, Y., Goodman, D. L., & Parker, D. (2009), Global climate change and child health: a review of pathways, impacts and measures to improve the evidence base. UNICEF Innocenti Research Centre. IDP No. 2009-03, https://www.unicef-irc.org/publications/560-global-climate-change-and-child-health-a-review-of-pathways-impacts-and-measures.html

Anderegg, W. R., Prall, J. W., Harold, J., & Schneider, S. H. (2010), Expert credibility in climate change. *Proceedings of the National Academy of Sciences, 107(27),* 12107-12109. doi:10.1073/pnas.1003187107.

Anderson, G.B., Dominici, F., Wang, Y., McCormack, M.C., Bell, M. L. and Peng, R. D. (2013), Heat-related emergency hospitalizations for respiratory diseases in the medicare population. *American Journal Respiratory Critical Care Medicine*, *187*, 1098–1103. Doi:10.1164/rccm.201211-1969OC.

Basagaña, X., Sartini, C., Barrera-Gómez, J., Dadvand, P., Cunillera, J., Ostro, B. Sunyer, J. & Medina-Ramón, M. (2011), Heat waves and cause-specific mortality at all ages. *Epidemiology*, 765-772. doi:10.1097/EDE.0b013e3182031c5.

Basu R. & Ostro B. D. (2008), A multicountry analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. *American Journal of Epidemiolog, 168*, 632-637. doi: 10.1093/aje/kwn170.

Boonstra, A., Versluis, A., & Vos, J. F. (2014), Implementing electronic health records in hospitals: a systematic literature review. *BMC Health Services Research*, *14,* 370. doi: 10.1186/1472-6963-14-370.

Bunyavanich, S., Landrigan, C. P., McMichael, A. J., & Epstein, P. R. (2003), The impact of climate change on child health. *Ambulatory Pediatrics*, *3(1),* 44-52. Doi: 10.1367/1539-4409(203)003<0044.

Checkley, W., Epstein, L. D., Gilman, R. H., Figueroa, D., Cama, R. I., Patz, J. A., & Black, R. E. (2000), Effects of EI Niño and ambient temperature on hospital admissions for diarrhoeal diseases in Peruvian children. *The Lancet*, *355(9202),* 442-450. doi: 10.1016/S0140-6736(00)82010-3.

Cook County Department of Public Health. (2013). Ten Leading Causes of Death Tables 2008. Oak Forest, IL: Community Epidemiology and Health Planning Unit.

Doran, P. T., & Zimmerman, M. K. (2009), Examining the scientific consensus on climate change. *Eos, Transactions American Geophysical Union*, *90(3),* 22-23. doi: 10.1029/2009EO030002.

Ebi, K. L., & Paulson, J. A. (2007). Climate change and children. Pediatric Clinics of North America, *54(2),* 213-226.

Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., Frayssinet, P.,Laurent, F., De Crouy-Chanel, P., Jougla, E. And Hémon, D. (2008), Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *International Journal of Epidemiology, 37(2),* 309-317. doi:10.1093/ije/dym253.

Golden, J. S., Hartz, D., Brazel, A., Luber, G., & Phelan, P. (2008), A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. *International Journal of Biometeorology*, *52(6),* 471-480. doi: 10.1007/s00484-007-0142-3.

Hales S., Kovats S., Lloyd S., Campbell-Lendru D. Eds. (2014), Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s. (2014). Geneva, Switzerland: World Health Organization; 2014:1–128. https://www.who.int/globalchange/publications/quantitative-risk-assessment/en/.

Hashizume, M., Armstrong, B., Hajat, S., Wagatsuma, Y., Faruque, A. S., Hayashi, T., & Sack, D. A. (2007), Association between climate variability and hospital visits for non-cholera diarrhoea in Bangladesh: effects and vulnerable groups. *International Journal of Epidemiology*, *36(5),* 1030-1037. doi: 10.1093/ije/dym148.

Hastie, T. J. (2017), Generalized additive models. In *Statistical models in S* (pp. 249-307). Routledge.

Honda, Y., Kondo, M., McGregor, G., Kim, H., Guo, Y. L., Hijioka, Y., Yoshikawa, M., Oka, K., Takano, S. Hales, S. & Kovats, R. S. (2014), Heat-related mortality risk model for climate change impact projection*. Environmental Health and Preventive Medicine*, *19(1),* 56-63. doi:10.1007/s12199-013-0354-6.

Huang W., Kan, H., and Kovarts, S. (2010), The impact of the 2003 heat wave on mortality in Shanghai, China. *Science of Total Environment. 408*, 2418—2420. doi: 10.1016/j.scitotenv.2010.02.009.

Knowlton, K., Rotkin-Ellman, M., King, G., Margolis, H. G., Smith, D., Solomon, G., Trent, R. & English, P. (2009), The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environmental Health Perspectives*, *117(1),* 61-67. doi: 10.1289/ehp.11594.

Kysely J. & Kim J., (2009), Mortality during heat waves in South Korea, 1991-2005: how exceptional was the 1994 heat wave? *Climate Research, 38*, 105-116. doi.org/10.3354/cr00775**.**

Lam, L. T. (2007), The association between climatic factors and childhood illnesses presented to hospital emergency among young children. *International Journal of Environmental Health Research*, *17(1),* 1-8. doi: 10.1080/0960312060112426.

Li S., Baker P. J., Jalaludin B. B., Guo Y., Marks, G. B. Denison, L. S., and Williams, G. M. (2014), Are children's asthmatic symptoms related to ambient temperature? A panel study in Australia. *Environmental Research*, *133*; 239-245. doi:10.1016/j.envres.2014.05.032.

Nastos, P. T., Paliatsos, A. G., Papadopoulos, M., Bakoula, C., & Priftis, K. N. (2008), The effect of weather variability on pediatric asthma admissions in Athens, Greece. *Journal of Asthma*, *45(1),* 59-65. doi: 10.1080/02770900701815818.

Nitschke M., Tucker, G. R. Hansen, A. L., Williams, S., Zhang, Y. and Bi. P., (2011), Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case series analysis. *Environmental Health, 10*, 42. doi:10.1186/1476-069X-10-42.

O'Lenick C. R, Winquist A, Chang H. H., Kramer M. R., Mulholland J.A., Grundstein A., & Sarnat S. E. (2017), Evaluation of individual and area-level factors as modifiers of the association between warm-season temperature and pediatric asthma morbidity in Atlanta, GA. *Environmental Research, 156*, 132-144. doi.org/10.1016/j.envres.2017.03.021.

Oreskes, N. (2004). The scientific consensus on climate change. *Science*, *306(5702),* 1686-1686. doi: 10.1125/science.1103618.

Panagiotakos, D. B., Chrysohoou, C., Pitsavos, C., Nastos, P., Anadiotis, A., Tentolouris, C., & Paliatsos, A. (2004), Climatological variations in daily hospital admissions for acute coronary syndromes. *International Journal of Cardiology*, *94*(2-3), 229-233. doi: 10.1016/j.ijcard.2003.04.050.

Schwartz, J. (1996), Air pollution and hospital admissions for respiratory disease. *Epidemiology*, 20-28. doi: 10.1097/00001648-199601000-00005.

Semenza, J. C., McCullough, J. E., Flanders, W. D., McGeehin, M. A., & Lumpkin, J. R. (1999), Excess hospital admissions during the July 1995 heat wave in Chicago. *American Journal of Preventive Medicine*, *16(4),* 269-277. doi: 10.1016/s0749-3797(99)00025-2.

Shea, K. M. (2007), Global climate change and children's health. *Pediatrics*, *120(5),* e1359-e1367.

Sheffield, P. E., & Landrigan, P. J. (2010), Global climate change and children's health: threats and strategies for prevention. *Environmental Health Perspectives*, *119(3),* 291-298. doi: 10.1289/ehp.1002233.

Sheffield, P. E., Knowlton, K., Carr, J. L., & Kinney, P. L. (2011). Modeling of regional climate change effects on ground-level ozone and childhood asthma. *American Journal of Preventive Medicine, 41(3),* 251-257. Doi: 10.1016/j.amepre.2011.04.017.

Smith, M. R., & Myers, S. S. (2018), Impact of anthropogenic CO2 emissions on global human nutrition. *Nature Climate Change*, *8(9),* 834. doi: 10.1038/s41558-018-0253-3.

Springmann, M., Mason-D'Croz, D., Robinson, S., Wiebe, K., Godfray, H. C. J., Rayner, M., & Scarborough, P. (2017), Mitigation potential and global health impacts from emissions pricing of food commodities. *Nature Climate Change*, *7(1),* 69. doi: 10.1038/nclimate3155.

United States Department of Commerce (2019). *US Census Bureau*. Accessed from: https://www.census.gov/quickfacts/fact/table/cookcountyillinois/PST120218

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997), Human domination of Earth's ecosystems. *Science*, *277(5325),* 494-499. doi: 10.1126/science.277.5325.494.

Winquist, A., Grundstein, A., Channg, H. H., Hess, J., and Sarnat, S. E. (2016), Warm season temperatures and emergency department visits in Atlanta, Georgia. *Environmental Research*, *147*, 314-323. doi:10.1016/j.envres.2016.02.022.

Wood, S. N. (2011), Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (B)*, *73(1),* 3-36. ISBN 1369-7412/11/73003.

Wood, S. (2017). *Generalized Additive Models: An Introduction with R*, 2nd edition. Chapman and Hall/CRC. doi: 10.18637/jss.v086.b01.

Xu, Z., Sheffield, P. E., Su, H., Wang, X., Bi, Y., & Tong, S. (2014), The impact of heat waves on children's health: a systematic review. *International Journal of Biometeorology, 58(2*), 239-247. doi: 10.1007/s00484-013-0655-x.

Yé Y., Louis, V. R., Simboro, S., & Sauerborn, R. (2007), Effect of Meteorological factors on clinical malaria risk among children: An assessment using village-based meteorological stations and community based parasitological survey. BMC Public Health, 7-101. doi: 10.1186/1471-2458-7-101.

Table 1. Predicting Total and High-Risk Emergency Department (ED) Encounters and Pediatric Intensive Care Unit (PICU) Admissions from Time and Temperature

Outcome	Predictor	Estimate	S.E.	*p*	pR^2
	Intercept	174.268	0.955	<0.001	
Total ED	Temperature	-0.406	0.024	<0.001	0.069
	Time	-3.684	0.172	<0.001	0.107
	Intercept	6.016	0.089	<0.001	
High-Risk ED	Temperature	-0.026	0.002	<0.001	0.036
	Time	-0.122	0.016	<0.001	0.016
	Intercept	5.08	0.080	<0.001	
Total PICU	Temperature	-0.012	0.002	<0.001	0.019
	Time	-0.040	0.014	0.005	0.025
	Intercept	1.047	0.048	<0.001	
High-Risk PICU	Temperature	-0.010	0.001	<0.001	0.010
	Time	0.083	0.009	<0.001	0.002

Note. Regression results for four models where time and temperature predict ED encounters and PICU admissions. Time is calculated as years since January 1, 2008, while temperature is in degrees Fahrenheit (centered at 50). Partial R^2 values indicate the proportion of variance in the admission type explained by each predictor.

Figure Legends

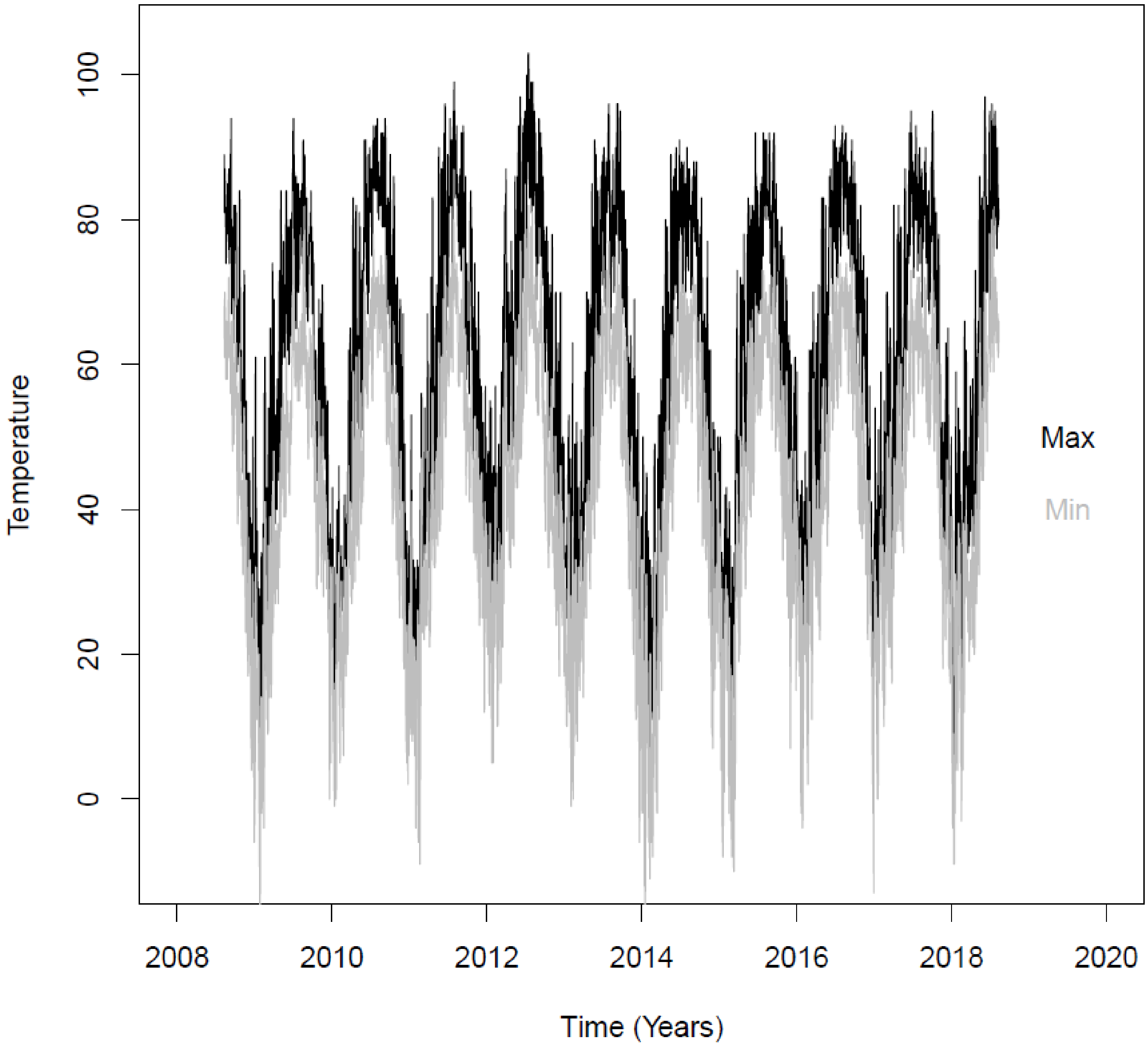
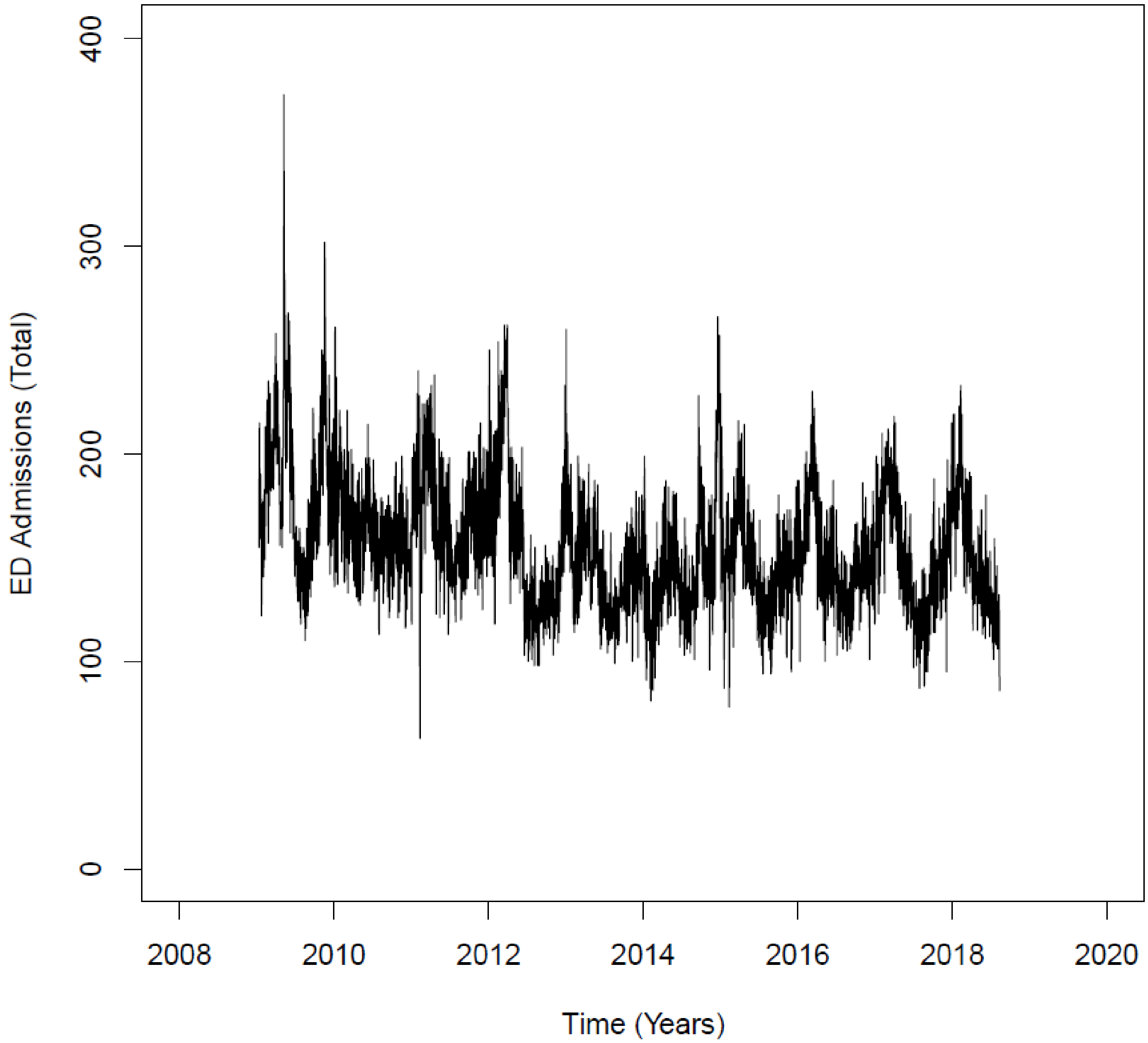
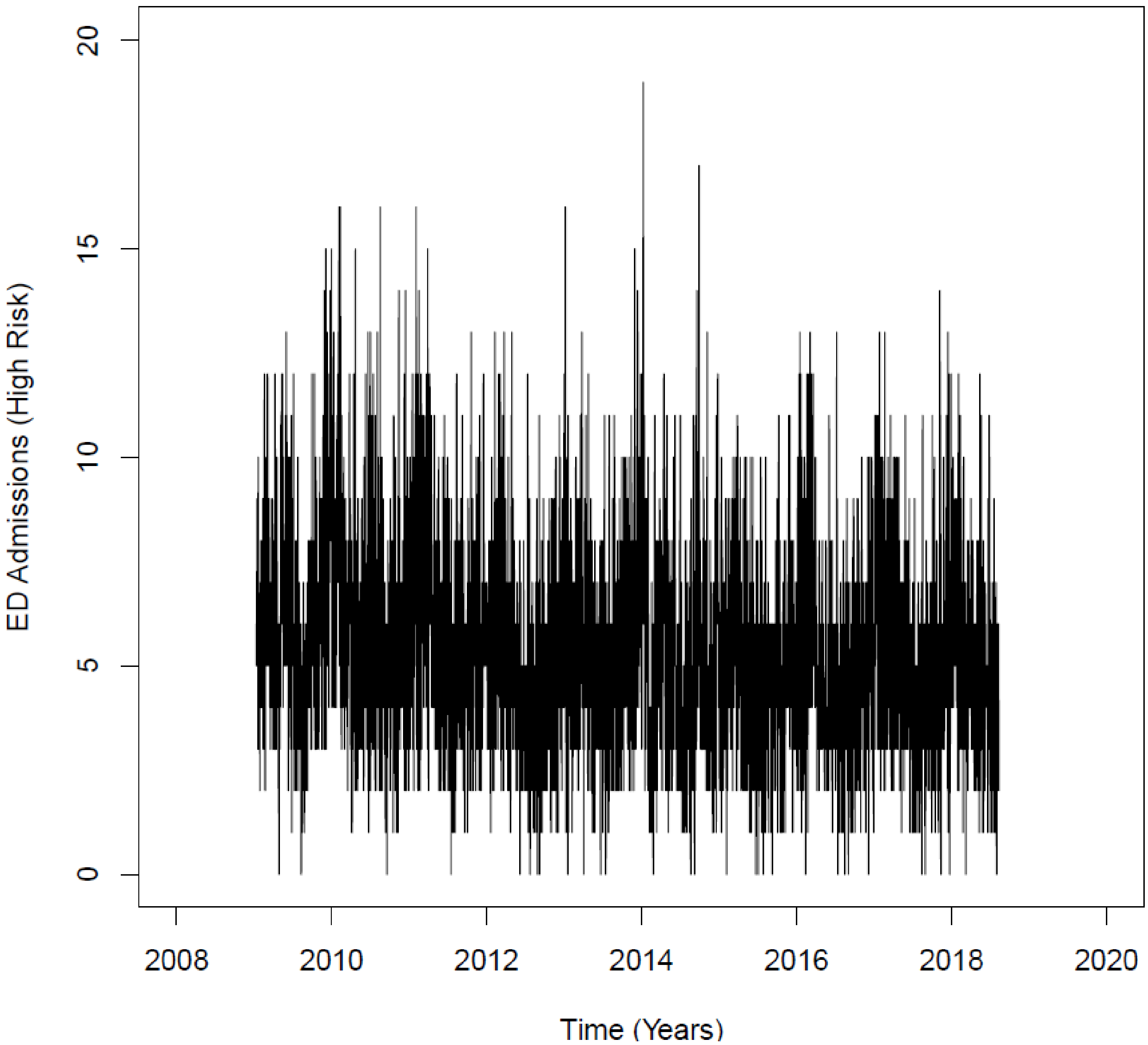


Figure 1. Change in daily environmental temperature over time. Vertical axis shows the maximum (black) and minimum (grey) temperature for each day in degrees Fahrenheit. Horizontal axis shows time in days from January 1, 2009 to August 1, 2018.



400
300
200
100
0
ED Admissions (Total)
2008
2010
2012
2014
2016
2018
2020
Time (Years)

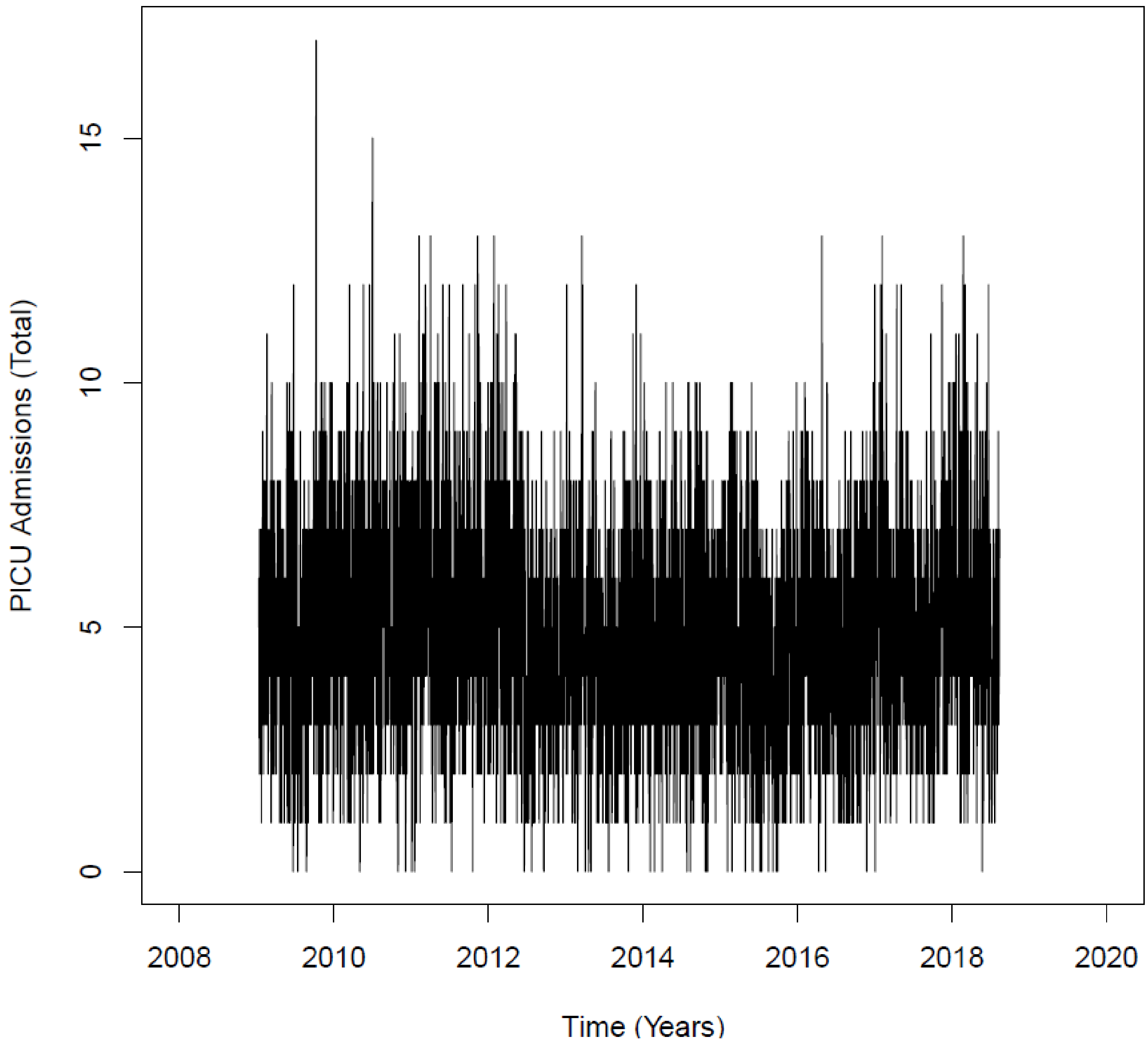
442 (a.)



(b.)

Figure 2. Changes in total (Figure 2a) and high risk (Figure 2b) emergency department (ED) encounters over time. Vertical axis shows the number of ED encounters for each day. Horizontal axis shows time in days from January 1, 2009 to August 1, 2018.

(a.)


PICU Admissions (Total)
0
5
10
15
2008
2010
2012
2014
2016
2018
2020
Time (Years)

(b.)

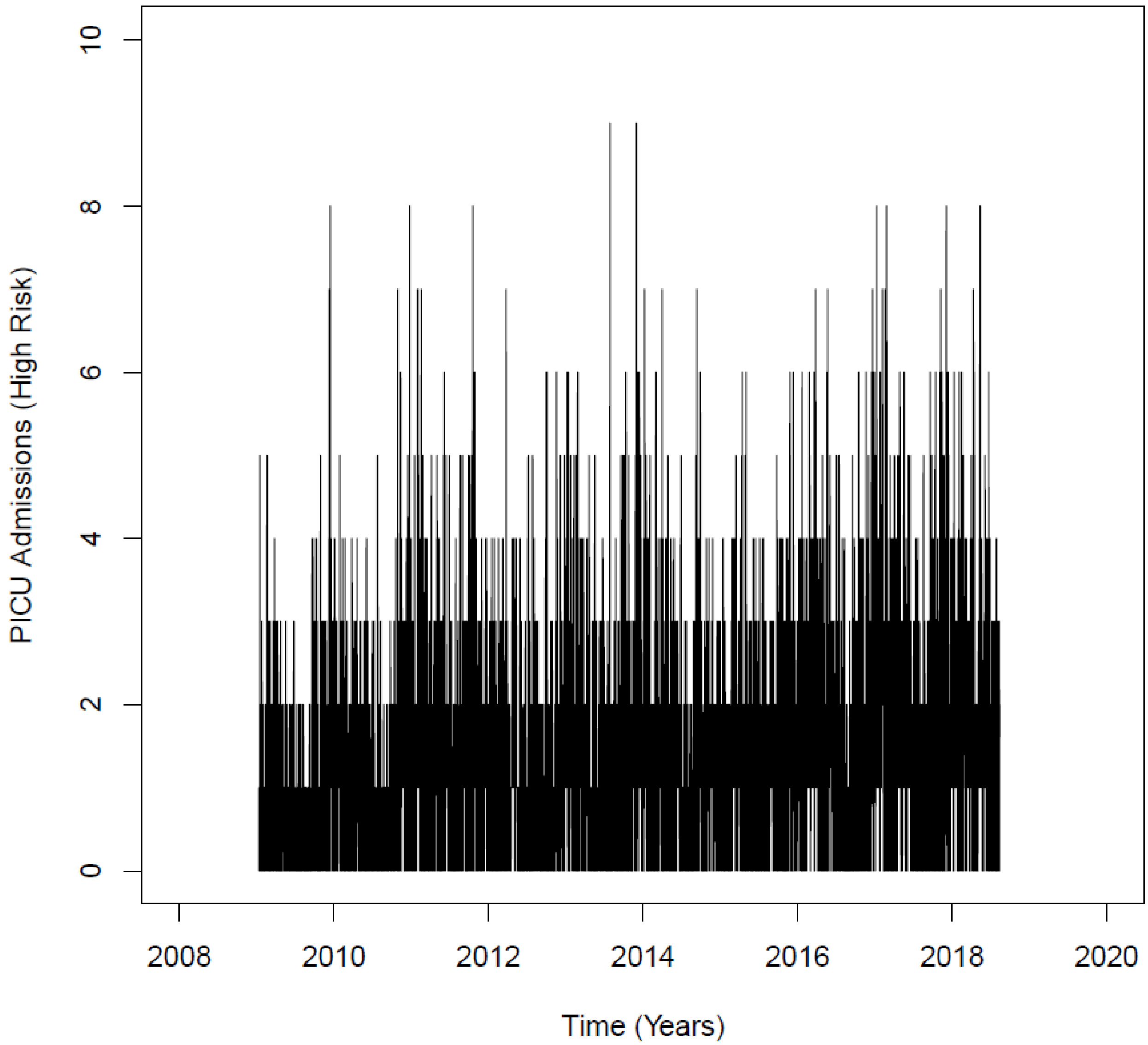


Figure 3. Change in total (Figure 3a) and high risk (Figure 3b) pediatric intensive care unit (PICU) admissions over time. Vertical axis shows the number of PICU admissions for each day. Horizontal axis shows time in days from January 1, 2009 to August 1, 2018.