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Health Effects of Asian Dust: A Systematic Review and Meta-Analysis

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Background: Potential adverse health effects of Asian dust exposure have been reported, but systematic reviews and quantitative syntheses are lacking.

Objective: We reviewed epidemiologic studies that assessed the risk of mortality, hospital admissions, and symptoms/dysfunction associated with exposure to Asian dust.

Methods: We performed a systematic search of PubMed and Web of Science to identify studies that reported the association between Asian dust exposure and human health outcomes. We conducted separate meta-analyses using a random-effects model for mortality and hospital admissions for a specific health outcome and assessed pooled estimates for each lag when at least three studies were available for a specific lag.

Results: We identified 89 studies that met our inclusion criteria for the systematic review, and 21 studies were included in the meta-analysis. The pooled estimates (percentage changes) of mortality from circulatory and respiratory causes for Asian dust days vs. non-Asian dust days were 2.33% [95% confidence interval (CI): 0.76, 3.93] increase at lag 0 and 3.99% (95% CI: 0.08, 8.06) increase at lag 3, respectively. The increased risk for hospital admissions for respiratory disease, asthma, and pneumonia peaked at lag 3 by 8.85% (95% CI: 0.80, 17.55), 14.55% (95% CI: 6.74, 22.94), and 8.51% (95% CI: 2.89, 14.44), respectively. Seven of 12 studies reported reduced peak expiratory flow, and 16 of 21 studies reported increased respiratory symptoms associated with Asian dust exposure. There were substantial variations between the studies in definitions of Asian dust, study designs, model specifications, and confounder controls.

Discussion: We found evidence of increased mortality and hospital admissions for circulatory and respiratory events. However, the number of studies included in the meta-analysis was not large and further evidences are merited to strengthen our conclusions. Standardized protocols for epidemiological studies would facilitate interstudy comparisons. https://doi.org/10.1289/EHP5312

Introduction

Asian dust is a seasonal meteorological phenomenon caused by dust storms that originate in the deserts of Mongolia and northern China and are carried eastward along mid-latitude westerlies to pass over China, Korea, and Japan. The dust travels thousands of kilometers and absorbs airborne pollutants from anthropogenic sources in industrial areas (Mori et al. 2003; Takemura et al. 2002). The coarse particles of desert dust are considered potentially toxic, and their constituents vary during long-range transport (Mori et al. 2003). Some studies have suggested that the health effects of Asian dust may vary by particle composition (Hiyoshi et al. 2005; Honda et al. 2014). Concerns have also been raised that the microorganisms in the dust may cause allergic reactions based on murine and *in vitro* studies and that dust events may increase the incidence of respiratory microbial-derived inflammation (Honda et al. 2017; Ichinose et al. 2006, 2008a).

The adverse effects induced by dust have been reported in Southern Europe, which is affected by Saharan dust (Perez et al. 2008; Stafoggia et al. 2016; Zauli Sajani et al. 2011). Multiple studies have reported the effect modification of dust events on the relationship between particulate matter (PM) exposure and mortality; the association of PM with mortality was stronger on dust days than on non-dust days (Jiménez et al. 2010; Mallone et al. 2011; Perez et al. 2008, 2012; Tobías et al. 2011). Other studies (Samoli et al. 2011a; Zauli Sajani et al. 2011) reported that dust events were independent risk factors for mortality, whereas the association of PM and mortality was similar on dust and non-dust days (Zauli Sajani et al. 2011) or was seen only on non-dust days (Samoli et al. 2011a). These discrepancies have also been reported in other studies of Southern European regions (Alessandrini et al. 2013; Middleton et al. 2008; Reyes et al. 2014; Samoli et al. 2011b). A study comparing the associations of desert- and non-desert–sourced PM ≤ 10 μm in aerodynamic diameter (PM_{10}) with mortality and hospital admissions reported that the health effects of desert-derived PM_{10} were of similar magnitude as those of non-desert sources (Stafoggia et al. 2016). The inconsistent findings in the Southern European studies were suggested to be due to different source areas and transport patterns of dust over the western and eastern sides of the Mediterranean (Stafoggia et al. 2016).

Epidemiological studies on the association between desert dust exposures and health outcomes have increased over the last decades. Previous review studies have reported the increased risk of respiratory and circulatory mortality after the dust exposures,

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but the findings are inconsistent across the studies and quantitative syntheses are lacking (de Longueville et al. 2013; Hashizume et al. 2010; Karanasiou et al. 2012; Zhang et al. 2016). We therefore conducted a systematic review and meta-analysis of epidemiologic studies on the health effects of exposure to Asian dust. To the best of knowledge, this is the first systematic review on the health effects of desert dust to perform a meta-analysis of suitable published studies.

Methods

Search Strategy

This study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to report the results (Moher et al. 2009).

We performed a systematic search using the PubMed and Web of Science databases (1980 to August 2019) to identify studies that reported the association between exposure to Asian dust and human health outcomes. The search strategy included the following combinations of keywords: ((“asian dust” or “asian sand” or “Asian Desert Dust” or “Yellow Dust” or “Yellow Sand” or “Dust events” or “Desert dust” or “Dust storm”) or ((“sand dust” OR “dust event”) and (Taiwan OR Mongolia OR Korea OR Japan OR Macau OR “Hong Kong” OR China OR “Far East”))) and ((“Adverse effect” or Allergy or “Ambulatory Care” or Ambulatory or Asthma or Cardiac or Cardiopulmonary or Cardiovascular or Death or “Emergency Medical Services” or Epidemiology or “Health Risk” or Health or “Hospital admission” or Hospital or Hospitalization or “Human Experimentation” or Irritants or Morbidity or Mortality or Pulmonary or Respiratory or Symptom or “Air Pollutant” or “Air Pollutants” or “Air Pollution” or “Air Pollutions” or “Adverse effects” or Cardio or “Hospital admissions” or Pneumonia or Stroke or Symptoms)).

The literature search was restricted to articles published in English. The reference lists in the selected articles were searched manually.

Study Eligibility Criteria

We included epidemiological studies that examined the association between exposure to Asian dust and health outcomes. A Populations of interest, Exposures, Comparators, and Outcomes (PECO) statement (Morgan et al. 2018) was developed to identify epidemiological studies relevant to health effects of exposure to Asian dust. The population of interest was populations without any restrictions. Laboratory studies and animal experiments were excluded. Relevant exposures were Asian dust without any restrictions of the definition, measurement methods, length, or timing. Studies that examined the effects of PM were only included if PM was used in defining the Asian dust. Studies that reported other dust events (e.g., Saharan dust, local dust) were excluded. Comparators were nonexposed or lower-exposure individuals or the same individuals at different time points. Outcomes included mortality, hospital admissions or visits, ambulance transport, emergency room attendance, and clinician diagnoses (recorded or self-reported), symptoms, and dysfunction for any health outcomes. Studies with awareness or perception as the outcome were excluded. Conference abstracts, letters, and editorials were excluded.

Study Selection

Titles and abstracts of all papers identified by the electronic searches were screened by two independent reviewers (authors M.H. and Y.N.). The full text of articles that met the selection criteria was then assessed for inclusion eligibility in the systematic review. Disagreements were resolved by discussion between the two reviewers.

Data Extraction

We extracted information from studies that met the inclusion criteria using a standardized checklist. We collected data on study period, location, age group, health outcome, study design, exposure (Asian dust) definition, number of dust-event days, concentrations of PM_{10}, PM ≤ 2.5 μm in aerodynamic diameter ($PM_{2.5}$), or other PM indicators such as suspended particulate matter (SPM) or PM between 10 and 2.5 μm in aerodynamic diameter ($PM_{10-2.5}$) on event and non-event days, effect estimates and lag period, and confounders controlled in the model. Authors were contacted for information missing from the published reports. The health outcomes were divided into mortality, hospital admissions/visits, and symptoms/dysfunction.

Study Quality Assessment

We used the National Institute of Health (NIH) framework for Observational Cohort and Cross-Sectional Studies (https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools) to assess the quality of the studies meeting inclusion criteria. For mortality and hospital admission studies, we adapted the NIH framework in the absence of a validated quality assessment tool for time-series and case-crossover designs, which were commonly used in such studies. Specifically, we modified the selected questions related to exposure assessment [Questions (Q) 6 and 10], outcome assessment (Q11) and confounding control (Q14) for this purpose (see Table S1). For exposure assessment, we examined whether the lagged associations were examined (Q6), whether the study examined different levels of the exposure (Q8), whether the Asian dust event was clearly defined (Q9), and whether the multiple lagged associations were examined (Q10). For outcome assessment, we examined whether mortality or morbidity data were based on the *International Classification of Diseases* (ICD) (Q11). For confounding control, we assessed whether major potential confounders such as long-term trends, seasonality, and temperature were accounted for in assessing the exposure–outcome associations (Q14). We assigned a good, fair, or poor quality rating, following the NIH framework. The quality assessment was conducted independently by two reviewers (M.H. and Y.K.) and the results were reconciled until a consensus was reached.

Meta-Analysis

Before pooling the estimates, we standardized the extracted data by converting the various forms of reported estimates to a log relative risk (Asian dust days vs. non-dust days) and the corresponding standard error. If a 95% confidence interval (CI) was only available as variance estimates from the studies, we first converted the upper and lower limits to the absolute difference measures (i.e., taking the natural logarithm for relative measures) and divided the difference between upper and lower limits by 3.92 to obtain the standard error (Higgins and Green 2011). We used a random-effects model with a DerSimonian-Laird estimator to pool the estimates. We quantified the extent of heterogeneity with the I^2 statistic, representing the proportion of total variance in pooled estimates attributable to heterogeneity in the true effects. The Q statistic was used to address whether the heterogeneity was statistically significant ($p < 0.05$).

Pooling estimates by specific health outcomes, lag, and subgroups. We performed meta-analysis for mortality and hospital admissions when at least three studies were available in order to ensure reliability of the pooled estimate (Borenstein et al. 2009) on a specific health outcome sharing ICD codes for a specific lag.

Accordingly, mortality studies were further divided into three outcome categories (all-cause, circulatory, and respiratory deaths) and hospital admissions studies were into four categories (respiratory disease, asthma, pneumonia, and ischemic heart disease/acute myocardial infarction). Stratified analysis was performed by sex and age groups (nonelderly and elderly) for a specific health outcome when at least three estimates were available from different populations for a specific lag. The age cutoff of elderly was ≥65 y, as defined in the original study (see Excel Table S2). Meta-analysis was not performed for the symptoms or dysfunction studies because the study design, study subject, and statistical analysis methods varied considerably.

Selecting a representative from multiple effect estimates. Some studies provided multiple effect estimates for the same health outcome by using different definitions of Asian dust, multiple models, or multiple study sites. If multiple definitions of Asian dust had been used in a given study, we included the estimates for one of the definitions that were most commonly used in other studies in the same city or country. If Asian dust had been classified according to its levels (e.g., moderate, heavy), we included the estimates for the higher level. Meta-analysis was not performed for estimates based on continuous exposure measures [i.e., nonspherical extinction coefficient of the light detection and ranging (LIDAR) method] because it was impossible to convert the continuous dust measure into a binary dust-day indicator based only on the information provided in the original studies. In addition, if multiple models (e.g., different sets of confounders) had been used in a study, we included the estimates from the main model as presented by the original authors. For multicity studies providing city-specific results, we included the estimates from each city separately if the cities were from different countries, but used pooled estimates reported if from the same country. The estimates and 95% CIs included in the meta-analysis for mortality and hospital admissions are shown in Excel Tables S1–S7.

Sensitivity analyses. We repeated the meta-analysis for studies using only time-series or case-crossover study designs by excluding studies with other study designs. We also repeated analysis for hospital admissions by including five additional studies of which the outcome was hospital visits, emergency room visits, or ambulance transport. Moreover, we examined the robustness of pooled estimates by excluding some studies with largely overlapping periods in the same study location one by one (i.e., the leave-one-out approach).

We planned to address for publication bias by using funnel plots and Begg's test if more than 10 studies were available, but we did not assess publication bias because of the small number of studies available on each outcome. All analyses were performed using R (version 3.5.1; R Development Core Team) and the metafor package.

Results

The searches of PubMed ($n = 707$) and Web of Science ($n = 1{,}008$) databases produced a total of 1,715 references (Figure 1). An additional article was identified through a manual search of the reference lists of the included articles and 179 duplicates were removed, leaving 1,537 references, of which 1,381 were excluded after reviewing the title or abstract. One hundred fifty-six studies underwent in-depth evaluation, of which 89 met the criteria for qualitative synthesis. Eleven of the studies measured mortality, 45 measured hospital admissions/visits, and 33 measured symptoms/dysfunction. Study characteristics are presented in Tables 1–3. The earliest study was published in 2002 (see Figure S1). For the meta-analysis, we did not consider all of the studies included in the qualitative review for the following reasons [33 described symptoms/dysfunctions, 15 had outcomes with fewer than three estimates, 9 estimated no quantitative risk specifically for Asian dust exposure, 7 described hospital visits/ambulance transport, 4 used continuous exposure variables rather than binary (Asian dust days vs non-dust days)], leaving 21 studies for inclusion in the meta-analysis.

Study Quality Assessment

Study quality varied substantially between the outcome categories (Tables 1–3). Overall, we rated quality more highly in mortality studies followed by hospital admission and symptoms/dysfunction studies. Seven (63.6%) studies were rated good in mortality studies, and 14 (31.1%) and 3 (9.1%) studies were rated good in hospital admission and symptom/dysfunction studies, respectively. Sixteen (48.5%) studies were rated poor in symptom/dysfunction studies, and 3 (6.7%) and 0 studies were rated poor in hospital admission and mortality studies, respectively. The high proportion of poor quality in symptom/dysfunction studies was mainly because multiple studies in this category did not control for confounders or did not describe confounder control, did not report how information bias was controlled when the outcomes were self-reported symptoms or self-measured PEF, or were of a cross-sectional design that is prone to causal inferences between exposures and outcomes. The lower-rated quality in hospital admission studies compared with mortality studies is partly because more hospital admission studies were conducted in the early 2000s, before the standard time-series or case-crossover designs were widely used in this field.

Mortality

All 11 studies assessed all-cause mortality (Table 1). Nine studies assessed mortality from circulatory causes (Chan and Ng 2011; Chen et al. 2004; Ho et al. 2018; Kashima et al. 2012, 2016; Kim et al. 2012; Lee et al. 2013, 2014; Wang and Lin 2015), 7 assessed mortality from respiratory causes (Chan and Ng 2011; Chen et al. 2004; Ho et al. 2018; Kashima et al. 2012, 2016; Lee et al. 2013, 2014), and 1 assessed mortality from both causes combined (Kwon et al. 2002). Seven studies used a time-series design (Kashima et al. 2012, 2016; Kim et al. 2012; Kwon et al. 2002; Lee et al. 2013, 2014; Wang and Lin 2015), 2 used a case-crossover design (Chan and Ng 2011; Ho et al. 2018), and 1 compared the number of deaths between dust days and control days using Poisson regression (Chen et al. 2004). For exposure definition, five studies used a local meteorological authority's definition of Asian dust (Chan and Ng 2011; Kim et al. 2012; Lee et al. 2013, 2014; Wang and Lin 2015), and 2 used the LIDAR as an indicator of Asian dust with the nonspherical extinction coefficient as a continuous variable (Kashima et al. 2012, 2016). Ten studies assessed multiple lag associations (Table 1).

Figure 2 displays the individual and pooled estimates of the associations between Asian dust exposure at lag 0 and all-cause, circulatory, and respiratory mortality. The pooled estimate (percentage change) of circulatory mortality for Asian dust days vs. non-Asian dust days at lag 0 was 2.33% (95% CI: 0.76, 3.93) ($n = 8$, $Q = 3.88$, $p = 0.79$, $I^2 = 0.0\%$). There was no evidence of a pooled association between all-cause mortality and Asian dust exposure at any lag up to lag 7 (Figure 3; see also Excel Table S1). There was a 3.99% (95% CI: 0.08, 8.06) increase in the pooled estimate of mortality from respiratory causes at lag 3 ($n = 5$, $Q = 3.90$, $p = 0.42$, $I^2 = 0.0\%$). There was little evidence of heterogeneity between the estimates for all three outcomes at all lags. The association between Asian dust and all-cause mortality did not differ between age groups (see Figure S2, Excel Table S2).

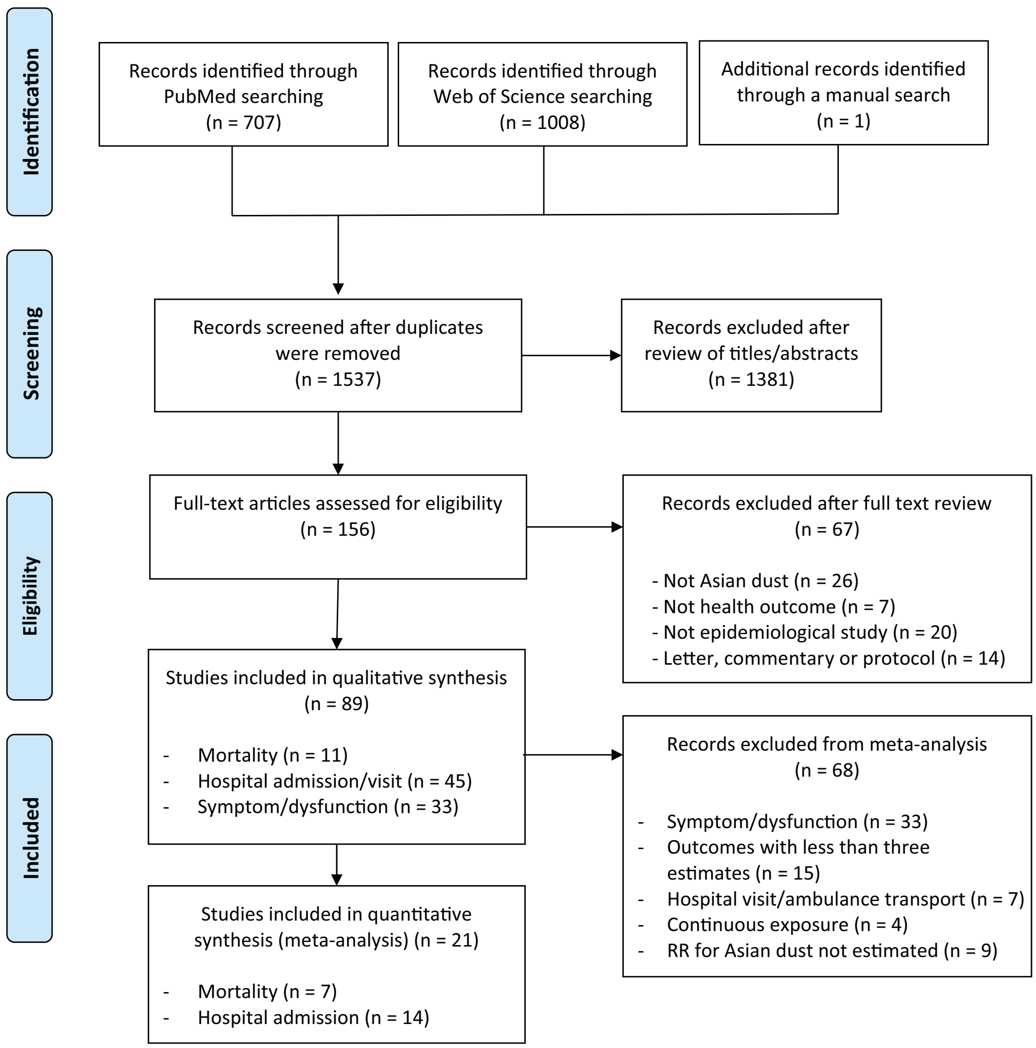

Figure 1. The literature search and screening results for studies reporting on the associations between Asian dust exposures and human health outcomes displayed as a PRISMA flow diagram (http://www.prisma-statement.org). Note: PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; RR, relative risk.

We repeated the analysis by limiting the studies to those with time-series and case-crossover designs by excluding one study (Chen et al. 2004) for all three categories of mortality outcomes. The study selection did not affect the main results and interpretation, but the pooled estimate for mortality from respiratory causes at lag 3 increased slightly to 4.22% (95% CI: 0.28, 8.32) (see Figure S3, Excel Table S3). Sensitivity analysis by excluding studies with largely overlapping periods in the same study location (the leave-one-out approach) showed that the pooled estimates were robust (see Figure S4, Excel Table S1).

Hospital Admissions

Studies examining hospital admissions/visits listed multiple diseases and conditions as the cause (Table 2). Fourteen studies used a time-series design, 13 used a case-crossover design, 11 simply compared the number of deaths between dust days and control days, 4 used spatiotemporal modeling (Chien et al. 2012, 2014; Yu et al. 2012, 2013), 2 used seasonal periodicity analysis and/or linear regression (Altindag et al. 2017; Wang et al. 2016), and 1 used correlation analysis (Wang et al. 2018). In terms of exposure definition, 20 studies used a local meteorological authority's definition of Asian dust, and 17 studies set their own definition using PM of a certain diameter, with or without other indicators such as wind profile or LIDAR. Four studies relied solely on LIDAR as a continuous variable (Kashima et al. 2014) or with a certain threshold for the nonspherical extinction coefficient (Kanatani et al. 2010; Kashima et al. 2014; Ueda et al. 2012), 2 studies used visibility (Ma et al. 2016, 2017a), and 1 study did not report the definition (Wang et al. 2018). Most of the studies published before 2010, with the exception of two (Bell et al. 2008; Meng and Lu 2007), simply compared the number of patients between event days and non-event days (7 d before and after each event day) rather than using time-series or case-crossover analysis.

Figure 4 shows the associations between Asian dust exposure at lag 3 [the lag with the most associations in the pooled analysis (Figure 5)] and hospital admissions for respiratory disease, asthma, pneumonia, and ischemic heart disease/acute myocardial infarction. The meta-analysis was not applied to other hospitalization causes because there were fewer than three estimates. The lag pattern of the meta-analysis showed evidence of a positive association for respiratory diseases (lag 3), asthma (lags 1 and 3), and pneumonia (lags 1 and 3) (Figure 5; see also Excel Table S4). The increased risk for respiratory diseases (8.85%), asthma (14.55%), and pneumonia (8.51%) peaked at lag 3. There was

Table 1. Summary of characteristics of mortality studies.

Study	Period (y)	Location	Age	Outcome	Study design	Exposure definition[a]	Days of event	Daily mean PM_{10} ($\mu g/m^3$): Event days	Daily mean PM_{10} ($\mu g/m^3$): Non-event days	Multi-lags	Confounder control: Season[c]	Trend[d]	DOW	Temp	Hum	PM	SO_2	O_3	NO_2	CO	Quality rating[b]
Kwon et al. 2002	1995–1998	Seoul (Korea)	All	All cause, circulatory, and respiratory disease	Time-series	Not specified	28	101.1	73.3	Y	Y	Y	Y	Y	Y	N	N	N	N	N	F
Chen et al. 2004	1995–2000	Taipei (Taiwan)	All	All cause, circulatory, and respiratory disease	Ad hoc approach[e]	Particular enhancements in PM_{10} at a background monitoring station	39	125.9	57.8	Y	Y	Y	Y	N	N	N	N	N	N	N	F
Chan and Ng 2011	1994–2001	Taipei (Taiwan)	All	All cause, circulatory, and respiratory disease	Case-crossover	Taiwan EPA	380	85.7 44.4 ($PM_{2.5}$)	49.6 31.1 ($PM_{2.5}$)	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N	G
Kashima et al. 2012	2005–2010	47 cities (Japan)	Elderly (≥65 y old)	All cause, circulatory, and respiratory disease	Time-series	Dust exposure was modeled as a continuous variable using dust extinction coefficient by LIDAR	42	44.3 (SPM)	24.8 (SPM)	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N	G
Kim et al. 2012	2003–2006	Seoul (Korea)	All	All cause and circulatory disease	Time-series	KMA	21	40.1 ($PM_{2.5}$)	41.1 ($PM_{2.5}$)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	G
Lee et al. 2013	2001–2009	Seven cities (Korea)	All	All cause, circulatory, and respiratory disease	Time-series	KMA	68–109	140.0–176.4	52.5–65.8	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	G
Lee et al. 2014	2001–2009	Seoul (Korea), Taipei (Taiwan), Kitakyushu (Japan)	All	All cause, circulatory, and respiratory disease	Time-series	KMA, JMA, Taiwan EPA	107 (Seoul) 125 (Taipei) 38 (Kitakyushu)	176.4 (Seoul) 71.4 (Taipei) 60.5 (Kitakyushu)	65.8 (Seoul) 52.8 (Taipei) 30.8 (Kitakyushu)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	G
Wang and Lin 2015	2000–2008	Taipei (Taiwan)	All and Elderly (≥65 y old)	All cause and circulatory disease	Time-series	Taiwan EPA	132	82.7	48.7 (all days)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	G
Kashima et al. 2016	2005–2011	Seoul (Korea), Nagasaki, Matsue, Osaka, Tokyo (Japan)	Elderly (≥65 y old)	All cause, circulatory, and respiratory disease	Time-series	Dust exposure was modeled as a continuous variable using dust extinction coefficient by LIDAR	Not specified	Not specified	Not specified	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N	G
Wong et al. 2017	2009–2010	Hong Kong	All	All cause	Time-stratified spatial regression	Not specified	8	Not specified	Not specified	N	Y	Y	Y	Y	N	N	N	N	N	N	F
Ho et al. 2018	2006–2010	Hong Kong	All	All cause, circulatory, and respiratory disease	Case-crossover	NASA Aerosol Robotic Network's sunphotometer size distribution inversion data, the backward trajectories model of hybrid single-particle Lagrangian integrated trajectory, and meteorological reports	10	33.3 ($PM_{2.5}$) 44.5 ($PM_{10-2.5}$)	33.6 ($PM_{2.5}$) 18.0 ($PM_{10-2.5}$)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	F

Note: CO, carbon monoxide; DOW, day of week; EPA, Environmental Protection Agency; F, fair; G, good; Hum, humidity; JMA, Japan Meteorological Administration; KMA, Korea Meteorological Administration; LIDAR, light detection and ranging; N, no; NO_2, nitrogen dioxide/NO_x; O_3, ozone/O_x; P, poor; PM, particulate matter; $PM_{2.5}$, PM ≤ 2.5 μm in aerodynamic diameter; PM_{10}, PM ≤ 10 μm in aerodynamic diameter; $PM_{10-2.5}$, PM between 10 and 2.5 μm in aerodynamic diameter; SPM, suspended particulate matter; SO_2, sulfur dioxide; Temp, temperature; Trend, time trend; Y, yes.

[a]Taiwan EPA: 1. Dust storm occurrence in China and Mongolia, 2. Hourly $PM_{10} > 100\,\mu g/m^3$ at either two background monitoring stations, and 3. Averaged hourly $PM_{10} > 100\,\mu g/m^3$ at three randomly selected stations among 16 stations in the Taipei metropolitan area. KMA: 1. Dust storm occurrence in China and Mongolia, and 2. visual observation. JMA: 1. Dust storm occurrence in China and Mongolia, and 2. visibility <10 km.

[b]We used the adapted National Institute of Health (NIH) framework for Observational Cohort and Cross-Sectional Studies (https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools) to assess the quality of the studies (see Table S1). We assigned a good (G), fair (F), or poor (P) quality rating following the NIH framework.

[c]If the referent selection was within 30 d of the event days, we regarded that the effects of season was controlled.

[d]If the referent selection was bidirectional or time-stratified, we regarded that the effects of time trend was controlled (Janes et al. 2005).

[e]Ad hoc approach: Comparison of the number of patients between event days and non-event days (7 d before and after each event day).

Table 2. Summary of characteristics of hospitalization studies.

									Daily mean PM_{10} ($\mu g/m^3$)		Multi-	Confounder control										Quality
Study	Period (y)	Location	Age	Outcome	Source	Study design	Exposure definition[a]	Days of event	Event days	Non-event days	lags	Season[c]	Trend[d]	DOW	Temp	Hum	PM	SO_2	O_3	NO_2	CO	rating[b]
Yang et al. 2005a	1996–2001	Taipei (Taiwan)	All ages	Stroke	Hospital admission	Ad hoc approach[e]	Hourly $PM_{10} > 125 \mu g/m^3$ lasting for at least 3 h at the background monitoring station	54	111.7	55.4	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Yang et al. 2005b	1996–2001	Taipei (Taiwan)	All ages	Asthma	Hospital admission	Ad hoc approach[e]	Hourly $PM_{10} > 125 \mu g/m^3$ lasting for at least 3 h at the background monitoring station	54	111.7	55.4	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Chen and Yang 2005	1996–2001	Taipei (Taiwan)	All ages	Cardiovascular diseases	Hospital admission	Ad hoc approach[e]	Hourly $PM_{10} > 125 \mu g/m^3$ lasting for at least 3 h at the background monitoring station	54	111.7	55.4	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Yang 2006	1997–2001	Taipei (Taiwan)	All ages	Conjunctivitis	Hospital visit	Ad hoc approach[e]	Hourly $PM_{10} > 125 \mu g/m^3$ lasting for at least 3 h at the background monitoring station	49	110.4	61.7	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Bennett et al. 2006	1997–1999	Vancouver (Canada)	All ages	Cardiac, respiratory diseases	Hospital admission	Comparison of the number of patients between event days in 1998 and non-event days in the same period in 1997	Gobi dust event in late April 1998	4	119–123 (hourly peak)	Not specified	N	N	N	N	N	N	N	N	N	N	N	P
Chang et al. 2006	1997–2001	Taipei (Taiwan)	All ages	Allergic rhinitis	Hospital visit	Ad hoc approach[e]	Hourly $PM_{10} > 125 \mu g/m^3$ lasting for at least 3 h at the background monitoring station	49	110.4	61.7	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Meng and Lu 2007	1994–2003	Minqin (China)	All ages	Cardiovascular, respiratory diseases	Hospital admission	Time-series	China Meteorological Administration	413	Not specified	Not specified	Y	Y	Y	Y	Y	Y	N	N	N	N	N	F
Lai and Cheng 2008	2000–2004	Taipei (Taiwan)	All ages	Respiratory diseases	Hospital admission	Ad hoc approach[e]	Taiwan EPA	97	19.8–33.9	Not specified	N	Y	Y	Y	N	N	N	N	N	N	N	F
Cheng et al. 2008	1996–2001	Taipei (Taiwan)	All ages	Pneumonia	Hospital admission	Ad hoc approach[e]	Hourly $PM_{10} > 125 \mu g/m^3$ lasting for at least 3 h at the background monitoring station	54	111.7	55.4	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Chiu et al. 2008	1996–2001	Taipei (Taiwan)	All ages	COPD	Hospital admission	Ad hoc approach[e]	Hourly $PM_{10} > 125 \mu g/m^3$ lasting for at least 3 h at the background monitoring station	54	111.7	55.4	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Chan et al. 2008	1995–2002	Taipei (Taiwan)	All ages	Ischemic heart disease, cerebrovascular disease, COPD	Emergency hospital visit	Comparison of the difference between model-predicted patients (without Asian dust effects) and observed patients on Asian dust days	Taiwan EPA High-dust days: $PM_{10} > 90 \mu g/m^3$ Low-dust days: $PM_{10} > 90 \mu g/m^3$	85 (39 high-dust days and 46 low-dust days)	112.7 (high-dust days) 61.1 (low-dust days)	Not specified	N	Y	Y	Y	Y	N	Y	N	N	Y	N	F
Bell et al. 2008	1995–2002	Taipei (Taiwan)	All ages	Asthma, pneumonia, ischemic heart disease, cerebrovascular disease	Hospital admission	Time-series	(a) PM_{10} levels $> 115 \mu g/m^3$ in Taipei and (b) $> 100 \mu g/m^3$ at the background monitoring station	2.1% of days for (a), 1.6% of days for (b)	49.1 (annual mean) 31.6 ($PM_{2.5}$, annual mean)	Not specified	Y	Y	Y	Y	Y[f]	N	N	N	N	N	N	G

Table 2. (*Continued.*)

Study	Period (y)	Location	Age	Outcome	Source	Study design	Exposure definition[a]	Days of event	Daily mean PM_{10} ($\mu g/m^3$): Event days	Daily mean PM_{10} ($\mu g/m^3$): Non-event days	Multi-lags	Confounder control: Season[c]	Trend[d]	DOW	Temp	Hum	PM	SO_2	O_3	NO_2	CO	Quality rating[b]
Yang et al. 2009	1996–2001	Taipei (Taiwan)	All ages	Congestive heart failure	Hospital admission	Ad hoc approach[e]	Hourly $PM_{10} > 125\ \mu g/m^3$ lasting for at least 3 h at the background monitoring station	54	111.7	55.4	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	F
Kanatani et al. 2010	February–April 2005–2009	Toyama (Japan)	Children (1–15 y old)	Asthma	Hospital admission	Case-crossover	Daily average dust extinction coefficient by the LIDAR method less than 1 km from the ground ($= 0.1\ mg/m^3$)	6	66.3 (SPM)	16.9 (SPM)	Y	Y	Y	Y	Y	Y	Y[g]	Y	Y	Y	N	G
Ueda et al. 2010	2001–2007	Fukuoka (Japan)	Children (≤12 y old)	Asthma	Emergency hospital admission	Case-crossover	JMA	106	62.8 (SPM)	34.3 (SPM)	N	Y	Y	Y	Y	Y	N	N	N	N	N	F
Ueda et al. 2012	March–May 2003–2007	Nagasaki (Japan)	All ages	Circulatory, respiratory disease	Ambulance transport	Case-crossover	Daily average dust extinction coefficient by the LIDAR method at 120–900 m from the ground but >0.105/km (for heavy Asian dust) and 0.066–0.105/km (for moderate Asian dust)	17 (heavy Asian dust) 31 (moderate Asian dust)	57.7 (SPM, heavy dust days) 44.4 (SPM, moderate dust days)	30.3 (SPM)	Y	Y	Y	Y	Y	Y	Y[g]	N	N	N	N	G
Kamouchi et al. 2012	1999–2010	Fukuoka (Japan)	Adults (≥20 y old)	Ischemic stroke	Hospital admission	Case-crossover	JMA	137	59.6 (SPM)	29.5 (SPM)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	G
Yu et al. 2012	1997–2007	Taipei (Taiwan)	Children (≤14 y old)	Respiratory diseases	Hospital visit	Spatiotemporal modeling	CCU database (1997–2000) Taiwan EPA (2001–2007)	172	90.6	52.7	Y	Y	Y	Y	Y	N	N	N	N	N	N	G
Kang et al. 2012	2000–2009	Taipei (Taiwan)	All ages	Pneumonia	Hospital admission	Time-series	Total particulate matter $> 100\ \mu g/m^3$ at three background monitoring stations	135	121.7	49.2	Y	N	Y	N	Y	N	N	Y	Y	N	Y	F
Tam et al. 2012a	1998–2002	Hong Kong (China)	Not specified	Circulatory diseases	Hospital admission	Case-crossover	• Air pollution index $> 100\ \mu g/m^3$ • $PM_{2.5}$:$PM_{10} < 0.4$ • Predominant easterly wind profile • At least three times higher concentrations of dust storm tracer elements than annual averages	5	134.3 59.9 ($PM_{2.5}$)	49.9 35.2 ($PM_{2.5}$)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	F
Tam et al. 2012b	1998–2002	Hong Kong (China)	Not specified	Respiratory diseases	Hospital admission	Case-crossover	• Air pollution index $> 100\ \mu g/m^3$ • $PM_{2.5}$:$PM_{10} < 0.4$ • Predominant easterly wind profile • At least three times higher concentrations of dust storm tracer elements than annual averages	5	134.3 59.9 ($PM_{2.5}$)	49.9 35.2 ($PM_{2.5}$)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	F
Chien et al. 2012	1997–2007	Taipei (Taiwan)	Children (≤14 y old)	Respiratory diseases	Hospital visit	Spatiotemporal modeling	CCU database (1997–2000) Taiwan EPA (2001–2007)	172	Not specified	Not specified	Y	N	Y	Y	Y	N	Y	N	N	N	N	G
Tao et al. 2012	March–May 2001–2005	Lanzhou (China)	Not specified	Respiratory diseases	Hospital admission	Time-series	Meteorological Bureau of Gansu Province	49	536.1	190.6	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	F
Yu et al. 2013	1998–2007	Taipei (Taiwan)	Children (≤14 y old)	Respiratory diseases	Hospital visits	Spatiotemporal modeling	Taiwan EPA	164	75.9	51.4	N	N	Y	Y	Y	N	Y	Y	Y	Y	N	F
Kang et al. 2013	2000–2009	Taipei (Taiwan)	All ages	Stroke	Hospital admission	Time-series	Total particulate matter $> 100\ \mu g/m^3$ at three background monitoring stations	135	121.7	49.2	Y	Y	Y	N	Y	N	N	Y	N	N	Y	F

Table 2. (*Continued.*)

Study	Period (y)	Location	Age	Outcome	Source	Study design	Exposure definition[a]	Days of event	Daily mean PM_{10} ($\mu g/m^3$)		Multi-	Confounder control										Quality
									Event days	Non-event days	lags	Season[c]	Trend[d]	DOW	Temp	Hum	PM	SO_2	O_3	NO_2	CO	rating[b]
Kashima et al. 2014	2006–2010	Okayama (Japan)	Elderly (≥65 y old)	All causes, cardiovascular, cerebrovascular, pulmonary diseases	Ambulance transport	Time-series	Asian dust was modeled as a continuous variable using the dust extinction coefficient by the LIDAR method	Not specified	43.8 (SPM, moderate dust days) 67.3 (SPM, severe dust days)	25.3 (SPM)	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	G
Chien et al. 2014	2002–2007	Taipei (Taiwan)	Children (≤14 y old)	Conjunctivitis	Hospital visit	Spatiotemporal modeling	Taiwan EPA	90	81.1	53.3	N	N	Y	Y	Y	N	Y	Y	Y	Y	N	F
Wang et al. 2014	2000–2009	Taiwan	All ages	Asthma	Hospital admission	Time-series	Taiwan EPA	Not specified	Not specified	Not specified	Y	Y	Y	N	Y	N	N	Y	Y	N	Y	F
Matsukawa et al. 2014	2003–2010	Fukuoka (Japan)	Adults (≥20 y old)	Acute myocardial infarction	Hospital admission	Case-crossover	JMA	75	58.1	29.7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	G
Nakamura et al. 2015	2005–2008	Seven prefectures (Japan)	All ages	Out-of-hospital cardiac arrest	Utstein-style data	Case-crossover	1. Daily maximum dust extinction coefficient by the LIDAR method >0.05/km 2. Daily maximum SPM >50 $\mu g/m^3$ 3. Correlation coefficient between hourly Asian dust extinction coefficient and hourly SPM >0.6	average 28 (minimum 7, maximum 79)	Not specified	Not specified	Y	Y	Y	Y	Y	Y	Y[g]	Y	Y	Y	N	G
Teng et al. 2016	2000–2009	Taiwan	All ages	Acute myocardial infarction	Hospital admission	Time-series	Taiwan EPA	46 events	Not specified	Not specified	Y	Y	Y	N	Y	N	N	N	N	Y	Y	F
Lin et al. 2016	2000–2008	Taipei (Taiwan)	All ages	All causes, circulatory, respiratory diseases	Emergency room visit	Time-series	Taiwan EPA	132	Not specified	Not specified	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N	G
Wang et al. 2016	2005–2012	Minqin (China)	All ages	Pulmonary tuberculosis	Hospital visit	1. Seasonal periodicity analysis 2. Linear regression with three atmospheric variables (visibility, duration, and wind speed)	China Meteorological Administration	Not specified	Not specified	Not specified	N	N	N	N	N	N	N	N	N	N	N	P
Y-S Park et al. 2016	2007–2013	Seoul and Incheon (Korea)	All ages	Asthma	Hospital visit	Case-crossover	KMA	7	448.6 (daily maximum)	163.1 (daily maximum)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	F
Nakamura et al. 2016	2010–2013	Nagasaki (Japan)	Children (≤15 y old)	Asthma, respiratory disease	Emergency room visit	Case-crossover	1. Daily maximum dust extinction coefficient by the LIDAR method >0.05/km 2. Daily maximum SPM >50 $\mu g/m^3$ 3. Correlation coefficient between hourly Asian dust extinction coefficient and hourly SPM >0.6	47	53.1 (SPM)	24.0 (SPM)	Y	Y	Y	Y	Y	Y	Y[g]	Y	Y	Y	N	G
Ma et al. 2016	2007–2011	Lanzhou (China)	All ages	Respiratory diseases	Emergency room visit	Time-series, effect modification of PM_{10}, SO_2, and NO_2 by Asian dust	Visibility <1,000 m	32	324	146	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	F

Table 2. (*Continued.*)

Study	Period (y)	Location	Age	Outcome	Source	Study design	Exposure definition[a]	Days of event	Daily mean PM_{10} ($\mu g/m^3$) Event days	Non-event days	Multi-lags	Confounder control Season[c]	Trend[d]	DOW	Temp	Hum	PM	SO_2	O_3	NO_2	CO	Quality rating[b]
Altindag et al. 2017	2003–2011	All cities (Korea)	Birth	Birth weight, low birth weight, gestation, premature birth, fetal growth	Birth certificate	Linear regression model	KMA	Not specified	Not specified	Not specified	N	Y	Y	N	Y	Y	Y	N	N	N	N	F
Kojima et al. 2017	2010–2015	Kumamoto (Japan)	All ages	Acute myocardial infarction	Hospital admission/visit	Case-crossover	JMA	41	34.9 ($PM_{2.5}$)	20.5 ($PM_{2.5}$)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	G
Sakata et al. 2017	1989–2012	Fukuoka (Japan)	All ages	Pollinosis	Hospital visit	Time-series	JMA	238	58.9 (SPM)	29.4 (SPM)	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	G
Liu et al. 2017	2006–2008	Central Taiwan	All ages	All causes, circulatory, respiratory diseases	Emergency room visit	Case-crossover, effect of $PM_{2.5}$ during Asian dust	Taiwan EPA	16	133.0 61.9 ($PM_{2.5}$)	77.8 48.9 ($PM_{2.5}$)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	F
Kashima et al. 2017	2006–2010	Okayama (Japan)	Elderly (≥65 y old)	Circulatory, respiratory diseases	Emergency room visit	Case-crossover	Asian dust was modeled as a continuous variable using the dust extinction coefficient by the LIDAR method	26	185.6 (converted from nonspherical extinction coefficient)	Not specified	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	G
Ma et al. 2017a	2007–2011	Lanzhou (China)	All ages	All causes, circulatory diseases	Hospital admission	Time-series, effect modification of PM_{10}, SO_2, and NO_2 by Asian dust	Horizontal visibility <1,000 m	32	324	146	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	F
Ma et al. 2017b	1965–2005	Gansu (China)	All ages	Measles	Not specified	Correlation, time-series	Meteorological Bureau of Gansu Province	Not specified	Not specified	Not specified	N	Y	Y	N	N	N	N	N	N	N	N	P
Chan et al. 2018	2000–2009	Taiwan	All ages	Diabetes	Hospital admission	Time-series	Taiwan EPA	55	Not specified	Not specified	Y	Y	Y	N	Y	N	N	N	Y	Y	Y	F
Wang et al. 2018	March 2016	Inner Mongolia (China)	All ages	Cardiovascular, respiratory diseases	Hospital visit	Correlation	Not specified	4	Not specified	Not specified	N	N	N	N	N	N	N	N	N	N	N	F

Note: CO, carbon monoxide; COPD, chronic obstructive pulmonary disease; DOW, day of week; EPA, Environmental Protection Agency; F, fair; G, good; Hum, humidity; JMA, Japan Meteorological Administration; KMA, Korea Meteorological Administration; LIDAR, light detection and ranging; N, no; NO_2, nitrogen dioxide/NO_x; O_3, ozone/O_x; P, poor; PM, particulate matter; $PM_{2.5}$, PM ≤ 2.5 μm in aerodynamic diameter; PM_{10}, PM ≤ 10 μm in aerodynamic diameter; SPM, suspended particulate matter;SO_2, sulfur dioxide; Temp, temperature; Trend, time trend; Y, yes.

[a]Taiwan EPA: 1. Dust storm occurrence in China and Mongolia, 2. Hourly $PM_{10} > 100\,\mu g/m^3$ at either of two background monitoring stations, and 3. Averaged hourly $PM_{10} > 100\,\mu g/m^3$ at three randomly selected stations of 16 in the Taipei metropolitan area. Chinese Culture University database: 1. Visibility less than 1 km for 24 h in any of three neighboring First GARP Global Experiment-type ground stations in East Asia, and 2. PM_{10} concentrations $>100\,\mu g/m^3$ observed by at least one of the air quality monitoring stations located in Wanli, Guanyin, Danshui, and Yilan. KMA (Korea Meteorological Administration): 1. Dust storm occurrence in China and Mongolia, and 2. Visual observation. JMA (Japan Meteorological Administration): 1. Dust storm occurrence in China and Mongolia, and 2. Visibility <10 km. China Meteorological Administration: Unknown definition of Asian dust.

[b]We used the adapted National Institute of Health (NIH) framework for Observational Cohort and Cross-Sectional Studies (https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools) to assess the quality of the studies (see Table S1). We assigned a good (G), fair (F), or poor (P) quality rating following the NIH framework.

[c]If the referent selection was within 30 d of the event days, we regarded the effects of season as controlled.

[d]If the referent selection was bidirectional or time-stratified, we regarded the effects of time trend as controlled (Janes et al. 2005).

[e]Ad hoc approach: Comparison of the number of patients between event days and non-event days (7 d before and after of each event day).

[f]Extinction coefficients for spherical particles.

[g]Apparent temperature.

Table 3. Summary of characteristics of symptom and dysfunction studies.

Study	Period (y)	Location	Subject	Outcome	Study design/statistical analysis	Exposure definition	Days of event	Daily mean PM_{10} ($\mu g/m^3$)		Summary results	Confounder control	Quality rating[a]
								Event days	Non-event days			
Park et al. 2005	March–June 2002	Incheon (Korea)	64 asthmatic adults (16–75 y old)	Changes in PEF, respiratory symptoms	PEF, respiratory symptoms, and daily activities were recorded twice daily. Generalized estimating equations were used to analyze the relationship between respiratory symptoms, pulmonary function, and air pollution levels.	Reduced visibility and meteorological experts' judgment	14	188.5	60.0	An increase in PM_{10} concentrations was associated with increases in PEF variability of >20%, more nighttime symptoms, and a decrease in the mean PEF.	Time trend	P
Yoo et al. 2008	March–May 2004	Seoul (Korea)	52 asthmatic children	Changes in PEF, respiratory symptoms	Respiratory symptoms and PEF were recorded twice daily; participants underwent methacholine bronchial challenge tests. Average levels of respiratory symptoms and pulmonary function parameters on the Asian dust days and the following 2 d were compared with those of the control days using the Kruskal-Wallis test.	KMA	5	Not specified	Not specified	The prevalence of acute respiratory symptoms and signs was significantly higher during Asian dust days. Reduction in morning and evening PEF and increases in PEF diurnal variability and bronchodilator response were significant during Asian dust days.	Not specified	P
Hong et al. 2010	May–June 2007	Seoul (Korea)	110 school children (9 y old)	Changes in PEF	PEF was measured three times a day and daily mean PEF was used for analysis. Linear mixed-effects model was used to estimate particulates or metal effects on daily PEF.	$PM_{10} > 130\ \mu g/m^3$	Not specified	Not specified	Not specified	$PM_{2.5}$ and PM_{10} concentrations were not significantly associated with PEF except in asthmatics. Most of the metals bound to the particulates were associated with a decrease in children's PEF.	Age, sex, height, weight, asthma history, passive smoking, daily mean temperature, mean relative humidity, air pressure, time trend	F
Mu et al. 2011	May–2008	Ulaanbaatar, Gobi Desert (Mongolia)	36 urban and 87 desert area residents (all ages)	Eye and respiratory symptoms	The prevalence of subjective eye and respiratory symptoms was compared between 36 urban and 87 desert area residents after a dust storm.	A dust storm on 26–27 May 2008	Not specified	Not specified	Not specified	The prevalence of tearing but not respiratory symptoms were significantly higher in the desert area residents than in the urban area residents.	Age, sex, and smoking	P
Watanabe et al. 2011a	February–March, December 2009	Yonago (Japan)	145 asthmatic adults (>18 y old)	Changes in PEF, respiratory symptoms	PEF was measured three times a day. Mean morning PEF was compared between Asian dust days and non-dust days.	JMA/MOE	11	65.3	27.8	There was no significant difference in mean morning PEF and respiratory symptoms between Asian dust days and non-dust days.	Temperature, atmospheric pressure, pollen, PM_{10}, SO_2, NO_2	F

Table 3. (*Continued.*)

Study	Period (y)	Location	Subject	Outcome	Study design/statistical analysis	Exposure definition	Days of event	Daily mean PM_{10} ($\mu g/m^3$)		Summary results	Confounder control	Quality rating[a]
								Event days	Non-event days			
Watanabe et al. 2011b	April–May 2007	Yonago (Japan)	98 asthmatic adults (>18 y old)	Changes in PEF, respiratory symptoms	Telephone survey: Aggravation of respiratory symptoms (cough, sputum, dyspnea, wheezing) 3 d after the Asian dust event. Mean morning PEF was compared between Asian dust days and non-dust days.	JMA/MOE	10	101.2	40.5	22% reported worsening lower respiratory symptoms during Asian dust events and significant reduction of the lowest PEF over a week expressed as a percentage of the highest PEF (Min% Max) during 6 d after the dust event.	Not specified	F
Otani et al. 2011	February 2009	Yonago (Japan)	54 healthy volunteers	Nasopharyngeal, ocular, respiratory, and dermal symptoms	Symptom scores collected by questionnaire were compared between Asian dust days and non-Asian dust days.	JMA	6	33.0 (SPM)	15.6 (SPM)	The total symptom score on Asian dust days was significantly higher than on non-Asian dust days. The dermal symptom scores were positively correlated with levels of SPM.	Not specified	P
Otani et al. 2012	March 2010	Yonago (Japan)	62 healthy volunteers	Dermal symptoms and allergic reactions to heavy metals	Allergic reactions to heavy metals were examined by patch test and compared between 9 participants with dermal symptoms and 11 participants without dermal symptoms on Asian dust days.	JMA	1	151 (SPM)	Not specified	Reactions to iron, aluminum, and nickel were higher in participants with dermal symptoms on Asian dust days.	Not specified	P
Watanabe et al. 2012	March 2007–2010	Tottori (Japan)	46 asthma patients	Respiratory, ocular, and dermal symptoms	Telephone survey: respiratory, ocular, and dermal symptoms on the Asian dust days compared with a week prior.	JMA/MOE	8	32.0–151.0 (SPM)	Not specified	The number of patients who reported exacerbation of symptoms varied between dust events. Only two patients consistently reported symptom exacerbation.	Not specified	P
Onishi et al. 2012	February–March 2009	Yonago (Japan)	54 healthy volunteers	Nasopharyngeal, ocular, respiratory, and dermal symptoms	Symptom scores recorded by questionnaire were compared between before and after Asian dust days and stratified by dust component	SYNOP report of WMO and JMA	9	Non-mineral dust aerosols: Type 1: 28.3–56.1; Type 2: 24.3–38.3; Type 3: 9.1	Not specified	Nasal and ocular symptoms scores increased after exposure to Type 1 events. Nasal symptom scores decreased after exposure to Type 3 events.	Not specified	F
Otani et al. 2014	2012	Tottori (Japan)	25 healthy volunteers	Nasal, pharyngeal, ocular, respiratory, and dermal symptoms	Symptom scores recorded by questionnaire were correlated with serum IgE levels measured after the Asian dust event.	JMA	3	34.3 (SPM)	13.6 (SPM)	There was a positive association between nasal symptom scores and two microbial-specific IgE levels.	Not specified	P

Table 3. (*Continued.*)

Study	Period (y)	Location	Subject	Outcome	Study design/statistical analysis	Exposure definition	Days of event	Daily mean PM_{10} ($\mu g/m^3$)		Summary results	Confounder control	Quality rating[a]
								Event days	Non-event days			
Ogi et al. 2014	February–March 2009	Fukui (Japan)	41 patients with nasal and ocular allergy symptoms (≥20 y old)	Nasopharyngeal and ocular symptoms, medication use	Symptom scores recorded by diary were compared between Asian dust days and non-Asian dust days.	Visibility <10 km	Not specified	Not specified	Not specified	Scores for nasal and ocular symptoms increased after an Asian dust event both pre- and post-Japanese cedar pollen season.	Not specified	P
Mimura et al. 2014	March 2011	Tokyo (Japan)	10 allergic rhinoconjunctivitis patients, 3 atopic keratoconjunctivitis patients, 10 healthy controls	Skin pick tests positive	Skin pick tests were performed with untreated Asian dust, Asian dust extract, heat-sterilized Asian dust, silicon dioxide, and phosphate-buffered saline.	Not specified	Not specified	Not specified	Not specified	Positive skin patch tests for untreated Asian dust, Asian dust extract, and heat-sterilized Asian dust were higher in the conjunctivitis groups than in the control group.	Not specified	P
Higashi et al. 2014a	2011	Kanazawa (Japan)	86 adult asthma patients	Cough	Incidence of cough symptoms recorded by diary was regressed with graded categories of Asian dust days.	Five-grade categories of Asian dust days created by dust extinction coefficient (LIDAR)	Not specified	Not specified	Not specified	A dose-response relationship between Asian dust concentrations and daily cough incidence was observed.	Sex, age, body mass index, temperature, rain, seasonality, spherical particles (LIDAR), and $PM_{2.5}$	G
Higashi et al. 2014b	2011	Kanazawa (Japan)	86 adult patients with chronic cough	Respiratory, nasal, and ophthalmic allergic symptoms	Incidence of symptoms recorded by diary was compared between Asian dust days and non-dust days.	Four consecutive days when the dust extinction coefficient (LIDAR) > 0.03/km at 1 km above the ground	15	68.4–125.1 (TSP)	17.5 (TSP)	More patients experienced coughing and itchy eyes during Asian dust periods.	Not specified	F
Watanabe et al. 2014	February–May 2011	Tottori (Japan)	231 adult asthma patients	Changes in PEF, respiratory symptoms	Daily PEF and respiratory symptom scores recorded by diary were compared between Asian dust days and non-Asian dust days.	JMA	3	64.0–109.0 (SPM)	17.2–28.8 (SPM)	Upper and lower respiratory tract symptom scores were higher on Asian dust days. There was no significant association between daily PEF and Asian dust exposure.	Not specified	P
Onishi et al. 2015	February 2009	Yonago (Japan)	54 healthy volunteers	Nasopharyngeal, ocular, respiratory, and dermal symptoms	Symptom scores recorded by questionnaire were regressed with air pollutants and ambient heavy metals.	JMA	6	35.8 (SPM)	16.8 (SPM)	The dermal symptom score was positively associated with levels of SPM and nickel. Heavy metal levels were significantly higher on Asian dust days.	Not specified	P
Watanabe et al. 2015a	March–May 2012	Yonago (Japan)	33 adult asthma patients	Changes in PEF and fractional exhaled nitric oxide (FeNO)	Daily records of morning PEF and FeNO were compared between Asian dust days and non-Asian dust days using linear regression.	JMA	2	Not specified	Not specified	No significant association of PEF and FeNO with Asian dust exposure.	Not specified	P

Table 3. (*Continued.*)

Study	Period (y)	Location	Subject	Outcome	Study design/statistical analysis	Exposure definition	Days of event	Daily mean PM_{10} ($\mu g/m^3$)		Summary results	Confounder control	Quality rating[a]
								Event days	Non-event days			
Watanabe et al. 2015b	2012–2013	Matsue (Japan)	399 schoolchildren (8–9 y old)	Changes in PEF	Daily records of morning PEF were compared between Asian dust days and non-Asian dust days using linear mixed models.	JMA and LIDAR method	7	17.2–37.8 ($PM_{2.5}$)	10.3 in 2012 ($PM_{2.5}$) 17.5 in 2013 ($PM_{2.5}$)	PEF decreased after Asian dust exposure from Day 0 to Day 3.	Age, sex, height, weight, allergy history, air pollutants (SPM, $PM_{2.5}$, O_3, SO_2, NO_2) and weather conditions (temperature, humidity, and atmospheric pressure)	F
Watanabe et al. 2015c	March–May 2013	Yonago (Japan)	137 asthma patients	Changes in PEF, respiratory symptoms	Daily PEF and respiratory symptom scores recorded by diary were compared between Asian dust days and non-Asian dust days using linear mixed models.	Hourly dust extinction coefficient $>0.1/km$ (LIDAR)	8	Not specified	Not specified	Symptom scores were higher on Asian dust days. There was no significant association between PEF and Asian dust exposure.	Age, sex, smoking, allergy history, treatments, pulmonary function, air pollutants (O_3, SO_2, NO_2), and weather conditions (temperature, humidity, and atmospheric pressure)	F
Aili and Oanh 2015	February–May 2013	Burgur (China)	810 residents (all ages)	Symptoms (cough, expectoration, shortness of breath, heavy chest, dry throat, dry eyes, tears, runny nose, sneezing, depressed mood)	Severity of symptoms recorded by questionnaire was compared between suspended dust days, blowing dust days, sand storm days, and non-dust days.	Suspended dust: visibility <10 km, blowing dust: visibility 1–10 km, sand storm: wind velocity >25 m/s and visibility <1 km	Suspended dust: 26; blowing dust: 8; sand storm: 3	1,073 (TSP, suspended dust); 1,379 (TSP, blowing dust); 2,522 (TSP, sand storm)	Not specified	Air pollutants that increased during the dust event were correlated with respiratory symptoms and ear, nose, and throat symptoms.	Not specified	P
Wang et al. 2015	2011	Minqin (China)	728 farmers ($\geq$40 y old)	Respiratory diseases and symptoms	Prevalence of respiratory symptoms measured by questionnaire was compared between randomly selected farmers living in exposed towns (near the desert) and control town.	China Meteorological Administration	Not specified	Not specified	Not specified	The odds ratios of chronic rhinitis, chronic bronchitis, and chronic cough were 3.1, 2.5, and 1.8, respectively.	Not specified	P
Watanabe et al. 2016a	April–May 2012	Shimane (Japan)	399 schoolchildren	Changes in PEF	The association between daily records of morning PEF and dust extinction coefficient was analyzed using linear mixed models.	Asian dust was modeled as a continuous variable using the dust extinction coefficient (LIDAR)	Not specified	Not specified	Not specified	Increase in sand dust particles was associated with a decrease in PEF.	Sex, height, weight, allergy history, air pollutants (SPM, $PM_{2.5}$, O_3, SO_2, NO_2), and weather conditions (temperature, humidity, and atmospheric pressure)	F
Watanabe et al. 2016b	March–May 2012	Tottori (Japan)	231 adult asthma patients	Changes in PEF	The association between daily records of morning PEF and Asian dust exposures was analyzed using linear mixed models.	Daily average dust extinction coefficient (LIDAR) $>0.032/km$ at a 120–150-m altitude	6	Not specified	Not specified	Daily PEF was significantly lower on Asian dust days.	Age, sex, smoking, allergic rhinitis, treatments, weather conditions (temperature, humidity, and atmospheric pressure) and air pollutants (O_3, SO_2, NO_2, spherical particles, SPM, and $PM_{2.5}$)	F

Table 3. (*Continued.*)

Study	Period (y)	Location	Subject	Outcome	Study design/statistical analysis	Exposure definition	Days of event	Daily mean PM_{10} ($\mu g/m^3$)		Summary results	Confounder control	Quality rating[a]
								Event days	Non-event days			
Watanabe et al. 2016c	2012	Tottori (Japan)	231 adult asthma patients	Changes in PEF	The association between daily records of morning PEF and Asian dust exposures was analyzed using linear mixed models.	JMA	2	Not specified	Not specified	PEF decreased after exposure to heavy Asian dust in patients with asthma and in patients with asthma and COPD.	Age, sex, smoking, treatment, ACT score, and weather conditions (temperature, humidity, and atmospheric pressure)	F
Kanatani et al. 2016	2011, 2013	Kyoto, Toyama, Tottori (Japan)	3,327 pregnant women	Allergic symptoms (allergy-control score)	Symptom scores were collected by questionnaire and compared between Asian dust and non-Asian dust days.	Daily average dust extinction coefficient (LIDAR) >0.07/km at a 135-m altitude	27	34.2 (SPM); 27.6 ($PM_{2.5}$)	11.6 (SPM); 11.8 ($PM_{2.5}$)	Pregnant women had an increased risk of allergic symptoms on high desert-dust days. The increase was mostly driven by sensitivity to Japanese cedar pollen.	Pollen, O_3, SO_2, NO_2, spherical particles, air pressure, pressure change from the previous day, mean temperature, temperature change from the previous day, temperature change within the day, minimum temperature, humidity	G
Ko et al. 2016	March–May 2013	Fukuoka (Japan)	45 patients with acute conjunctivitis	Acute conjunctivitis	Clinical symptoms were recorded and scored for patients newly diagnosed with acute conjunctivitis. The clinical scores were compared between patients with higher and lower silicon/aluminum-rich compounds (components of Asian dust).	JMA	2	Not specified	Not specified	Clinical conjunctivitis scores were higher in patients on Asian dust days.	Not specified	P
Majbauddin et al. 2016	March 2013	Yonago (Japan)	42 healthy volunteers (mean age 33.6 y old)	Nasal, ocular, respiratory, and skin symptoms	Symptom scores collected by web-based survey application were compared between Asian dust days and non-Asian dust days.	JMA	4	52.3 (SPM) 40.9 ($PM_{2.5}$)	19.6 (SPM) 17.1 ($PM_{2.5}$)	Ocular, nasal, and skin symptom scores were significantly higher on Asian dust days than on non-Asian dust days.	Not specified	P
Watanabe et al. 2017	February 2015	Matsue (Japan)	345 elementary school students (10–12 y old)	Skin symptoms	Daily records of skin symptoms were regressed with air pollutants and Asian dust indicator measured by LIDAR	Daily median dust extinction coefficient (LIDAR) at a 120–150-m altitude	Not specified	Not specified	Not specified	Dust extinction coefficient was not associated with skin symptoms.	Sex, height, weight, asthma, allergic rhinitis, allergic conjunctivitis, atopic dermatitis, and food allergies and meteorological variables (temperature, humidity, and atmospheric pressure)	F
Onishi et al. 2018	October–November 2011	Yonago (Japan)	29 healthy volunteers (mean age 39.3 y old)	Nasal, ocular, respiratory and skin symptoms, fever, headache	Symptom scores recorded by diary questionnaire were regressed with air pollutants (dust, SO_4, BC, OC).	Dust concentrations by the numerical aerosol simulation models	Not specified	Not specified	Not specified	A significant linear association of dust concentrations with respiratory symptoms was observed.	Age, sex, temperature, humidity, and atmospheric pressure	F

Table 3. (*Continued.*)

Study	Period (y)	Location	Subject	Outcome	Study design/statistical analysis	Exposure definition	Days of event	Daily mean PM_{10} ($\mu g/m^3$)		Summary results	Confounder control	Quality rating[a]
								Event days	Non-event days			
Li et al. 2018	2010–2012	North of Qinling Mountail-Huaihe River Line (China)	2,693 children (30–180 months old)	Cognitive function	The association between prenatal exposure to dust and children's cognitive function was examined using data from a nationally representative panel study.	Visibility <1 km, observation of the storm at three or more neighboring meteorological stations	6 d (median exposure during the entire prenatal period)	Not specified	Not specified	Prenatal exposure to dust in the seventh gestational month was significantly associated with reduced mathematics test scores and word test scores, additional months to begin speaking in sentences and to begin counting.	Children's, parents', and household characteristics and cooking fuel	G
Nakao et al. 2018	2013–2015	Hwaseong (Korea)	75 COPD patients (40–79 y old)	Respiratory symptoms and health-related quality of life	Panel study: patients with and without COPD filled out the symptom questionnaire and were followed up.	Criteria by National Institute of Environmental Research	Not specified	Not specified	Not specified	There was no evidence for the association between dust events and respiratory symptoms.	Age, sex, body mass index, smoking, COPD severity, use of air conditioner, time spent outdoors	F
Nakao et al. 2019	2010–2015	Kumamoto/ Niigata (Japan)	2,287 healthy adults (40–79 y old)	Respiratory symptoms and health-related quality of life	Panel study: participants filled out the symptom questionnaire and were followed up.	Not specified	39 (Kumamoto); 12 (Niigata)	Not specified	Not specified	Increased number of dust exposures was associated with cough in Kumamoto and with allergic symptoms in both areas.	Years of survey, age, sex, body mass index, smoking, working status	F

Note: BC, black carbon; COPD, chronic obstructive pulmonary disease; F, fair; G, good; JMA, Japan Meteorological Agency; KMA, Korea Meteorological Agency; LIDAR, Light detection and ranging; MOE, Ministry of Environment; NO_2, nitrogen dioxide; OC, organic carbon; O_3, ozone; P, poor; PEF, peak expiratory flow; PM, particulate matter; $PM_{2.5}$, PM ≤ 2.5 μm in aerodynamic diameter; PM_{10}, PM ≤ 10 μm in aerodynamic diameter; SO_2, sulfur dioxide; SO_4, sulfate; SPM, suspended particulate matter; TSP, total suspended particulates; WMO, World Meteorological Organization.

[a]We used the National Institute of Health (NIH) framework for Observational Cohort and Cross-Sectional Studies (https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools) to assess the quality of the studies (see Table S1). We assigned a good (G), fair (F), or poor (P) quality rating following the NIH framework.

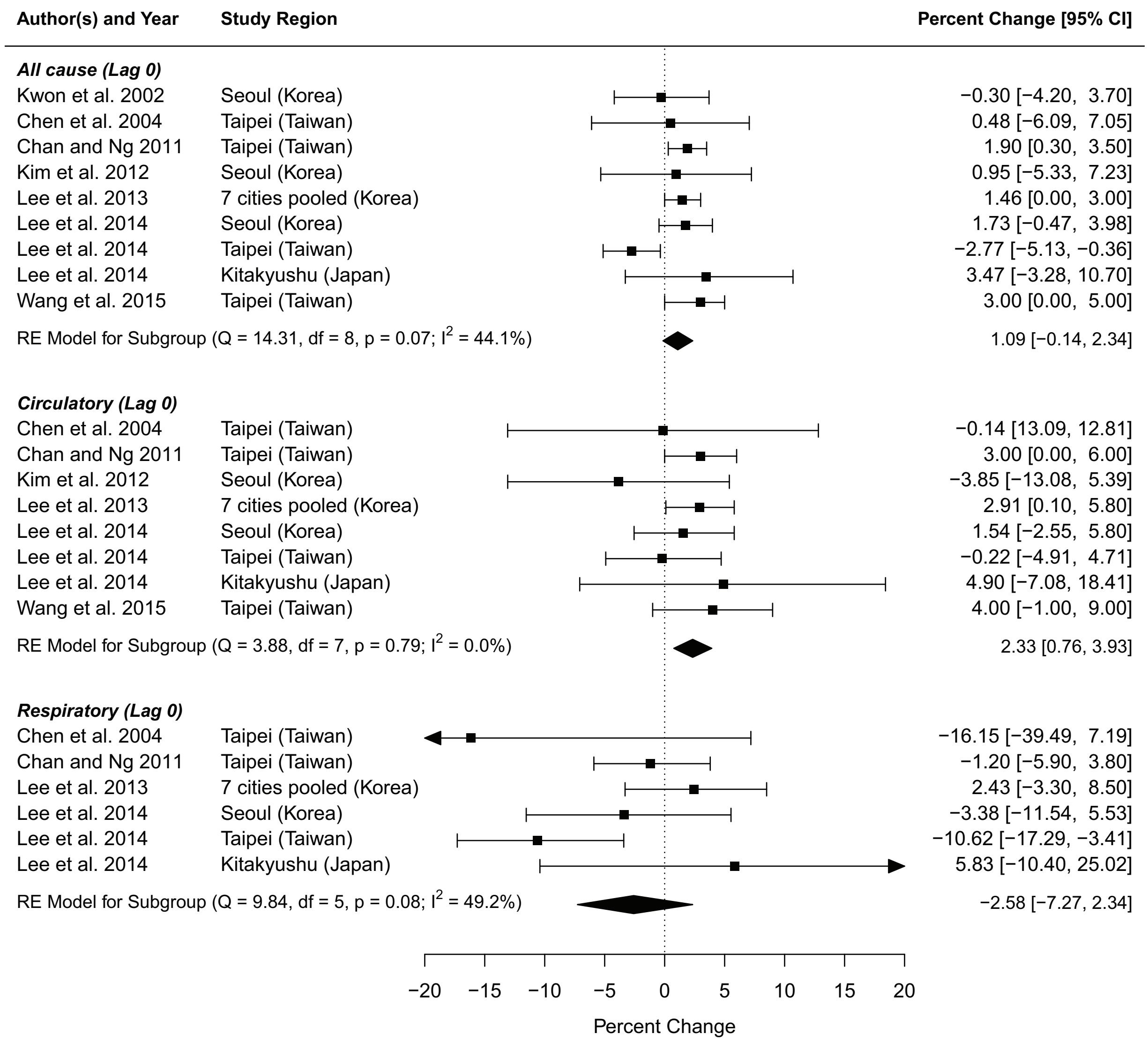

Figure 2. Forest plot of the meta-analysis for the association of all-cause, circulatory, and respiratory mortality with Asian dust days vs. non-Asian dust days at lag 0. Solid squares represent point estimates (percentage changes) of the individual studies, and the whiskers represent the 95% CIs. Arrowheads indicate where the CI extends outside the range allocated. Diamonds represent the pooled random-effects estimates, with the width indicating the 95% CIs. The vertical dotted line represents a percentage change of 0. Point estimates and 95% CIs for Chen et al. 2004 and Kim et al. 2012 were recalculated by the authors based on the information in the paper. Note: CI, confidence interval; df, degrees of freedom; RE, random effects.

little evidence of an association with ischemic heart disease/acute myocardial infarction. There was little evidence of heterogeneity between the estimates for respiratory disease (lag 3) and asthma (lags 1 and 3) when there was an evidence of the pooled association ($I^2 = 0.0\%$). The association between Asian dust exposure and hospital admissions for respiratory distress did not differ by sex (see Figure S5, Excel Table S5).

We repeated the analysis using only time-series and case-crossover studies by excluding Lai and Cheng 2008 from respiratory disease category, Yang et al. 2005b from asthma category and Cheng et al. 2008 from pneumonia category. The study selection did not affect the main results and interpretation (see Figure S6, Excel Table S6). The addition of two studies of hospital visits and emergency room visits (Nakamura et al. 2016; J Park et al. 2016) made the pooled estimates for asthma 1.4–1.8 times higher than the original (lag 1–3), whereas the pooled estimate for respiratory disease at lag 0 became significantly protective after adding five studies of hospital visits, emergency room visits, or ambulance transport (Chien et al. 2012; Lin et al. 2016; Nakamura et al. 2016; Ueda et al. 2012; Yu et al. 2012) (see Figure S7, Excel Table S7). The addition of one study of hospital visits for ischemic heart disease (Chan et al. 2008) at lag 0 did not change the interpretation (see Figure S7, Excel Table S7). Sensitivity analysis by excluding studies with largely overlapping periods in the same study location (the leave-one-out approach) showed that the pooled estimates were robust (see Figure S8, Excel Table S4).

Symptoms/Dysfunction

The most common outcome was respiratory symptoms and peak expiratory flow (PEF) rate, followed by eye, nasopharyngeal, and skin symptoms (Table 3). Daily PEF rates and symptoms (of asthmatic patients or healthy volunteers) were typically recorded in diaries and compared between dust and non-dust days. Of the 12 studies that examined the association between Asian dust exposure and PEF, 8 (66.7%) studies (Hong et al. 2010; Park et al. 2005; Watanabe et al. 2011b, 2015b, 2016a, 2016b, 2016c; Yoo et al. 2008) reported reduced PEF following exposure, although 1

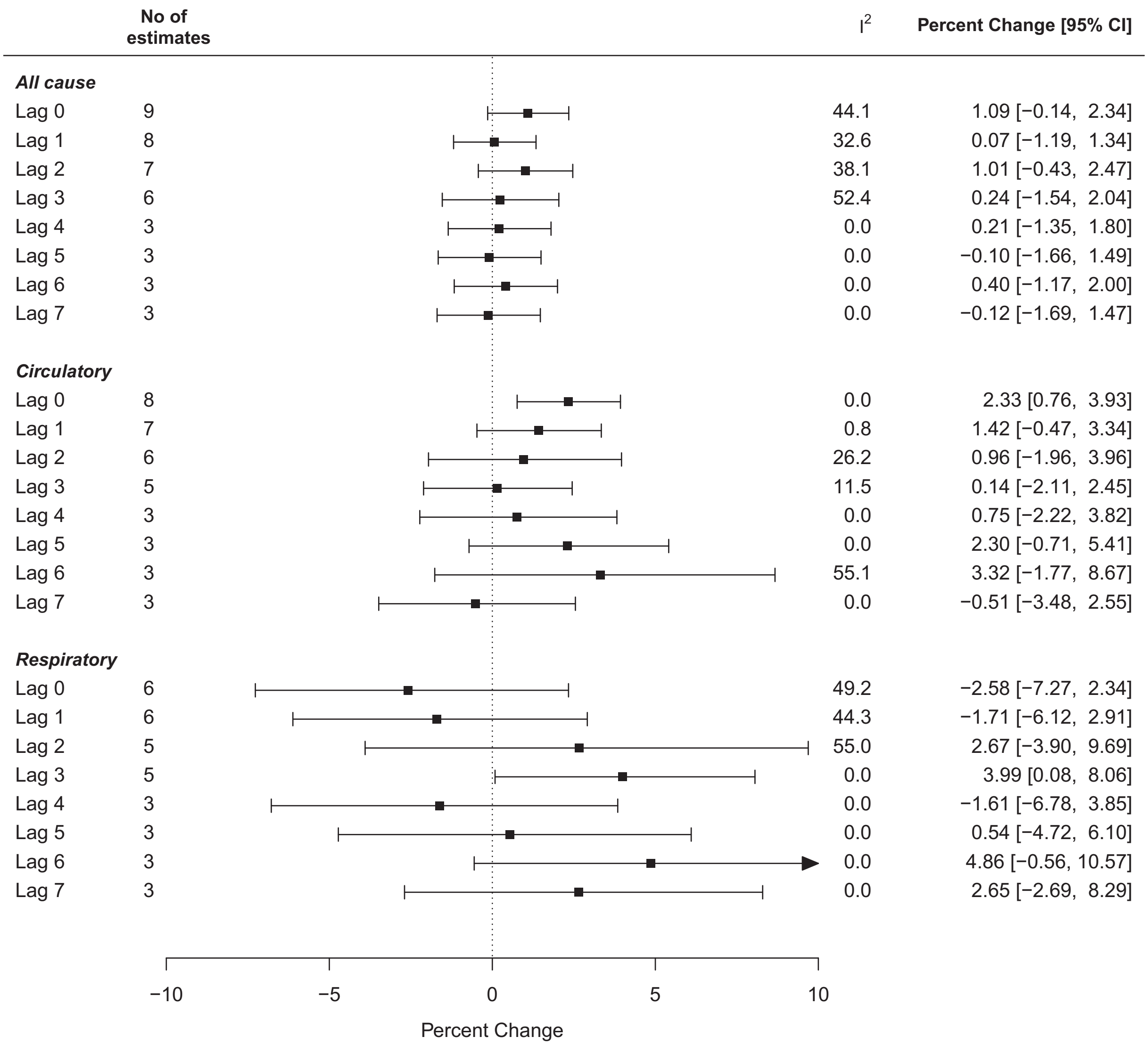

Figure 3. Random-effects pooled estimates (percentage changes) of mortality for Asian dust days vs. non-Asian dust days, stratified by outcome and lag time. Solid squares represent point estimates (percentage changes) of the individual studies, and the whiskers represent the 95% CIs. Arrowheads indicate where the CI extends outside the range allocated. The vertical dotted line represents a percentage change of 0. Note: CI, confidence interval.

(Watanabe et al. 2011b) reported reduced PEF only among individuals with existing lower respiratory symptoms. Four (33.3%) studies reported no evidence of an association with PEF (Watanabe et al. 2011a, 2014, 2015a, 2015c). Among the 21 studies that examined the association between Asian dust exposure and respiratory symptoms, 16 (76.2%) reported increased respiratory symptoms associated with Asian dust exposures (Table 3). Most studies that examined eye, nasopharyngeal, skin, and allergy symptoms reported increased risk of these symptoms during Asian dust events.

Discussion

In the present study, we reviewed epidemiologic studies that assessed the risk of mortality, hospital admissions, and symptoms/dysfunction associated with exposure to Asian dust. The results of the meta-analyses indicate an exposure to Asian dust was associated with an immediate increased risk of mortality from circulatory causes (lag 0) and a slower increased risk of mortality from respiratory causes (lag 3). Risk of hospital admissions for asthma or pneumonia also increased after exposure. There was little evidence of heterogeneity between the estimates for both mortality and hospital admissions when there was evidence of increased risk.

There were substantial variations between the studies in dust concentrations on Asian dust days. Mean PM_{10} concentrations on Asian dust days varied by location, from $60.5\,\mu g/m^3$ in Kitakyushu, Japan, to $176.4\,\mu g/m^3$ in Seoul, South Korea (Lee et al. 2014). This could be partly explained by the differing definitions of Asian dust used in the studies. Among the 56 mortality and hospital admission studies, 25 studies used a local meteorological authority's definition of Asian dust, and 18 studies set their own definition using PM of a certain diameter, with or without other indicators such as wind profile and LIDAR. For example, Tam et al. (2012a, 2012b) defined Asian dust days as when the following four conditions were met: *a*) air pollution index $>100\,\mu g/m^3$; *b*) $PM_{2.5}$:$PM_{10} < 0.4$; *c*) predominant easterly wind profile; and *d*) at least three times higher concentrations of dust storm tracer elements than annual averages. Bell et al. (2008) used several definitions, such as days with $PM_{10} > 115\,\mu g/m^3$ in the city (Taipei) and days with $PM_{10} > 100\,\mu g/m^3$ at a background monitoring location.

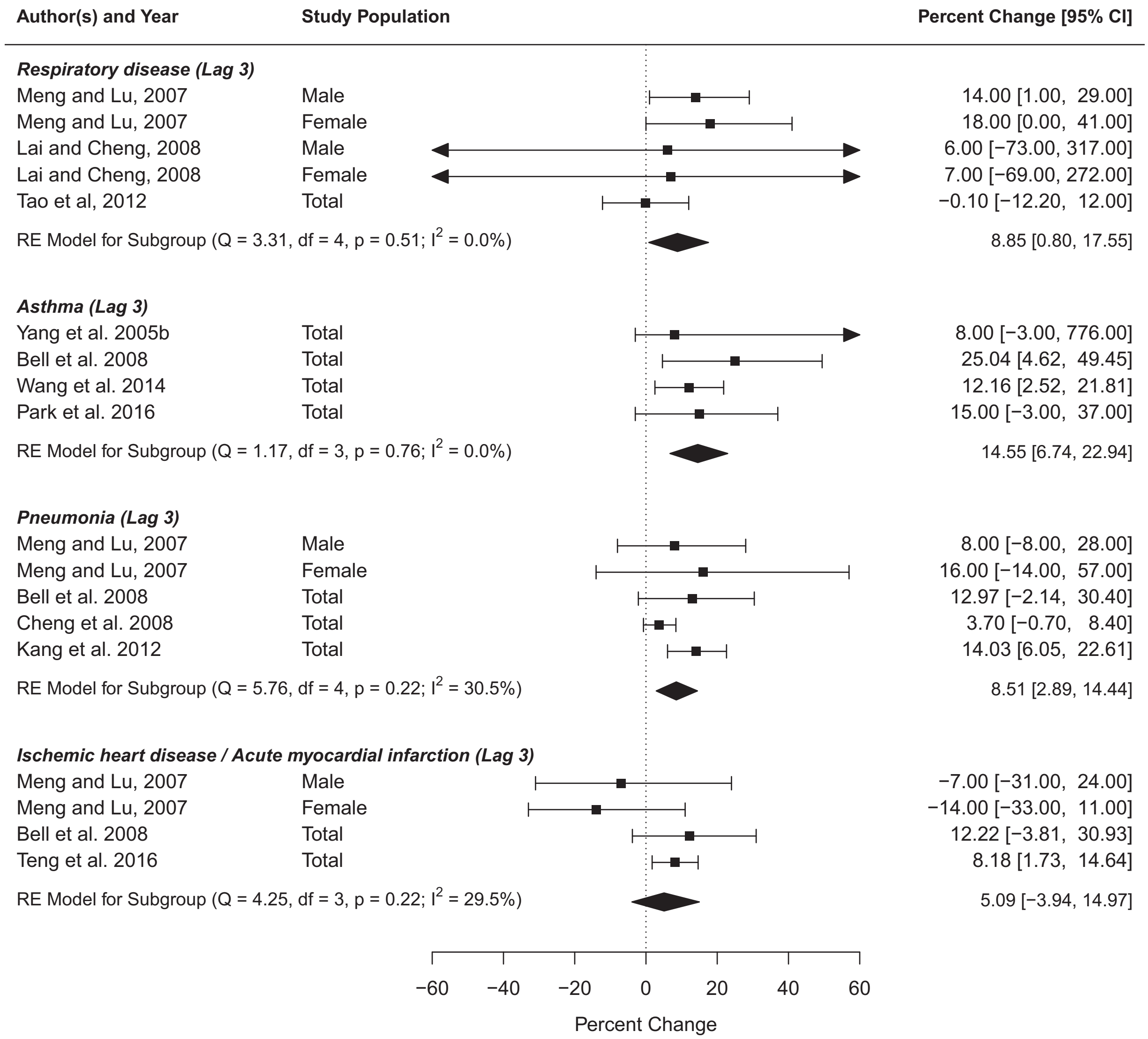

Figure 4. Forest plot of the meta-analysis for the association of hospital admissions for respiratory disease, asthma, pneumonia, and ischemic heart disease/acute myocardial infarction with Asian dust days vs. non-Asian dust days at lag 3. Solid squares represent point estimates (percentage changes) of the individual studies, and the whiskers represent the 95% CIs. Arrowheads indicate where the CI extends outside the range allocated. Diamonds represent the pooled random-effects estimates, with the width indicating the 95% CIs. The vertical dotted line represents a percentage change of 0. Note: CI, confidence interval; df, degrees of freedom; RE, random effects.

Nevertheless, the average PM_{10} concentrations varied by location (from 139.9 $\mu g/m^3$ in Incheon to 176.4 $\mu g/m^3$ in Seoul, Korea) even when using the same definition (Lee et al. 2013). A study tracking the mass concentration of aerosol along its transport route reported that the concentration decreased by one order of magnitude as the dust was transported from inland China to Japan (Mori et al. 2003). Dust concentrations on Asian dust days also appear to vary over time: In Taipei, Taiwan, PM_{10} concentrations on Asian dust days were reported as 85.7 $\mu g/m^3$ and 125.9 $\mu g/m^3$ in the late 1990s (Chan and Ng 2011; Chen et al. 2004) and decreased to 71.4 $\mu g/m^3$ and 82.7 $\mu g/m^3$ in the 2000s (Lee et al. 2014; Wang and Lin 2015).

Eight mortality/hospitalization studies used LIDAR as an indicator of Asian dust with a certain threshold (Kanatani et al. 2010; Nakamura et al. 2015, 2016; Ueda et al. 2012) or as a continuous variable (Kashima et al. 2012, 2014, 2016, 2017) for the nonspherical extinction coefficient. LIDAR is an optical remote sensing technology that can distinguish nonspherical mineral dust particles from spherical nonmineral dust particles at certain heights (typically 120–1,000 m from the ground for epidemiological studies) (Shimizu et al. 2004, 2011; Sugimoto et al. 2003). The effect of Asian dust days can differ substantially by altitude and the cutoff values of the extinction coefficient (Ueda et al. 2014); interstudy comparability would therefore require a standardized definition of Asian dust.

Variations in particle size and chemical and biological constituents have been reported (Cha et al. 2016; Ichinose et al. 2008b; Mori et al. 2003; Zhang et al. 2003). Particle size was altered during long-range transport from inland China to Japan (Mori et al. 2003; Zhang et al. 2003). Measurements of mass size distributions of aerosols have shown that 64% of total mass was attributable to coarse particles (>2.1 μm aerodynamic diameter), lower than the percentage of coarse particles reported for aerosols sampled in Beijing, China (93%) (Mori et al. 2003). The addition of sea salt during transport over the sea increased particle size, and between 60% and 91% of dust aerosols in southwestern Japan were reported to be mixed with sea salt and sulfate, whereas dust collected in China did not (Zhang et al. 2003). Previous studies have provided evidence for the effects of PM, especially $PM_{2.5}$,

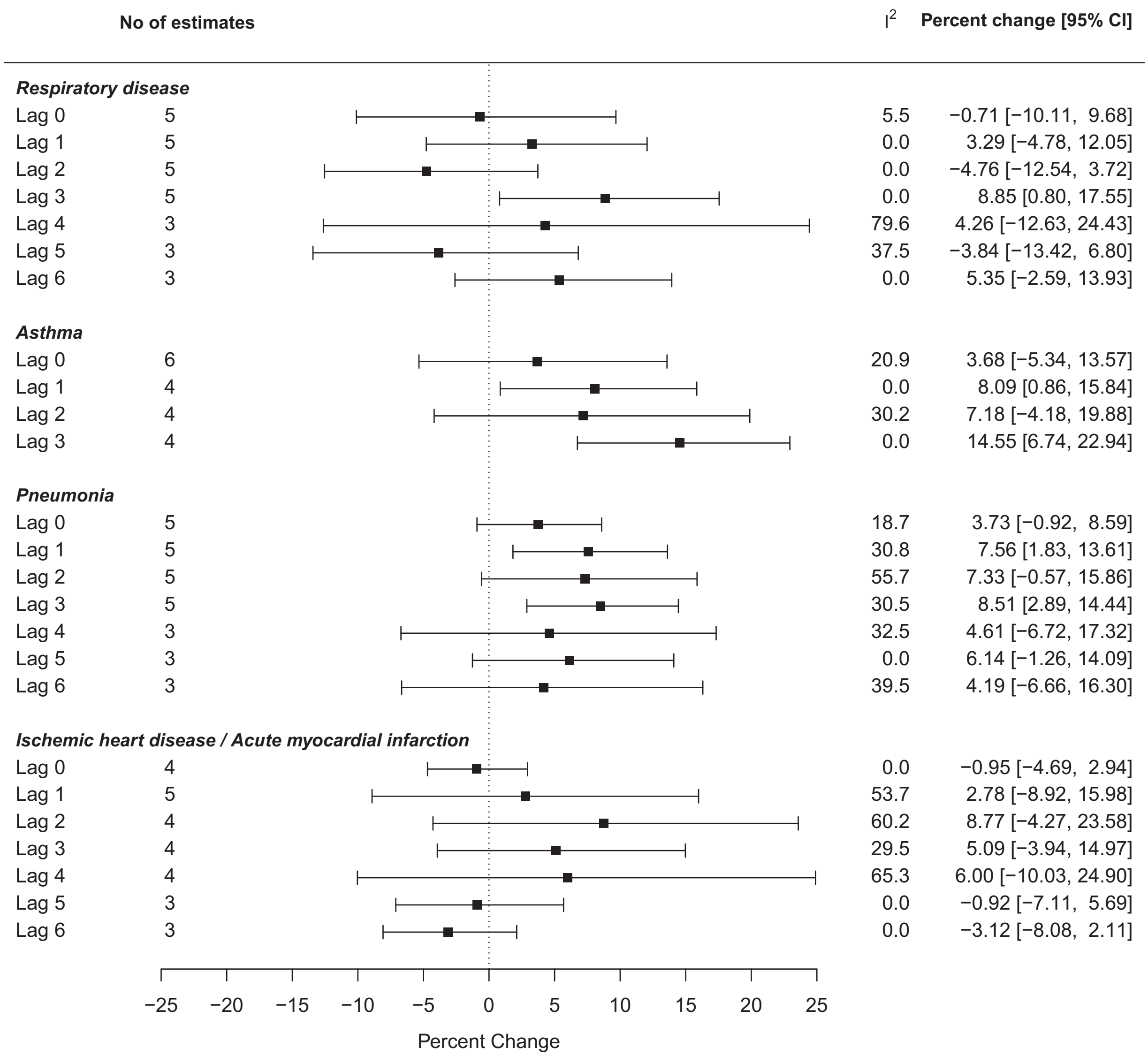

Figure 5. Random-effects pooled estimates (percentage changes) hospital admissions for Asian dust days vs. non-Asian dust days, stratified by outcome and lag time. Solid squares represent point estimates (percentage changes) of the individual studies, and the whiskers represent the 95% CIs. Arrowheads indicate where the CI extends outside the range allocated. The vertical dotted line represents a percentage change of 0. Note: CI, confidence interval.

on systemic inflammation and heart rate variability (U.S. EPA 2009). Asian dust contains both coarse and fine particles (Mori et al. 2003), which may contribute to the effects on cardiovascular and respiratory mortality.

The main constituents of Asian dust are silica and alumina (Ichinose et al. 2008b), and crystalline silica and aluminum have been suggested to cause cytokine-mediated inflammatory responses in the murine lung (Eisenbarth et al. 2008; Ichinose et al. 2008b). Dust can mix with anthropogenic substances during long-range transport, changing its chemical composition by, for example, the addition of nitrates (Mori et al. 2003). Aerosols in the dust provide surfaces for chemical and physical reactions and serve as carriers of anthropogenic substances (Sun et al. 2005). Sulfate also accumulates on the surface of dust particles during transport from China to Japan; the formation of sulfate and nitrate on the surface of dust particles has been well documented by laboratory simulations, model calculations, and individual particle analysis (Dentener et al. 1996; Iwasaka et al. 1988; Okada et al. 1990; Song and Carmichael 2001; Sun et al. 2005; Underwood et al. 2001; Zhang and Iwasaka 1999). Sulfate in Asian dust has been shown to potentiate allergic reactions in mice (Hiyoshi et al. 2005).

Asian dust particles transported at a lower altitude may contain higher levels of anthropogenic chemicals, consequently exerting more severe health effects. Higher levels of metals were found in Asian dust when the air masses passed through heavily industrial areas (Onishi et al. 2012). Ueda et al. (2012) found increases in ambulance dispatches on Asian dust days when air masses passed through industrial areas in China at an altitude of <2 km. The toxicity of Asian dust may, therefore, depend in part on its metal contents, but the sources of pollutants in Asian dust are not well understood, and the modifying effects of transport pathways on pollutant composition are complex.

Another important characteristic of Asian dust involves microorganisms such as bacteria, fungi, and viruses. Microorganisms in the dust can affect the immune system of individuals sensitive to those agents, and lipopolysaccharide and β-glucan in the microorganisms are known to provoke immune responses (Willart and Lambrecht 2009). Asian dust with microbial contents was shown to enhance allergic lung inflammation in mice (Ichinose et al.

2006, 2008b), and inhalation of dust sand containing β-glucan caused eosinophil infiltration in the murine airway (Ichinose et al. 2006). Heated desert sand, from which microorganisms had been removed, had less effect on allergic lung inflammation (Ichinose et al. 2008a). Studies have reported that atmospheric bacterial abundance can increase 10–100 times during Asian dust events (Cha et al. 2016; Hara and Zhang 2012), but aerosol bacterial communities near a dust source were more affected by wind activity (J Park et al. 2016).

Some of the studies we reviewed simply compared health events on dust and non-dust (control) days, a procedure that may not fully account for time trends and seasonality as well as typical time-series and case-crossover analyses. Our sensitivity analyses, however, showed that limiting the data to the time-series regression and case-crossover studies did not affect the main results and interpretation. Still, differences in time-series studies such as the degrees of freedom used per year for the time variable, the covariates included in the analyses, and the lag and degrees of freedom used to control for weather variables imply that the nature of residual confounding may differ between studies.

Despite these potential sources of heterogeneity, we found, in general, little evidence of heterogeneity between the estimates for both mortality and hospital admissions. This may be due to the meta-analyses being conducted in most cases by pooling the estimates of fewer than 10 studies and that some study-specific estimates were accompanied by large uncertainty (i.e., large CIs or standard error values). In such cases, the pooling may be influenced largely by a few study-specific estimates with small uncertainty, and the statistics to quantify the heterogeneity should be interpreted with caution. (Higgins and Green 2011)

A standardized protocol for epidemiological studies would facilitate comparisons between studies. For example, one study (Stafoggia et al. 2016) employed a so-called EU reference method whereby multiple tools were used to establish dust events, including monitoring stations selected for regional background investigation of PM, back-trajectory calculations using a hybrid single-particle Lagrangian integrated trajectory model, remote sensing data (aerosol maps), satellite imagery, and meteorological charts to understand the transport mechanism, and chemical composition analysis of PM (Pey et al. 2013). By applying official EU methodologies (Escudero et al. 2007), it was possible to further estimate the separate, independent contribution of dust to the short-term health effects.

There are some limitations to our study. First, chemical and biological components of Asian dust may interact and affect the risks. Studies investigating the effects of particle composition on health outcomes are scarce, and this association warrants further research. The components of Asian dust may vary from those of other dusts, thus the findings may not be applicable to other dust events. Second, the studies included in our meta-analysis compared risks between Asian dust and non-dust days, but the dust concentrations and duration of the events varied. Future studies should consider this when formulating exposure assessments. Distinguishing between local and long-range-transported dust is also worthwhile. Third, we did not conduct a meta-analysis for outcomes with fewer than three estimates; there may have been other effects. In addition, meta-analysis for the long-term effects was not done due to the lack of qualified studies. Fourth, we did not assess the quality of the overall body of evidence using the National Toxicology Program Office of Health Assessment and Translation framework or any other quality scale in the absence of a validated quality assessment tool for time-series and case-crossover designs that were commonly used for mortality and hospitalization studies. Finally, the estimates of the meta-analysis in this study are from a total of 21 studies and, at maximum, only 9 estimates for specific categories of the diseases: Future evidences are merited to strengthen our overall conclusion.

Conclusion

Overall, the existing evidence indicates a positive association between Asian dust exposure and mortality and hospital admissions for circulatory and respiratory events. However, the number of studies included in the meta-analysis was not large and further evidence is merited to strengthen our conclusions. Furthermore, a variety of definitions of Asian dust, study designs, confounder controls, and model specifications have been applied in the original studies. Standardized protocols for epidemiological studies are needed and should be taken into consideration the composition of the dust and a consistent definition of Asian dust.

Acknowledgments

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