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Associations of short-term exposure to air pollution and increased ambient temperature with psychiatric hospital admissions in older adults in the USA: a case–crossover study

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Contributors

XQ contributed to the conceptualisation of the study, data curation, formal analysis, methodology, validation, visualisation, writing the original draft, and review and editing of the manuscript. MD-Y contributed to data curation, the methodology, validation, and review and editing of the manuscript. YW contributed to data curation, the methodology, and review and editing of the manuscript. QD contributed to data curation, resources, and review and editing of the manuscript. AJ contributed to data curation, resources, and review and editing of the manuscript. AZ contributed to funding acquisition, supervision, and review and editing of the manuscript. MW contributed to the conceptualisation, methodology, review and editing, and supervision of the study. FD contributed to data curation, supervision, and review and editing of the manuscript. JS contributed to the conceptualisation, funding acquisition, methodology, supervision, and review and editing of the manuscript. XQ and MDY have verified the underlying data. No authors were precluded from accessing data in the study and all authors accept responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Related source US nationwide air pollution prediction data at 1 km grid cell can be found in the NASA Socioeconomic Data and Applications Center (SEDAC). Related source meteorological data can be accessed online on the LDAS data site. Aggregated data of air pollution predictions, temperature, and precipitation at the zipcode level for the contiguous states of the USA as well as other non-confidential documents are available upon reasonable request. We are not allowed to disclose the Medicare inpatient data used in this study to the public due to the regulation of level 3 medical data.

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Summary

Background—Little is known about the associations between ambient environmental exposures and the risk of acute episodes of psychiatric disorders. We aimed to estimate the link between short-term exposure to atmospheric pollutants, temperature, and acute psychiatric hospital admissions in adults aged 65 years and older in the USA.

Methods—For this study, we included all people (aged ≥65 years) enrolled in the Medicare programme in the USA who had an emergency or urgent hospital admission for a psychiatric disorder recorded between Jan 31, 2000, and Dec 31, 2016. We applied a case-crossover design to study the associations between short-term exposure to air pollution (fine particulate matter [$PM_{2·5}$], ozone, and nitrogen dioxide [NO_2]), ambient temperature, and the risk of acute hospital admissions for depression, schizophrenia, and bipolar disorder in this population. The percentage change in the risk of hospital admission and annual absolute risk differences were estimated.

Findings—For each 5°C increase in short-term exposure to cold season temperature, the relative risk of acute hospital admission increased by 3·66% (95% CI 3·06–4·26) for depression, by 3·03% (2·04–4·02) for schizophrenia, and by 3·52% (2·38–4·68) for bipolar disorder in the US Medicare population. Increased short-term exposure to $PM_{2·5}$ and NO_2 was also associated with a significant increase in the risk of acute hospital admissions for psychiatric disorders. Each 5 μg/m^3 increase in $PM_{2·5}$ was associated with an increase in hospital admission rates of 0·62% (95% CI 0·23–1·02) for depression, 0·77% (0·11–1·44) for schizophrenia, and 1·19% (0·49–1·90) for bipolar disorder; each 5 parts per billion (ppb) increase in NO_2, meanwhile, was linked to an increase in hospital admission rates of 0·35% (95% CI 0·03–0·66) for depression and 0·64% (0·20–1·08) for schizophrenia. No such associations were found with warm season temperature.

Interpretation—In the US Medicare population, short-term exposure to elevated concentrations of $PM_{2·5}$ and NO_2 and cold season ambient temperature were significantly associated with an increased risk of hospital admissions for psychiatric disorders. Considering the increasing burden of psychiatric disorders in the US population, these findings suggest that intervening on air pollution and ambient temperature levels through stricter environmental regulations or climate mitigation could help ease the psychiatric health-care burden.

Introduction

It is well known that air pollution and ambient temperature are important environmental risk factors for global physical health.[1,2] Emerging toxicological evidence has also indicated that air pollution and ambient temperature are associated with adverse brain health outcomes and changes in the CNS.[3–5] Increased exposure to air pollution and temperature has been shown to be associated with an increased risk of dementia and other neurological disorders.[6–8] Given the possible common and shared biological mechanisms between neurological and psychiatric disorders, further research is needed to investigate how ambient exposures including air pollution and global warming can increase the burden of psychiatric disorders.[9,10]

In a review of 19 related studies, short-term exposure to air pollutants (including fine and coarse particulate matter [$PM_{2\cdot5}$ and PM_{10}], sulphur dioxide, carbon monoxide, and nitrogen oxide) was shown to be associated with increased daily hospital admissions and emergency visits for mental disorders.[11] An increased risk of developing psychiatric disorders due to particulate matter exposure, traffic-related nitrogen dioxide exposure, and temperature variability has been observed among various cohorts internationally.[9,10,12] However, more high-quality evidence is needed to explore the short-term and long-term effects of air pollutants on population mental health, by simultaneously adjusting for co-pollutants through large national-scale cohorts. Although evidence is accumulating for the harmful effects of air pollution and increasing temperatures on depression as well as schizophrenia,[13–16] little is known about their influence on bipolar disorder. With global warming, any effect of temperature changes could be important.

The majority of the population affected by psychiatric disorders are women, young people, and older people (ie, those aged ≥65 years).[17] Older people with severe psychiatric disorders that often lead to inpatient care are potentially more sensitive to environmental changes.

In this study, we focused on three major psychiatric disorders that contribute to the majority of psychiatric inpatient health care in adults: depression, schizophrenia, and bipolar disorder. These three disorders are also leading causes of disability and loss of quality of life.[18] We examined the acute risk of hospital admission due to each of these three disorders associated with short-term exposures to air pollutants and ambient temperature in the Medicare population for the contiguous United States from 2000 to 2016. Modification of the associations by personal and social determinants of mental health was also explored.

Methods

Study population

In this case–crossover study, we included all people enrolled in the Medicare programme in the USA with a primary diagnosis of an identified psychiatric disorder. Medicare is a fee-for-service, national health insurance programme in the USA that primarily provides health insurance for Americans aged 65 years and older, covering more than 52 million people in the USA.[19] The cohort is an open cohort, with new participants entering the Medicare programme each year as they reach 65 years of age. We looked at acute psychiatric hospital admissions in this cohort regardless of whether the admissions were from an incident case or an acute event in a prevalent case, as long as the admission occurred during our study period. We included all emergency and urgent admissions recorded between Jan 31, 2000, and Dec 31, 2016, due to depression (n=458 492), schizophrenia (n=165 572), and bipolar disorder (n=166 833). For each beneficiary, information was extracted on admission type (eg, emergency, urgent, or elective); date of admission; age at admission; sex; race or ethnicity; zip code of residence; and Medicaid coverage, which is a marker of low socioeconomic status. Data on age, zip code of residence, and Medicaid status were updated annually. Data were obtained from the Center for Medicare and Medicaid Services'[20] Medpar files. This study was approved by the Human Subjects Committee of the Harvard T. H. Chan School of Public Health.

Outcomes

Psychiatric hospital admissions were identified on the basis of published literature data and expert knowledge by use of International Classification of Diseases (ICD) codes, versions 9 and 10, for primary discharge diagnoses: depression (296.2x, 296.3x, 300.4x, 309.0x, 309.1x, 311.xx, F32.xx, F33.xx, F34.1x, F39.xx, and F43.21), schizophrenia (295.xx, F20.xx, F25.0x, and F25.1x), and bipolar disorder (296.0x, 296.40, 296.4x, 296.5x, 296.6x, 296.7x, 296.89, 301.13, 296.80, F30.xx, F31.xx, and F34.0x). The identifying codes were also verified through the Diagnostic and Statistical Manual of Mental Disorders, 5th edition (DSM-5).

Study design

We applied a time-stratified case–crossover study design,[21,22] where each person admitted to hospital was matched to themselves on control days when they were not admitted. The control days were matched with case days by day of week, calendar month, and year with a matching ratio of 3 or 4 (control) to 1 (case). A case day was defined as the date of psychiatric hospital admission. Relative risk was estimated by comparing daily exposure levels on case days with levels on controls days.

Environmental data

Daily ambient concentrations of air pollutants (24 h average $PM_{2·5}$, 1 h maximum NO_2, and 8 h maximum ozone) were predicted on the basis of a combination of machine learning algorithms in a geographically weighted regression. The algorithm combined ground monitoring data (from the Air Quality System operated by the US Environmental Protection Agency [EPA] and other monitoring data sources), satellite-derived measurements, 32 km × 32 km meteorological conditions retrieved from the North American Regional Reanalysis dataset (eg, air temperature, humidity, and wind speed), chemical transport model simulations, and 1 km × 1 km land-use data (eg, land-use coverage types, road intensity, elevation, and normalised difference vegetation index) during the study period (2000–16).[23–26]

Using these models, we predicted daily air pollutant concentrations at every 1 km × 1 km grid cell in the contiguous United States with no missing areas from Jan 1, 2000, to Dec 31, 2016. Cross-validation comparing predicted values and monitored data indicated good performance of the prediction models (ten-fold cross- validation: r^2=0·86 for $PM_{2·5}$, r^2=0·91 for ozone, and r^2=0·79 for NO_2). Using the 1 km × 1 km grid cell daily predictions, we estimated air pollution levels in each zip code of the contiguous United States by averaging the predictions at grid cells whose centroids were inside the polygonal area for general zip codes, or by assigning the prediction at the nearest grid cell for other zip codes that do not have polygon representations (eg, an apartment building, a military base, or a post office).

Daily ambient air surface temperature and precipitation data were obtained from NASA's Land Data Assimilation System (NLDAS-2),[27] with approximately 12 km × 12 km spatial resolution in the contiguous United States with no missing areas, and were later aggregated to each zip code over the study period following similar aggregation procedures.

We assigned daily air pollution and meteorological predictions based on date (case or control days, including lag days) and the zip code of residence of the individual.

Covariates

Data on age, race, sex, and Medicaid eligibility were obtained for each individual for each year from the denominator files. We obtained small area-level socioeconomic and housing characteristic variables from the 2000 and 2010 US Census Summary File 3 at the zip code tabulation–area level.[28,29] We used data on population density, median household income, proportion of the population that was Hispanic, proportion of the population living under the poverty level (an official measure used by the US Census Bureau, which uses a set of income thresholds that vary by family size and composition to determine who is in poverty), and proportion of the population with a high school education or less. These variables are controlled by matching, but might still be effect modifiers. For that purpose, we dichotomised population density as high (≥75th percentile) or medium to low (<75th percentile), median household income as low (≤25th percentile) or medium to high (>25th percentile), and the proportion of the population that was Hispanic as high (>75th percentile) or medium to low (≤75th percentile). The proportion of the population living under the poverty level was coded as high (≥75th percentile) or medium to low (<75th percentile), and the proportion of people with a high school education or less was used to code low level of education (≥75th percentile) or high level of education (<75th percentile).

Statistical analysis

We applied a conditional logistic regression for the case–crossover datasets, with the case–control indicator as the outcome variable, and daily levels of air pollutants and temperature as the exposures. First, we constructed single-exposure cubic constrained distributed lag models, and distributed lag plots were generated.[30] Second, the constrained distributed lag models were extended to include multiple pollutants, including all lag day exposures for each exposure of interest that showed associations in single-exposure distributed lag models to inform the final sensitive lag windows ($PM_{2·5}$, temperature, and NO_2). All models were adjusted for precipitation by use of a natural cubic spline with 3 degrees of freedom for moving averages of lag0 to lag6.[31] Non-linearity of the relationship between temperature and the risk of psychiatric hospital admission was examined with natural cubic splines for temperature (3 degrees of freedom).[32,33] Temperature increases might have different effects in warm and cold seasons, so we examined the temperature–response curves in warm (April to September) and cold seasons (January to March plus October to December) separately. Linear terms were used for pollutants, since a large number of studies have reported close to linear associations between pollutants and various health outcomes in the USA, both nationwide and across specific cities.[21,22,34] The final regression models included moving averages of the lags of choice (appendix p 2) for each pollutant of interest, linear partitioned warm or cold season temperature, and a natural spline of 3 degrees of freedom for precipitation based on preliminary analyses.

We also examined the effects of air pollutants below the current EPA short-term exposure standards (35 μg/m^3 for $PM_{2·5}$ and 100 ppb for NO_2). We did stratified analyses with each psychiatric disorder for each US region (midwest, northeast, south, and west) to see if there is a modification effect by region on estimation of temperature effects.[35] Interactions between pollutants and ambient temperature were examined by fitting multiplicative interaction terms between them in the final multi-exposure models. Modification of the associations of interest by individual covariates (sex, race, and Medicaid coverage) and contextual covariates (population density, proportion of Hispanic people, median household income, proportion living under the poverty level, and level of education) was also examined through multiplicative interaction terms. Bonferroni correction was applied to the significance of the interaction p values to account for multiple testing. Detailed steps of model building are included in the appendix (pp 2–3).

The robustness of the estimates was assessed with respect to moving averages of lag day of choice; residual confounding (e-value);[36] alternative adjustment of specific humidity; alternative adjustment of moving average of lag0 to 3-day temperature exposure; and temperature-only modelling.

The percentage change in the risk of hospital admissions for depression, schizophrenia, and bipolar disorder was reported for each 5-unit increase in $PM_{2·5}$ (μg/m^3), NO_2 (ppb), and warm or cold season temperature (°C). For the main analyses, absolute risk differences of hospital admissions for depression, schizophrenia, and bipolar disorder were also reported for the same 5-unit increase in air pollutants and temperature, and defined as $\alpha \times (RR-1)/RR$, where RR denotes relative risk and α denotes baseline hospital admission risk, which is the baseline average number of targeted psychiatric hospital admissions recorded per year over the study period of 2000–16.

All analyses were done with R software (version 3.5.1) under the Research Computing Environment cluster supported by the Institute for Quantitative Social Science in the Faculty of Arts and Sciences at Harvard University, Boston, MA, USA.

Role of the funding source

The sponsors of the study had no role in study design, data collection, data analysis, data interpretation, writing of the report, or the decision to submit the manuscript for publication.

Results

Between Jan 1, 2000, and Dec 31, 2016, there were 458 492 hospital admissions for depression, 165 572 for schizophrenia, and 166 833 for bipolar disorder across the Medicare population in the USA. All three psychiatric diagnoses were more commonly reported in women than in men, with women constituting more than 65% of total cases. White people were the primary race or ethnicity group. However, the proportion of African American individuals was much higher for schizophrenia than for depression and bipolar disorder (23·4% of all schizophrenia cases, compared to 5·9% for depression and 7·0% for bipolar disorder). People with Medicaid coverage took up a higher proportion (65·2%) of hospital admissions for schizophrenia than those without Medicaid coverage. Further details of individual characteristics, contextual backgrounds, and ambient exposure levels are summarised in table 1.

Each 5 $\mu g/m^3$ increase in $PM_{2\cdot5}$ was associated with a 0·62% (95% CI 0·23–1·02) increase in the risk of hospital admission for depression and an annual absolute risk difference of 167 (95% CI 62–272) more cases for depression; a 0·77% (0·11–1·44) increase in the risk of hospital admission for schizophrenia and an annual absolute risk difference of 74 (10–138) more cases for schizophrenia; and a 1·19% (0·49–1·90) increase in the risk of hospital admission for bipolar disorder and an annual absolute risk difference of 116 (48–183) more cases for bipolar disorder. Each 5 ppb increase in NO_2 was linked to a 0·35% (95% CI 0·03–0·66) increase in the risk of hospital admission for depression and an annual absolute risk difference of 93 (95% CI 9–178) more cases for depression, and a 0·64% (0·20–1·08) increase in the risk of hospital admission for schizophrenia and an annual absolute risk difference of 62 (20–105) more cases for schizophrenia. For the cold season temperature, each 5°C increase was associated with a 3·66% (95% CI 3·06–4·26) increase in the acute admission risk for depression, a 3·03% (2·04–4·02) increase in the acute admission risk of schizophrenia, and a 3·52% (2·38–4·68) increase in the acute admission risk for bipolar disorder. The annual absolute risk difference for a 5°C increase in cold season temperature was 952 (95% CI 802–1102) more cases for depression, 266 (195–376) more cases for schizophrenia, and 334 (228–438) more cases for bipolar disorder. Warm season temperature was not associated with any of the outcomes. Low-level analyses restricted to populations with short-term exposure to air pollution levels below the current US ambient air pollutants regulation short-term standards showed similar results (table 2).

Regional estimations did not show much disparity in the associations between an increase in cold season temperature and hospital admissions for targeted psychiatric disorders across the four US regions (figure 1; appendix p 6).

NO_2 and cold season temperature had a significant negative interaction effect for schizophrenia (interaction p<0·0001). Additionally, $PM_{2\cdot5}$ and NO_2 had a significant negative interaction effect for depression (interaction p=0·010). More details are presented in the appendix (p 7), and a related discussion is included in the appendix (p 4).

Modification analyses showed how the effect estimates differed across populations (figure 2; appendix pp 8–9). Effect estimates shifted between subpopulations with different proportions of Hispanic people, different levels of median household income, and different levels of education, depending on the psychiatric outcome and exposure of interest. Detailed descriptions are summarised in the appendix (pp 3–4).

The dose–response relationships are shown in figure 3. Examination of the curves yielded a close to linear relationship between temperature and risk of psychiatric hospital admission in the cold season, and a non-significant association for the warm season. We also did sensitivity analyses by including all moving averages of lag0–2 and lag3–6 for $PM_{2\cdot5}$ and NO_2 in multi-exposure models. The results still showed robust and significant estimates for the moving averages of choice in the main analyses and non-significant results for the other moving averages (appendix p 10). Both single-pollutant and multi-pollutant constrained distributed lag plots also supported our moving averages of choice on short-term exposure to air pollutants (lag0–2 $PM_{2\cdot5}$ plus lag0–2 NO_2 for depression; lag3–6 $PM_{2\cdot5}$ plus lag0–2 NO_2 for schizophrenia; and lag3–6 $PM_{2\cdot5}$ for bipolar disorder) and warm or cold season ambient temperature (lag0–6; appendix pp 15–17). Correlations among air pollutants and temperature were examined in warm versus cold seasons separately (appendix p 18). We did not find strong evidence for unmeasured confounding based on e-value estimation (appendix p 11). Results remained robust after alternative adjustment for specific humidity and moving averages of lag0–3-day temperature exposure (appendix p 12). The associations with warm and cold season temperatures remained robust in temperature-only models (appendix p 13). Pollutant levels and ratios of levels in cold seasons to levels in warm seasons are presented in the appendix (p 14).

Discussion

This nationwide study looking at short-term associations between the ambient environment and acute psychiatric hospital admissions shows a link between increased cold season ambient temperature, air pollution, and psychiatric hospital admissions in the older population in the USA. The observed associations remained robust after restricting analyses to levels below current EPA short-term standards.

Air pollution, especially particulate matter, has been linked to an increased risk of adverse psychiatric health outcomes in systematic reviews and meta-analyses.[37,38] One possible mechanism for this observation could be that increased inflammatory responses triggered by air pollutants exacerbate depressive or manic symptoms in people with psychiatric disorders, causing people with these symptoms to require hospital treatment and monitoring. In rat and mouse models, particulate matter has been shown to cross the blood–brain barrier into the CNS, leading to adverse neuro-inflammatory responses (via modulation of the Nrf2–NLRP3 pathway) and autoimmune responses, which could trigger or worsen psychiatric conditions.[39,40] Researchers have previously observed acute inflammation in the brains of people exposed to air pollution in Mexico City, Mexico.[41] Another possible pathway by which air pollutants might trigger psychiatric episodes is by increasing glucocorticoid activity and stress hormone cortisol concentrations.[42,43] There is more uncertainty about how NO_2 contributes to non-respiratory adverse effects. Our study and other studies of hospital admissions report the harmful links between NO_2 and psychiatric outcomes.[44] However, one study in California, USA, looked at the relationship between ambient CO,

NO_2, and mental health-related emergency department visits, and found that although NO_2 was associated with homicides, the results were not robust for mental disorders.[45] One possibility for this observation is that the associations seen with NO_2 in the present study are from other correlated traffic pollutants (such as polycyclic aromatic hydrocarbons and ultrafine particles), which have the potential to lead to brain atrophy and cognitive impairment.[4,46] The interpretation of these findings should take into account the different study designs, study periods, and adjustment for confounding factors.

Climatic variables, including ambient temperature, have also been shown to modulate core body temperature and certain biological chemicals by changing the bioavailability of plasma tryptophan, dopaminergic transmission, and the production and availability of serotonin, all of which are related to the physiology and severity of the symptoms of several psychiatric disorders.[16,47] The reasons why we did not observe a similar association for warm season temperature remain unclear, but could be due to modification by different behavioural patterns during warm seasons, including increased physical activity, less vitamin deficiency, increased exposure to green spaces and sunlight, and more outdoor leisure and social connections in warm seasons. Additionally, we believe the underlying mental health-care seeking behaviour as well as other behaviours might be different for the older population. It is possible that although increasing temperatures in the warm season also contribute to mental health problems, this temperature increase is counteracted by the more comfortable weather and physical environment, as well as easier transportation, resulting in older people being more willing to seek help for their adverse mental health issues in the early stages and reducing the need for a hospital admission, which often results from more severe episodes that did not get enough previous medical care assistance. Although we did not find an increased risk of hospital admissions for psychiatric disorders with increasing temperature in warm seasons in older people, this does not preclude increased emergency room visits or increased hospital admissions in younger populations. Overall, studying the link between the physical environment and mental health outcomes could be complicated by the different behavioural patterns involved. This might be especially important when focusing on climate exposures that affect people's daily activities and indoor versus outdoor locations, such as temperature. Further work is needed to better understand the current findings. Additionally, the linear dose–response relationships we reported for cold season temperature and acute psychiatric hospital admissions were consistent with the results reported by a study looking at acute impacts of ambient temperature (–20°C to 30°C) on emergency room visits for mental and behavioural disorders in Toronto, Ontario, Canada.[16] However, different exposure–response relationships were also observed in other cohorts, possibly due to differences in outcome assessment, study designs, geographical locations, study population, and exposure windows of assessment.[48–50]

We observed a unique lag pattern for the effect of daily exposure to $PM_{2·5}$ on hospital admissions for psychiatric disorders, different from what has been reported in the literature for mortality and cardiovascular outcomes.[21,22,51–54] We found a less immediate impact of $PM_{2·5}$ on acute hospital admissions for schizophrenia and bipolar disorders, but not for depression. For example, the effect of $PM_{2·5}$ on hospital admissions for schizophrenia and bipolar disorder was not significant for the days immediately preceding the admission, but appeared with exposures 3–6 days earlier. This observation indicates a delayed response, which might be related to the common delay between the onset of acute symptoms and admissions for schizophrenia and bipolar disorder, as well as the mechanism of action of $PM_{2·5}$.

Although none of the interaction analyses suggested significant modifiers for the associations after applying multiple testing correction, some contextual factors did show a modification tendency. For example, one possible modifier is the proportion of Hispanic people living in the area. Areas with more Hispanic people were observed to be less affected by elevated air pollution and cold season temperature with regard to the risk of psychiatric hospital admissions. This observation could be due to stronger social cohesion as well as multi-generational extended home structures among Hispanic communities.[55,56] Evidence has shown that mental health scores are higher among people living in communities with better social or family cohesion, such as Hispanic communities.[57] Another notable observation is that the Medicare population is mostly retired and so their mental status is more affected by their interactions with family and friends or other close relationships within their communities than by personal socioeconomic status. Additional discussions on other potential modifiers, late-life psychiatric disorders, and the observed higher prevalence of schizophrenia in the African American population are also provided in the appendix (pp 4–5).

This study has several strengths. First, to our knowledge, this is the first and largest analysis based on Medicare data to look at the associations between the ambient environment and three major psychiatric conditions. Second, owing to the application of high-resolution air pollutant and ambient temperature prediction models based on satellite data, our analysis covered 27 458 zip codes across the USA. We looked at different atmospheric pollutants and ambient temperature while simultaneously adjusting for precipitation, which is an important climate risk factor for mental health conditions.[58] Third, we presented the dose–response relationship between ambient temperature and the relative risk of hospital admission for a psychiatric disorder through non-linear modelling, providing deeper insight into the effects of temperature. Fourth, we did an interaction analysis between air pollutants and temperature, which has rarely been examined previously. Finally, the effect modification analysis looking at various individual and area-level factors uncovered some potential modifiers of the associations between the ambient environment and population mental health, which has implications for population mental health interventions and urban planning in the era of climate change.

This study also has some limitations. First, residual confounding from other climatic factors and atmospheric air pollutants cannot be ruled out. However, because we did a bi-directional time stratified case–crossover analysis, only variables that change in the short term (ie, between case and control days) can generate bias to estimation. Based on our e-value sensitivity analyses, we did not find strong evidence for unmeasured confounding. Second, although we observed a link between increasing temperature in cold seasons and hospital admission for psychiatric disorders, there might be certain seasonal and health-care-seeking behavioural patterns underlying this change, which coincide with the increase in ambient temperature in cold seasons. Third, past change in residential history (ie, from living in areas with low air pollution to areas with high air pollution, or from cold temperature zones to warmer regions) could influence the short-term effect estimates we observed. However, since the long-term exposure history would be the same for case and control days within the same month, it cannot confound the observed associations, but rather could modify the strength of the associations.

In conclusion, this study is the first and, to our knowledge, the largest nationwide study to investigate the associations between the ambient environment and the risk of hospital admissions for psychiatric disorders in the US Medicare population; acute exposure to elevated concentrations of $PM_{2·5}$, NO_2, and cold-season ambient temperature was associated with an increased risk of psychiatric hospital admissions in this population.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Research in context

Evidence before this study

Based on the cumulative research published to date, ambient air pollution and climate change is posing an increasing risk for many aspects of human health, including mortality; cardiovascular, respiratory, pregnancy, and birth outcomes; as well as neurological and cognitive disorders. Emerging evidence indicates that the ambient environment also plays a role in influencing mental health. We searched PubMed and Google Scholar for epidemiological studies investigating the associations between air pollution, ambient temperature, and psychiatric disorders published from Jan 1, 2000, to Dec 1, 2020, and restricted the search to English language publications. Key search terms used were ("Air Pollution" OR "Air Pollutions" OR "Air Quality" OR "PM2·5" OR "fine particulate matter" OR "fine particles" OR "Ozone" OR "Low Level Ozone" OR "Ground Level Ozone" OR "Nitrogen Dioxide" OR "NO2" OR "Traffic Pollution" OR "Ambient temperature" OR "Temperature") AND ("Mental Disorder" OR "Psychiatric Disease" OR "Psychiatric Illness" OR "Psychiatric Disorder" OR "Psychiatric Diagnosis" OR "Behavior Disorders"). Most of the studies we found have focused on the associations between fine particulate matter ($PM_{2·5}$) and mood disorders, such as major depression. Less is known for gas pollutants, such as ozone and nitrogen dioxide (NO_2). One case–crossover study in Toronto, Ontario, Canada, explored short-term exposure to increased levels of ambient temperature and emergency department visits for all mood and behavioural disorders, and showed that exposure to elevated temperatures was linearly associated with an increased risk of emergency visits for mood and behavioural disorders. However, we found no studies focusing on the older population in the USA, even though mental illness in older age has been consistently associated with an increased risk of disability and mortality. Related studies have been done mainly in a single hospital, region, or major cities of China, Israel, and some European countries. Additionally, most of the US-based studies were done in selected hospitals or cities where air quality monitoring is abundant, with a small sample size and partial area coverage.

Added value of this study

To the best of our knowledge, this is the first nationwide epidemiological study to investigate the risk of psychiatric hospital admissions associated with various ambient exposures (particles, gas, and increased temperature) in the older population in the USA. The findings show that ambient air pollutants and increased cold season temperature are linked to an increased risk of acute exacerbation of psychiatric episodes. These findings have the potential to aid policy making, risk assessments, and mental health interventions. The observed associations remained robust when restricting pollutants to levels below current US short-term Environmental Protection Agency air pollution standards, indicating the hidden health risks associated with the current regulation. By using high-resolution air pollutant and ambient temperature prediction models based on satellite data, we analysed 27 458 zip codes across the USA, including less populated and less investigated rural areas. Our effect modification analysis, looking at the modification effect by various individual and area-level contextual factors, uncovered some potential modifiers of the observed associations between ambient environment and population mental health. Additionally, our dose–response investigation of the effect of ambient temperature on hospital admissions for psychiatric disorders indicated a close-to-linear positive relationship between acute exposure to increased cold-season temperatures and hospital admissions for depression, bipolar disorder, and schizophrenia. Given the increase in global ambient temperature due to climate change, this association is concerning.

Implications of all the available evidence

Our study provides some quantitative evidence for the risk factors associated with hospital admissions for psychiatric disorders, supporting a link between ambient exposures and acute psychiatric episodes. Although some behavioural and clinical interventions are available to treat patients with psychiatric disorders, with varying levels of effectiveness, if environmental exposures are proven to be risk factors, they are modifiable on a population basis. In an era of global environmental and climate change, more efforts should be devoted to addressing this issue.

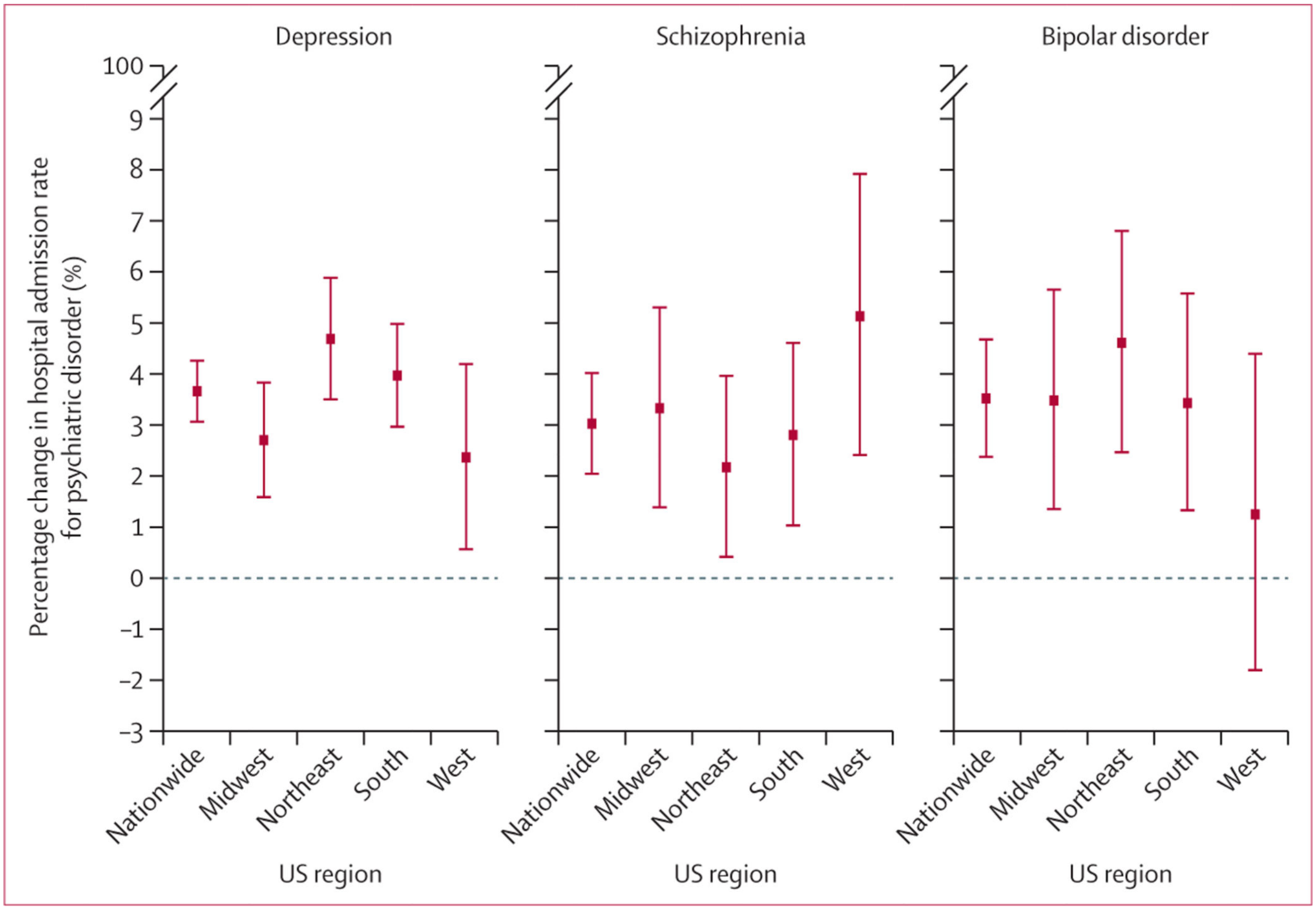

Figure 1: National and regional percentage changes in hospital admission rates for targeted psychiatric disorders per 5°C increase in cold season temperature

Error bars depict 95% CIs.

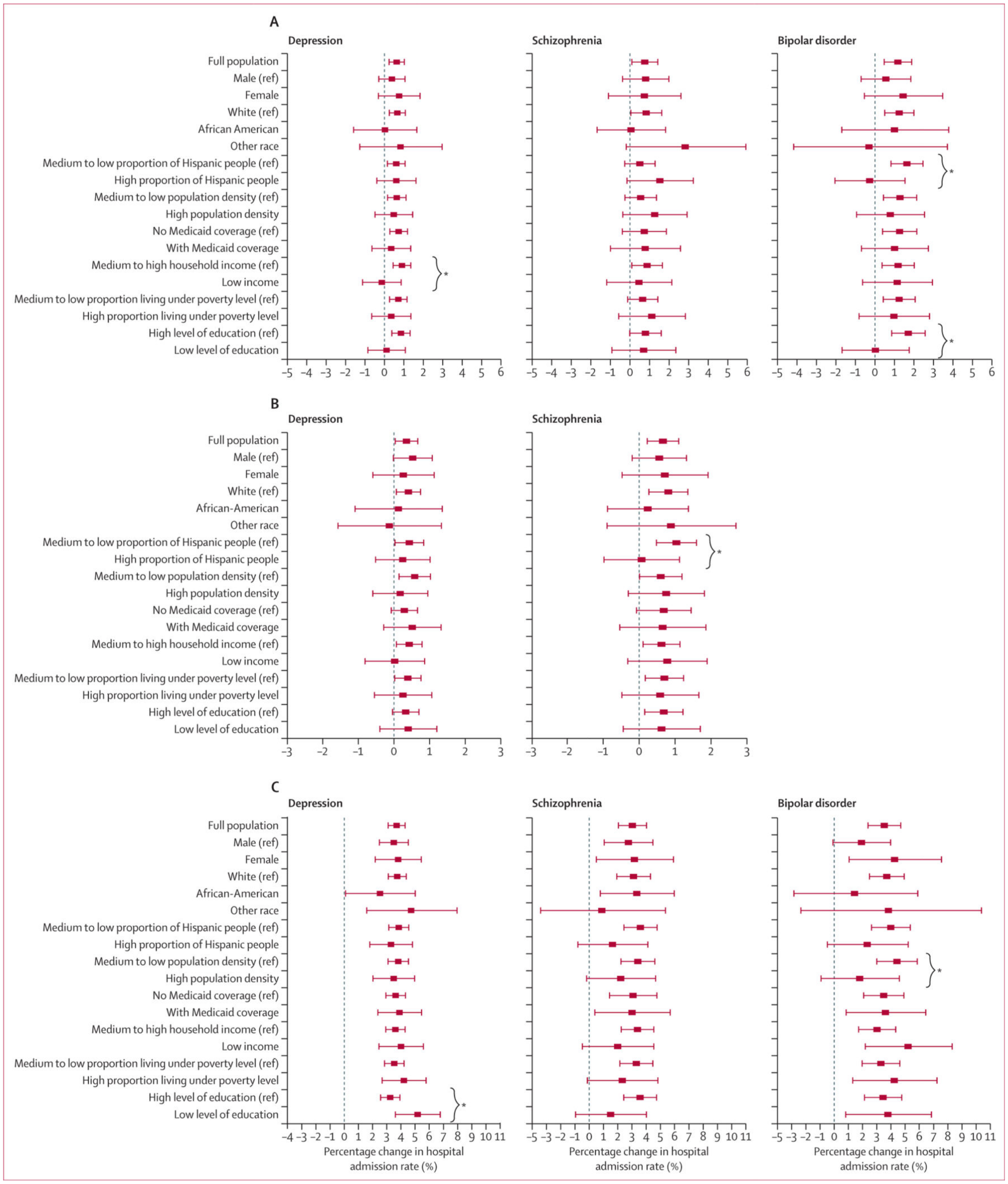

Figure 2: Forest plots of percentage changes in hospital admission rates for targeted psychiatric disorders among the full US Medicare population and subpopulations

(A) 5-unit increase in $PM_{2.5}$ (µg/m^3). (B) 5-unit increase in NO_2 (parts per billion). (C) 5°C increase in cold season temperature. *Significant difference between the reference and each subgroup or subgroups ($p_{interaction}$<0.05). Error bars depict 95% CIs. The exact p values of interaction are given in the appendix (pp 8–9).

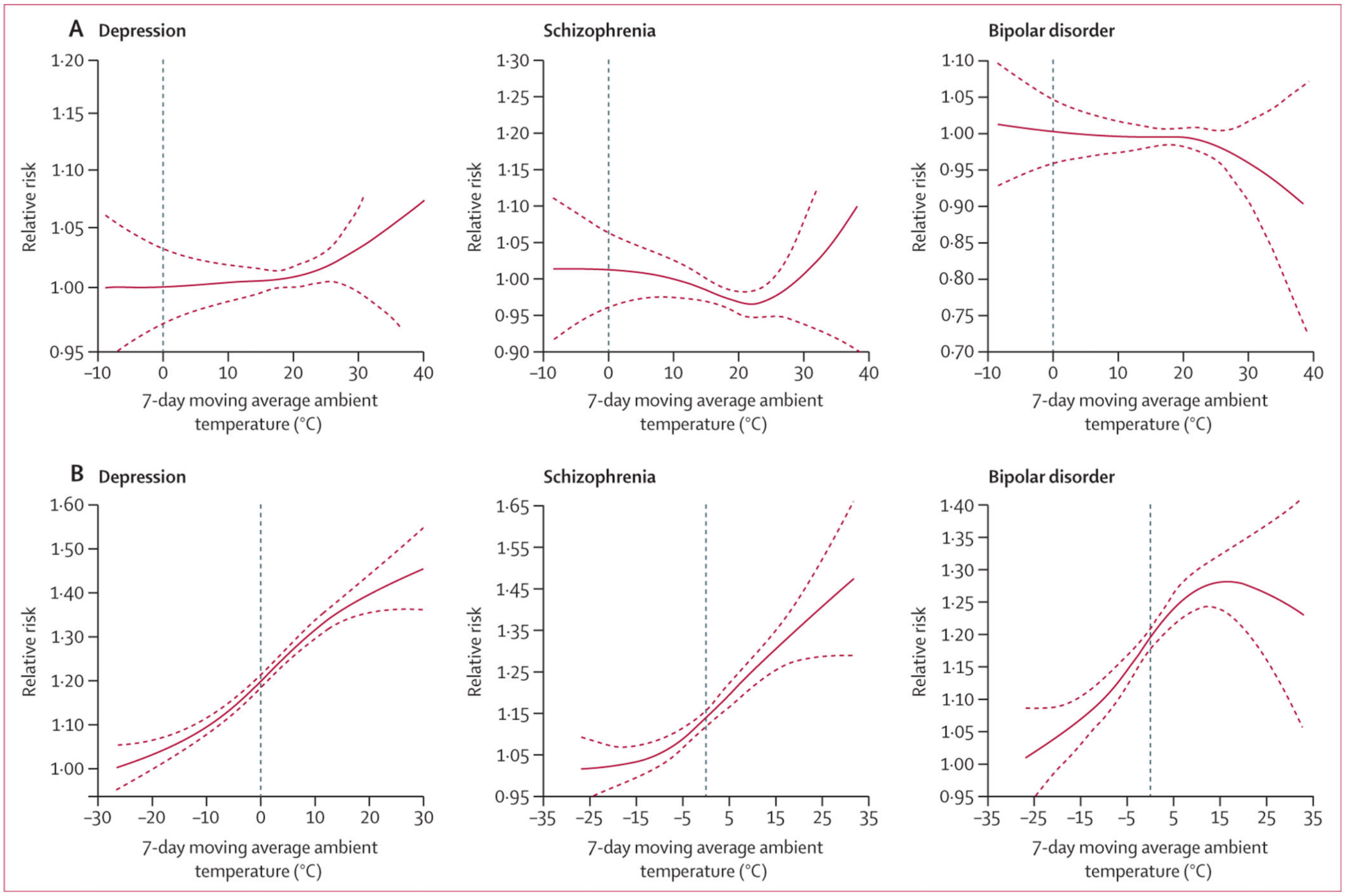

Figure 3: Dose–response curves for warm (A) and cold (B) season temperature

The solid red line depicts the relative risk of hospital admission for the targeted psychiatric disorders under warm and cold season temperatures; the dashed red lines depict the 95% CI.

Table 1:

Baseline characteristics of study population, 2000–16

	Depression	Schizophrenia	Bipolar disorder
Number of event days coded			
Case days	458 492	165 572	166 833
Control days	1 552 408	562 745	567 183
Demographic profile of all Cases			
Sex			
Female	302 411 (66·0%)	111 988 (67·6%)	115 295 (69·1%)
Male	156 081 (34·0%)	53 584 (32·4%)	51 538 (30·9%)
Race			
White	415 585 (90·6%)	117 941 (71·2%)	149 775 (89·8%)
African American	27 172 (5·9%)	38 754 (23·4%)	11 688 (7·0%)
Other races	15 735 (3·4%)	8877 (5·4%)	5370 (3·2%)
Medicaid coverage			
No	342 564 (74·7%)	57 655 (34·8%)	108 912 (65·3%)
Yes	115 928 (25·3%)	107 917 (65·2%)	57 921 (34·7%)
Age at admission, years			
65−74	218 379 (47·6%)	124 201 (75·0%)	112 206 (67·3%)
75−84	176 915 (38 6%)	36 366 (22·0%)	46 523 (27·9%)
>84	63 198 (13·8%)	5005 (3·0%)	8104 (4·9%)
Community contextual factors			
Proportion of Hispanic people in the area	4 (2 to 11)	6 (2 to 21)	5 (2 to 13)
Population density per mile^2	1079 (189 to 3565)	2402 (385 to 6665)	1349 (251 to 3945)
Area median household income per year, US$	45 786 (36 252 to 60 309)	42 348 (32 940 to 55 512)	46 600 (36 809 to 61 623)
Proportion of people in the area living under the poverty level	8 (5 to 12)	11 (7 to 17)	8 (6 to 13)
Proportion of people in the area with a high school education or less	26 (17 to 37)	30 (20 to 41)	25 (16 to 36)
Ambient exposure levels among all days			
$PM_{2·5'}$ µg/m^3	9·43 (6.30 to 13·99)	9·48 (6·39 to 14·01)	9·25 (6·18 to 13·72)
Ozone, ppb	37·69 (29·34 to 47·38)	37·27 (28·91 to 46·80)	37·80 (29·55 to 47·35)
$NO_{2'}$ ppb	18·24 (10·70 to 29·25)	21·25 (12·40 to 32·93)	18·72 (11·01 to 29·75)
Warm season temperature, °C	19·13 (13·57 to 23·86)	18·46 (12·94 to 23·09)	18·85 (13·29 to 23·51)
Cold season temperature, °C	0·29 (−8·13 to 8·79)	−1·46 (−9·79 to 7·26)	−0·13 (−8·58 to 8·32)
Precipitation, mm	0·00 (0·00 to 0·05)	0·00 (0·00 to 0·04)	0·00 (0·00 to 0·05)

Data are n, n (%), or median (IQR). $PM_{2.5}$=fine particulate matter. NO_2=nitrogen dioxide. ppb=parts per billion.

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Table 2:

Percentage change in hospital admission rate and absolute risk difference for targeted psychiatric disorders

	Main analyses		Low-level analyses	
	Percentage change* (95% CI)	**Absolute risk difference† per year (95% CI)**	**Percentage change* (95% CI)**	**Absolute risk difference† per year (95% CI)**
Depression				
$PM_{2·5}$	0·62% (0·23 to 1·02)	167 (62 to 272)	0·75% (0·32 to 1·19)	202 (85 to 318)
NO_2	0·35% (0·03 to 0·66)	93 (9 to 178)	0·35% (0·03 to 0·67)	94 (7 to 180)
Temperature (warm season)	0·30% (–0·44 to 1·06)	82 (–120 to 282)	0·35% (–0·40 to 1·11)	94 (–109 to 295)
Temperature (cold season)	3·66% (3·06 to 4·26)	952 (802 to 1102)	3·66% (3·06 to 4·26)	953 (802 to 1103)
Schizophrenia				
$PM_{2·5}$	0·77% (0·11 to 1·44)	74 (10 to 138)	0·72% (–0·01 to 1·45)	69 (–1 to 139)
NO_2	0·64% (0·20 to 1·08)	62 (20 to 105)	0·65% (0·20 to 1·10)	63 (20 to 106)
Temperature (warm season)	–0·72% (–1·93 to 0·51)	–71 (–192 to 50)	–0·75% (–1·97 to 0·48)	–74 (–196 to 47)
Temperature (cold season)	3·03% (2·04 to 4·02)	266 (195 to 376)	3·00% (2·02 to 4·00)	284 (193 to 374)
Bipolar disorder				
$PM_{2·5}$	1·19% (0·49 to 1·90)	116 (48 to 183)	1·22% (0·45 to 1·99)	118 (44 to 192)
Temperature (warm season)	–0·43% (–1·66 to 0·81)	–43 (–166 to 79)	–0·43% (–1·67 to 0·81)	–43 (–166 to 79)
Temperature (cold season)	3·52% (2·38 to 4·68)	334 (228 to 438)	3·46% (2·31 to 4·62)	328 (222 to 433)

Data are shown for each 5-unit increase in $PM_{2·5}$ (μg/m^3), NO_2 (ppb), and warm or cold season temperature (°C), based on the main multi-pollutant-temperature model and low-level model restricting analyses to observations under the US Environmental Protection Agency's Air Pollutant National Ambient Air Quality Standards Short-term Criteria. $PM_{2·5}$=fine particulate matter. NO_2=nitrogen dioxide. ppb=parts per billion.

*Percentage change in admission risk per 5-unit increase in air pollutants and ambient temperature.

†Absolute risk difference (number of additional admissions) per 5-unit increase in air pollutants and ambient temperature per year at risk.