RESEARCH ARTICLE

Impact of Ambient Humidity on Child Health: A Systematic Review

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Abstract

Background and Objectives: Changes in relative humidity, along with other meteorological factors, accompany ongoing climate change and play a significant role in weather-related health outcomes, particularly among children. The purpose of this review is to improve our understanding of the relationship between ambient humidity and child health, and to propose directions for future research.

Methods: A comprehensive search of electronic databases (PubMed, Medline, Web of Science, ScienceDirect, OvidSP and EBSCO host) and review of reference lists, to supplement relevant studies, were conducted in March 2013. All identified records were selected based on explicit inclusion criteria. We extracted data from the included studies using a pre-designed data extraction form, and then performed a quality assessment. Various heterogeneities precluded a formal quantitative meta-analysis, therefore, evidence was compiled using descriptive summaries.

Results: Out of a total of 3797 identified records, 37 papers were selected for inclusion in this review. Among the 37 studies, 35% were focused on allergic diseases and 32% on respiratory system diseases. Quality assessment revealed 78% of the studies had reporting quality scores above 70%, and all findings demonstrated that ambient humidity generally plays an important role in the incidence and prevalence of climate-sensitive diseases among children.

Conclusions: With climate change, there is a significant impact of ambient humidity on child health, especially for climate-sensitive infectious diseases, diarrhoeal diseases, respiratory system diseases, and pediatric allergic diseases. However, some inconsistencies in the direction and magnitude of the effects are observed.

Introduction

"Warming of the climate system is unequivocal", according to the United Nations Intergovernmental Panel on Climate Change, and is expected to continue for the next several decades [1]. Even if the concentrations of all greenhouse gases and aerosols remain constant at year 2000 levels, a further warming of about 0.1℃ per decade would be expected [1,2].

Climate warming will change rainfall patterns, and increase humidity and risk of floods, although a geographical and temporal heterogeneity in the occurrence of these changes is expected [3,4]. There is strong consensus among expert scientists that with climate change, meteorological factors (e.g. temperature, humidity) are affecting and will increasingly influence human health [5–8]. Humidity along with other weather factors can affect the incidence and distribution of infectious diseases by influencing the reproduction, development and population dynamics of vectors [9,10]. Increasingly warm and humid climates have been observed to be associated with increasing atmospheric levels and density of aeroallergens, indicating that ambient humidity may indirectly affect the incidence and prevalence of allergic diseases [11,12]. In addition, humidity also plays a great role in the transmission of viral diseases, such as influenza [7,13].

Compared with adults, children are inherently sensitive to climate change because they are physiologically and metabolically less effective at adapting to ambient humidity and other weather-related exposures. Their relatively immature immune systems increase the risk of serious consequences from a variety of infectious diseases [14]. In 2000, the World Health Organization estimated that climate change contributed to more than 150,000 deaths and 5.5 million lost disability-adjusted life years worldwide and more than 88% of this burden occurs in children under the age of 5 years [15]. According to a 2012 report of the World Health Organization, pneumonia, diarrhoeal disease and malaria, all of which are climate-sensitive diseases, are three of the leading causes of death among children under age five. For example, malaria is a climate-sensitive illness to which children are particularly vulnerable, currently causing 350–500 million illnesses annually, and more than 1 million deaths, with children experiencing disproportionately high levels of both morbidity and mortality (75% of malaria deaths occur in children younger than 5 years of age) [16].

However, although pediatric health care professionals have written about the effects of climate change on child health, relatively limited research has been conducted specifically on the impact of ambient humidity on child health. To our knowledge, almost all of the studies investigating the association between climate change and child health mainly focus on temperature or rainfall, while ambient humidity is usually considered as a dispensable and alternative variable.

Additionally, to date, no systematic review has specifically focused on the relationship between ambient humidity and child health. In order to fill this knowledge gap, the primary objective of this review is to improve our understanding of how humidity, both directly and indirectly, can influence child

health and to promote additional research in this field by presenting and summarizing the findings of all relevant studies related to the impact of ambient humidity on child health.

Methods

Data sources and search strategy

Relevant peer-reviewed journal databases (PubMed, Medline, Web of Science, ScienceDirect (Elsevier), OvidSP and EBSCO host) were searched using the following MeSH (Medical Subject Headings) terms and keywords: "climate change", "humidity", "wet", "dew point", "child", "infant", "adolescent" and "pediatric". The search terms and keywords were adapted to suit the requirements of each database to facilitate a comprehensive search. After selection of the full text, the references of the identified articles were reviewed and the necessary hand search was performed to recover potentially relevant studies not included in the major databases.

The search sought to identify journal articles published in English up to March 2013. In accordance with *the Convention on the Rights of the Child* proclaimed by the United Nations, we defined children as the group of people 0–18 years of age [17].

Inclusion criteria

The following eligibility criteria were used in this study:

- Types of studies: the present review only included peer-reviewed original articles. Thus, reviews, books, meta-analyses and conference abstracts were excluded.
- Target population: only the studies involving children between 0–18 years of age were considered.
- Research factors: only studies in which humidity was one of the exposure indicators of interest were considered.
- Outcome measures: the reported results of the included studies should have included at least one quantitative effect estimate associated with humidity. An outcome measure was reported as either: percent change, regression coefficient, correlation coefficient, relative risk or odds ratio. We also required *P*-values or 95% confidence intervals (CIs) to have been reported.

Study selection and data extraction

Three of the authors (Gao, Sun and Lu) independently assessed the potential relevance of all publications, identified during the database search, based on the information provided in the titles and abstracts. When reviewers disagreed, a discussion was held to obtain consensus. After screening by titles and abstracts,

the full texts of the remaining articles were then obtained and critically reviewed by the first author.

We extracted data, from the final selected references, using a pre-designed data extraction form. The quantitative estimates of each study that met the eligibility criteria were carefully retrieved and the following key characteristics were captured: study region, target population, study design, humidity exposure variable, health outcomes and adjustment of confounders. All data extraction was performed by the first author (Gao) and cross-checked by another researcher (Sun). Any errors identified were corrected through discussion among all authors.

Quality assessment

To date, the use of quality assessment tools to appraise observational studies included in systematic reviews is less well established than in reviews of randomized controlled trials, and there is no existing generally accepted quality assessment tool for observational and cross-sectional studies [18, 19]. Therefore, the STROBE method (Strengthening the Reporting of Observational Studies in Epidemiology), a guideline for reporting observational studies, was selected and adapted for our purpose to describe the reporting quality of the final identified articles [20, 21].

As in a previous systematic review, an adapted version of the STROBE checklist (Table 1) was used to create a binomial scoring system (e.g. criterion met =1, criterion not met =0). Final score percentages were based on the number of reporting quality criteria met divided by the number of criteria that were relevant during the quality assessment [22]. During this process, studies that controlled for potential confounding factors and included an outcome measure, such as relative risk, odds ratio or regression coefficient, were given higher quality ratings. Meanwhile, studies were given lower quality ratings if they did not include adjustment of confounders or only included outcome measures such as an estimated slope coefficient from simple linear regression or a correlation coefficient for which only the P-value was given. As no accepted gold standard exists for judging the quality of observational studies, in the present review we did not exclude any identified studies based on the quality assessment, which used an adapted version of the STROBE checklist.

Data synthesis

Due to heterogeneity in the target populations, outcome measures and design of studies, we did not conduct an overall summary estimate (e.g. meta-analysis). Instead, we summarized the evidence in a descriptive synthesis.

Results

A total of 3787 records were identified from the electronic database searches, and 10 additional studies were retrieved by reviewing references. After screening by

Table 1. Adapted STROBE Statement—checklist of items that should be included in reports of observational studies (including additions/adaptations for accommodating meteorological data).

	Item No	Recommendation
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found
Introduction		
Background	2	Explain the scientific background and rationale for the investigation being reported
Objectives	3	State specific objectives, including any pre-specified hypotheses
Methods		
Study design	4	Present key elements of study design early in the paper
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up
		Case-control study—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls
		Cross-sectional study—Give the eligibility criteria, and the sources and methods of selection of participants
		(b) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed
		Case-control study—For matched studies, give matching criteria and the number of controls per case
Variables	7	Clearly define all meteorological variables, outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable
Data sources	8*	For each variable of interest, especially meteorological and outcome variables, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group
Bias	9	Describe any efforts to address potential sources of bias
Study size	10	Explain how the study size was arrived at
Quantitative variables	11	Explain how quantitative meteorological and outcome variables were handled in the analyses, including how meteorological variables were handled before using for analysis, and what kind of statistical software(s), as well as its/their version number were used to complete related statistical analysis. If applicable, describe which groupings were chosen and why
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounders
		(*b*) Describe any methods used to examine meteorological and outcome subgroups and interactions
		(*c*) Explain how missing data of meteorological variable and outcome were addressed
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed
		Case-control study—If applicable, explain how matching of cases and controls was addressed
		Cross-sectional study—If applicable, describe analytical methods taking account the sampling strategy

Table 1. Cont.

	Item No	Recommendation
		(e) Describe any sensitivity analyses
Results		
Participants	13*	(a) Report numbers of individuals at each stage of the study—e.g. numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed
		(b) Give reasons for non-participation at each stage
		(c) Consider use of a flow diagram
Descriptive data	14*	(a) Give characteristics of study participants (e.g. demographic, clinical, social) and information on exposures and potential confounders. Summarize meteorological characteristics of the study area (if applicable)
		(b) Indicate the number of participants with missing data for each variable of interest, especially meteorological and outcome variables
		(c) *Cohort study*—Summarize follow-up time (e.g. average and total amount)
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time
		Case-control study—Report numbers in each exposure category, or summary measures of exposure
		Cross-sectional study—Report numbers of outcome events or summary measures
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (e.g. 95% confidence interval). Make clear which confounders were adjusted for and why they were included
		(b) Report category boundaries when meteorological or continuous variables were categorized
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period
Other analyses	17	Report other analyses done—e.g. correlation analysis, analyses of subgroups and interactions, and sensitivity analyses
Discussion		
Key results	18	Summarise key results with reference to study objectives
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence
Generalizability	21	Discuss the generalizability (external validity) of the study results
Other information		
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.
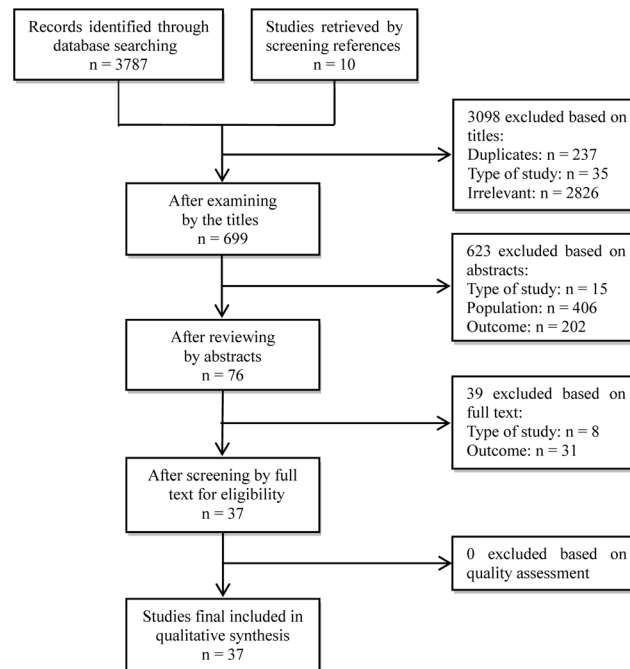
Fig. 1. Flow chart of the screening and selection process of the study articles.

titles and abstracts, 76 articles were selected for examination of the full text. Finally, 37 papers remained for inclusion in this systematic review (Fig. 1). Then quality assessment and data synthesis were performed to obtain the key results presented and summarized in Table 2. Among the 37 studies, 24% (9/37) involved infectious diseases, 32% (12/37) were on respiratory system diseases, and 35% (13/37) were focused on asthma and other allergic diseases. Nearly 73% (27/37) of the studies were conducted in high-income countries or regions. According to the adapted STROBE checklist, the reported quality scores ranged from 53.33% to 88.89%, with the majority of records (29/37) having scores above 70%, indicating a relatively high reporting quality of the articles. Studies using time-series analysis, Poisson regression or negative binomial regression were usually given higher scores.

Gastrointestinal and other infectious diseases

Studies found that ambient humidity plays an important role in the occurrence and prevalence of pediatric infectious diseases. A Brazilian study found that among the children hospitalized with community-acquired pneumonia, overall viral and Chlamydia trachomatis infections correlated with monthly mean relative humidity [23]. In Taiwan, a study identified a positive association between daily mean relative humidity and the incidence of enterovirus 71 (EV71) infections

Table 2. Characteristics of included studies about ambient humidity and children's health (n=37).

Author(year)[a]	Study region and period	Target population (number, age)	Study design and analysis method	Humidity exposure variable	Target outcome	Statistical indicator and effect estimate	Adjustment for confounding factors	Reporting quality(% score)
YÜKSEL et al.[b] (1996) [47]	Izmir, Turkey 1993–1994	21 children aged 5–14 years	Descriptive study, Correlation and variance analysis	Daily relative humidity	Total daily complaints of the asthma patient	r=0.578 P<0.01	No adjustments were conducted	53.33
Guo et al.[b] (1999) [48]	Taiwan 1995–1996	331,686 children aged 0–15 years	Descriptive study, Logistic regression analysis	Daily winter month humidity	Asthma prevalence rate	Boys: R^2=0.57, β=0.37 (95% CI: 0.0078–0.73, P<0.05)	Adjusted for age, history of atopic eczema and parental education	64.29
Checkley et al.[b] (2000) [31]	Lima, Peru, 1993–1998	57 331 children under 10 years	Time-series study, Poisson GAM	Daily mean relative humidity	Daily hospital admissions for diarrheal diseases per 1% increase in relative humidity at 37 lag days	RR=0.97 (95% CI: 0.97–0.98)	No adjustments were conducted	71.43
Weiland et al.[b] (2004) [53]	Western Europe 1992–1996	Children aged 6–7 and 13–14 years	Multilevel linear regression analyses	Monthly mean lowest relative humidity	Prevalence rates of symptoms of asthma	1) 13–14 years old children : β=0.13 (95% CI:0.04–0.23) 2) 6–7 years old children : β=0.09 (95% CI:0.02–0.15)	Adjusted for gross national product per capita (GNP)	60.00
Hashimoto et al.[b] (2004) [55]	Tokyo, Japan 1998–2002	5559 children aged 2–15 years	Multiple logistic regression analyses	Daily mean relative humidity	Number of emergent visits for childhood asthma	β=0.075, (95% CI: 0.06–009, P<0.001)	Adjusting for calendar month and day of the week	74.07
Viegas et al.[b] (2004) [33]	Buenos Aires, Argentina 1998–2002	18561 children aged under 5 years	Spearman's rank correlation test	Monthly mean relative humidity	Respiratory viruses frequencies among the patients	1) RSV: r=0.6, P<0.0001; 2) IA: r=0.47, P=0.0068	No adjustments were conducted	62.96
Lapeña et al.[b] (2005) [34]	Leon, Spain.	167 children	Case-control study,	Weekly humidity	Admission with lower	1) r=−0.15, P=0.045;	No adjustments	72.41

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Table 2. Cont.

Author(year)[a]	Study region and period	Target population (number, age)	Study design and analysis method	Humidity exposure variable	Target outcome	Statistical indicator and effect estimate	Adjustment for confounding factors	Reporting quality(% score)
	1995–2000	aged under 2 years	Correlation analysis	relative	respiratory tract infection due to RSV	2) OR=0.96 CI: 0.92–0.99	were conducted	
			Multivariate logistic regression model	humidity		P<0.01(absolute humidity was not included in the model)		
Prifis et al.[b] (2006) [44]	Athens, Greece 1978–2000	18950 children aged 0–4 years	Multiple regression analysis	Monthly mean relative humidity	Monthly hospital admission rates for childhood asthma	β=1.106, P<0.05, r²=0.592	No adjustments were conducted	75.86
Al-Toum et al.[b] (2006) [35]	Amman, Jordan 2002–2004	200 Children aged under 2 years	Descriptive study, Correlation analysis	Monthly mean relative humidity	Prevalence of RSV	r=0.66, P<0.05	No adjustments were conducted	62.96
Xirasagar et al.[b] (2006) [52]	Taiwan 1998–2001	27275 Children aged 0–14 years	Cross-sectional study, ARIMA models, Spearman rank correlations analysis	Monthly mean relative humidity	Monthly asthma admission rates	1) Children aged 2–5 years: r= −0.290, P<0.01 2) Children aged 6–14 years: r= −0.415, P<0.001	Seasonality trend was evaluated	70.97
Yé et al.[b] (2007) [28]	Kossi, Burkina Faso 2003–2004	676 children aged 6–59 months	Descriptive study, Logistic regression	Daily mean relative humidity	Incidence of clinical malaria	β= −23.2151 (95% CI: −36.7151 to −9.7152)	Site of the study, sex; age; presence of animal were considered	75.86
Kurt et al.[b] (2007) [45]	Turkey 2004	25843 children aged 6–15 years	Cross-sectional study, and Multivariate logistic regression analysis	Yearly mean relative humidity >70%	Allergic diseases	1) Asthma: OR=1.009 (95% CI: 1.002–1.015) 2) Wheezing: OR=1.01 (95% CI: 1.003–1.02) 3) Allergic rhinitis: OR=	Adjusted for age, rural/urban sex, residence and sibling number	78.57

Table 2. Cont.

Author(year)[a]	Study region and period	Target population (number, age)	Study design and analysis method	Humidity exposure variable	Target outcome	Statistical indicator and effect estimate	Adjustment for confounding factors	Reporting quality(% score)
D'Souza et al.[b] (2008) [32]	3 Australian cities 1993–2003	Children aged 0–5 years	Time–series study and log-linear regression model	Weekly mean relative humidity	Weekly admissions for rotavirus diarrheal per 1% increase in relative humidity of the previous week	1.006 (95% CI: 1.001–1.01); 1) Canberra: IRR=0.98 (95% CI: 0.97–0.99); 2) Brisbane: IRR=0.98 (95% CI: 0.97–0.99); 3) Melbourne: IRR=0.99 (95% CI: 0.99–1.00)	Adjusted for trend, season and previous 2 weeks' admission	76.00
Omer et al.[b] (2008) [36]	Lombok island, Indonesia 2000–2002	2878 children aged 0–2 years	Negative binomial regression and multivariate regression	Daily mean relative humidity	Daily number of RSV cases 8 days later	IRR=1.06, P<0.001 (95% CI: 1.03–1.10)	No adjustments were conducted	85.71
Noyola. D. E. and Mandeville, P. B[b] (2008) [38]	San Luis Potosí, Mexico. 2002–2006	1393 children aged 0–18 years	Regression analysis	Weekly mean relative humidity at 08:00 hours	Weekly number of RSV cases	β=0.035, P=0.0027 (95% CI: 0.012–0.058)	Temperature, light and precipitation hours were considered in the model	61.29
Nastos et al.[b] (2008) [49]	Athens, Greece 1978–2000	Children aged 0–4 years	Poisson GLM	Monthly mean relative humidity	Monthly number of childhood asthma admissions(CAA)	β=0.0273, P<0.0001 (95% CI: 0.0264–0.0282)	No adjustments were conducted	76.92
Lee et al.[b] (2008) [54]	Taiwan 1995–1996	317,926 children aged mostly between 12–14	Cross-sectional study and Logistic regression	Monthly mean lowest relative humidity	Prevalence of flexural eczema	1)Boys: RR=1.15, P<0.05 (95% CI: 1.04–1.27); 2)Girls: RR=1.22, P<0.05 (95% CI: 1.08–1.38)	Adjusted for age, parental education level, asthma and active smoking habit	78.13

Table 2. Cont.

Author(year)[a]	Study region and period	Target population (number, age)	Study design and analysis method	Humidity exposure variable	Target outcome	Statistical indicator and effect estimate	Adjustment for confounding factors	Reporting quality(% score)
du Prel et al.[b] (2009) [40]	Mainz, Germany 2001–2006	3044 children aged 0–16 years	Multiple time series analysis	Mean relative humidity	Hospitalization frequency due to acute respiratory tract infections (ARI)	Human rhinovirus : $\beta=0.218$, $P=0.002$	Correlations among meteorological parameters were controlled for	77.78
Murdoch and Jennings (2009) [41]	Christchurch, New Zealand 1995–2006	Children aged <5 years	Ecological study, Negative binomial regression analysis	Monthly occurrence of daily mean 9am humidity>75%	Incidence rates of invasive pneumococcal disease(IPD) for the 1-month lag	IRR=1.87, $P=0.04$ (95% CI: 1.02–3.45)	No adjustments were conducted	80.77
Mireku et al. (2009) [51]	Detroit, America 2004–2005	25,401 children aged 1–18 years	Time–series study, Generalized additive model (GAM)	Intraday humidity change	The counts of asthma admissions 1-day later	$\beta=0.10$, $P=0.04$	Adjusted for seasonality, air pollution, and aeroallergen exposure	73.08
Charland K. M. et al.[b] (2009) [57]	37 paediatric hospitals in USA 2000–2005	63,334 children aged 0–18 years	Bayesian hierarchical models	Daily mean dew point	The peak week of influenza visits	$\beta=-0.085$, (95% CI: −0.20 to 0.031)	Population type, latitude, longitude, solar radiation and temperature were considered	74.19
García-Marcos et al. (2009) [50]	Coastal areas, Spain 1994–2002	Children aged 6–7 years and 13–14 years	Poisson regression model	Annually mean relative humidity	Adjusted prevalence ratios (PR) of current wheeze per 10% increase in humidity	1) 6–7 years old: PR=1.28 (95% CI: 1.12–1.46) 2) 13–14 years old: PR=1.25 (95% CI: 1.13–1.39)	No adjustments were conducted	81.48
Connelly et al.[b] (2010) [59]	Kansas,	25 children	Multilevel model	Daily thrice	Probability of	$\beta=0.02$, $P=0.01$;	Controlling for	74.07

Table 2. Cont.

Author(year)[a]	Study region and period	Target population (number, age)	Study design and analysis method	Humidity exposure variable	Target outcome	Statistical indicator and effect estimate	Adjustment for confounding factors	Reporting quality(% score)
	America 2007–2008	aged 8–17 years	analyses	relative humidity	headache occurrence	OR=1.02	changes in the child's negative affect	
Chou et al.[b] (2010) [30]	Taiwan 1996–2007	290331 children aged 0–14 years	Time-series study, Poisson regression	Monthly mean relative humidity	Monthly morbidity of diarrhea (no lag)	β=−0.033, P=0.004	Adjusted for seasonality, long-term trends, lag effects and autocorrelation	84.62
Tchidjou et al.[b] (2010) [42]	Yaoundé, Cameroon 2006–2007	1306 children aged 0–18 years	Negative binomial regressions	Daily relative humidity	Frequency of hospitalization for acute respiratory infections	RR=1.22 (95% CI: 1.07 –1.40)	Adjusted for seasonality and annual trend	80.00
Nascimento-Carvalho et al.[b] (2010) [23]	Salvador, Brazil 2003–2005	184 children aged 0–5 years	Correlation analysis	Monthly mean relative humidity	Infections caused by different aetiological agents	1) Overall viral infections: r=0.6, P=0.006; 2) Chlamydia trachomatis: r=−0.5, P=0.02	No adjustments were conducted	72.00
Konstantinou et al.[b] (2011) [46]	Norwich, UK; Heraklion, Greece 2005–2007	56624 children aged 0–14 years	Poisson regression model	Monthly mean relative humidity	Monthly incidence rate of acute urticarial	1) Norwich: IRR=0.972 (95% CI: 0.959–0.985); 2) Heraklion: IRR=1.035 (95% CI: 1.015–1.056)	Adjusted for seasonal effect	69.23
Zacarias, Majlender[b] (2011) [29]	Maputo, Mozambique 2007–2008	60943 infants aged 0–4 years	Bayesian hierarchical models	Monthly mean relative humidity	Malaria incidence	RR=0.049 (95%CI: 0.03048-0.06531)	The spatial and temporal correlations were considered	73.08
Loh et al.[b] (2011) [43]	Singapore	42155 children	Time–series	Weekly	Admissions due to	1) URTI: β=−0.228,	Select model with	84.00

Table 2. Cont.

Author(year)[a]	Study region and period	Target population (number, age)	Study design and analysis method	Humidity exposure variable	Target outcome	Statistical indicator and effect estimate	Adjustment for confounding factors	Reporting quality(% score)
	2003–2008	almost aged 0–5 years	study, and ARIMA model	relative humidity	upper and lower respiratory tract infection (URTI and LRTI)	P=0.0200; 2) LRTI: β= −0.760, P<0.0001	the lowest Akaike's Information Criterion	
Onozuka, Hashizume[b] (2011) [25]	Fukuoka, Japan 2000–2008	67000 children aged<15 years	Time–series study, Negative binomial regression	Weekly mean relative humidity	Weekly number of mumps cases per 1% increase in humidity for 0–2 weeks lag	Percentage increase: 1.4% (95% CI: 0.5–2.4)	Adjusting for temporal, seasonal and inter-annual variations, and temperature	88.46
Arnedo Pena et al.[b] (2011) [56]	Spain 1971–2005	24301 children aged 13–14 years	Logistic regression, Multiple regression models	Annually mean relative humidity	Prevalence rate of asthma	β=−0.00334, P<0.0001	Prevalence rate of asthma and collinearity were adjusted	85.19
Onozuka, Hashizume[b] (2011) [26]	Fukuoka, Japan 2000–2010	61736 children aged 0–4 years	Time–series study, Negative binomial regression	Weekly mean relative humidity	Percentage increase in number of hand, foot, and mouth disease per 1% increase in humidity with 0–3 weeks lag	Percent change: 4.7% (95% CI: 2.3–7.1)	Adjusting for seasonal, long-term trends, and inter-annual variations	85.71
Onozuka, Hashizume[b] (2011) [27]	Fukuoka, Japan 2000–2008	423142 children aged<15 years	Time–series study, Negative binomial regression	Weekly mean relative humidity	Percentage increase in number of infectious gastroenteritis per 1% decrease in humidity for lags of 0–6 weeks	Percent change: 3.9% (95% CI: 2.8–5.0)	Adjusting for seasonal, inter-annual, and temperature variations	88.89

Table 2. Cont.

Author(year)[a]	Study region and period	Target population (number, age)	Study design and analysis method	Humidity exposure variable	Target outcome	Statistical indicator and effect estimate	Adjustment for confounding factors	Reporting quality(% score)
Wang et al.[b] (2012) [58]	15 states in USA 2004–2006	1459 children <2 years of age	Multivariable logistic regression	Daily mean dew point	Hospital admission	OR=0.9 , P=0.04 (95% CI: 0.8–0.996)	Adjusting for pressure altitude, wind speed, and temperature	76.67
Khor et al.[b] (2012) [39]	Kuala Lumpur, Malaysia 1982–2008	10269 children aged 0–5 years	Multiple regression analysis	Monthly mean relative humidity	Monthly number of respiratory syncytial virus (RSV) cases	β=−1.070, P<0.001	No adjustments were conducted	74.07
Chang et al.[b] (2012) [24]	Taiwan 1998–2008	1914 children aged<15 years	Case-crossover study, and Logistic regression	Daily mean relative humidity	Incidence of Enterovirus 71 infections	IRR=1.08, P<0.001 (95% CI: 1.05–1.10)	Adjusted for seasonal, temporal trends and annual variations	68.97
Turkish Neonatal[b] (2012) [37]	Turkey 2008–2010	3464 children aged<2 years	Correlation analysis and Spearman correlation test	Monthly mean relative humidity	Hospitalization with respiratory syncytial virus infection	r=0.627, P<0.001	Trends and seasonality were described	73.08

Abbreviations: GAM, generalized additive model; GLM, generalized linear models; ARIMA models, autoregressive integrated moving average modeling; r, correlation coefficient; β, regression coefficient; R²/r², coefficient of determination; RR, relative risk; OR, odds ratio; IRR, incident rate ratio; CI, 95% confidence interval; RSV, human respiratory syncytial virus; IA, influenza virus A.

[a]These included articles are ordered by the date of publication and the first word of their titles.

[b]In these studies there is more than one meteorological factor that was investigated and analyzed, respectively or simultaneously.

[N]: N is the specific citation number of the related study included in the present review.

among children under 15 years of age (IRR=1.08, 95% CI: 1.05–1.10), with seasonal and annual trends being controlled [24].

In Japan, one study indicated that for each 1% increase in the weekly mean relative humidity, the number of mumps cases increased by 1.4% (95% CI: 0.5–2.4%) among children [25]. In another Japanese study, the weekly number of hand, foot, and mouth disease cases increased by 4.7% (95% CI: 2.3–7.1%), in children between 0–4 years of age, for each 1% increase in relative humidity [26]. An additional study investigated the relationship between weather variability and infectious gastroenteritis (IG) in children. However, the results indicated that for every 1% decrease in weekly mean relative humidity, the number of IG cases increased by 3.9% (95% CI: 2.8–5.0%) [27].

Existing studies suggest that ambient humidity has a significant impact on malaria risk and diarrhoeal diseases among children. A prior study found that the clinical malaria risk increased non-linearly with the increase in mean relative humidity of the previous month [28]. A Mozambican study reported that humidity was a significant predictor of malaria incidence, with every additional 1% increase in relative humidity level leading to a 5% increase in risk of malaria incidence [29]. In Taiwan, a study examining the relationship between climate variations and diarrhea-associated morbidity found that there was a significant negative correlation between relative humidity and the morbidity of diarrhea in 0- to 14-year-old children ($\beta=-0.033$, $P=0.004$) [30]. Another study performed in Peru indicated that an increase of 1% in mean relative humidity was associated with a 3% decrease in the number of diarrhoeal admissions [31]. The results of an Australian study showed that higher humidity in the previous week was associated with a decrease in rotavirus diarrhoeal admissions among children hospitalized for rotavirus diarrhoea after controlling for season [32].

Respiratory system diseases

Many pediatric respiratory system diseases are sensitive to relative humidity. An Argentinean study reported that respiratory syncytial virus (RSV) and influenza virus A had a positive correlation with mean monthly relative humidity among children hospitalized due to acute lower respiratory viral infections [33]. Another study found that low absolute humidity presented a protective effect on the admission of infants who had lower respiratory tract infection (LRTI) due to RSV [34]. In a study conducted in Jordan, a significant positive correlation between the prevalence of RSV infection and relative humidity was identified among hospitalized children [35]. A similar study in Indonesia indicated that for children hospitalized with clinical pneumonia, a 1% rise in mean relative humidity was associated with a 6% increase in RSV cases [36]. An additional study of children hospitalized with LRTI in Turkey reported that the number of RSV infection cases positively correlated with relative humidity, similar to results reported by Noyola and Mandeville for Mexico [37, 38]. Another retrospective study was performed in Malaysia to investigate the viral etiology of children who were admitted with viral

respiratory tract infections. However, the results showed that monthly RSV cases were inversely correlated with relative humidity [39].

In Germany, a study found that human rhinovirus positively correlated with relative humidity among children who were hospitalized with acute respiratory tract infections (ARIs) [40]. Another study in New Zealand showed that the number of days per month with a mean 9 AM humidity >75% positively correlated with the incidence of invasive pneumococcal disease in children [41]. The results of a study in Cameroon showed that high relative humidity was directly associated with an increase in the frequency of hospitalization from ARIs [42]. However, in one Singapore study, of 42155 children presenting in the hospital with one of five common paediatric diseases, both upper respiratory tract infections and LRTI were negatively correlated with relative humidity [43].

Dermatopathy and pediatric allergic diseases

Childhood asthma and other pediatric allergic diseases are important adverse consequences of humidity. In Greece, the results of a study showed that relative humidity was an implicated meteorological variable for younger asthmatic children [44]. A study performed in fourteen cities in Turkey found that asthma, wheezing and allergic rhinitis were associated with higher mean yearly outdoor humidity among school children [45]. Another study reported an interesting finding that relative humidity was significantly associated with the incidence of acute urticaria in childhood. However, the humidity accounted for different effects in the two study cities. Specifically, decreasing incidence was found for humidity increases in Norwich, Britain, while the inverse was observed in Heraklion, Greece [46].

In one Turkish study of 21 bronchial asthma children, results indicated that increasing relative humidity leads to an increase in total daily complaints of asthma patients [47]. A study reported that winter humidity was positively associated with the prevalence of asthma in Taiwanese middle-school students [48]. A positive relationship between mean monthly relative humidity and childhood asthma admissions (CAAs) was reported in Greece. For this study, a 10% increase in humidity was related to a 31% increase in the probability of having a CAA [49]. In addition, an analysis, carried out exclusively within the coastal region of Spain, showed that relative humidity constituted a significant risk factor for wheezing in both the 6–7 and 13–14 age groups [50]. A retrospective study performed in America indicated that a 10% intraday increase in humidity one or two days before admission was associated with approximately 1 additional emergency department visit for asthma [51].

On the contrary, a study in Taiwan indicated that relative humidity was negatively correlated with asthma admission rates of pre-school and school-age children [52]. In Western Europe, a positive relationship between the lowest monthly mean relative humidity and prevalence rates of asthma symptoms was found among children [53]. Another similar study conducted among school children in Taiwan indicated that the lowest monthly mean relative humidity is

positively related to eczema [54]. An additional study conducted in Japan reported that the number of emergency visits for childhood asthma per night increased significantly when climate conditions showed a rapid decrease from higher humidity [55]. A study in Spain also showed that relative humidity was negatively associated with asthma in the 13–14 age group [56].

Others

Dew point, another measure of ambient humidity, is the temperature at which water vapor in the air becomes saturated and water droplets begin to form. To date, relative humidity and dew point are two widely used indicators for the amount of moisture in air. Accordingly, some other studies also investigated the association between ambient humidity and child health by choosing dew point as the indicator. A negative association between the peak week of child-related influenza visits and dew point was reported by Charland and colleagues, although the relationship was not significant [57]. In another study, Wang et al. found that a higher dew point was associated with a lower risk of hospital admission among children [58].

In addition, ambient humidity may also play a role in other diseases among children. For instance, the results of an American study showed a positive association between relative humidity and the likelihood of headache among children [59].

Discussion

The purpose of the present systematic review was to summarize key findings related to the effects of ambient humidity on child health, and identify the relationship between humidity exposure and common pediatric diseases. The systematic review of the 37 included publications performed herein demonstrates that ambient humidity generally plays a significant role in the incidence and prevalence of childhood climate-sensitive diseases, especially for gastrointestinal, respiratory system, and allergic diseases. Considering the expected continuation of climate change, the adverse influence of ambient humidity on children may become increasingly serious. However, some inconsistencies or even contradicting directions and magnitudes of the effects were also observed.

Almost 73% of the final included studies were conducted in high-income countries or regions, indicating that more attention should be paid to the developing countries of Asia and Africa. Because of low-income, a large population and poor infrastructure, people in these countries are usually more vulnerable to climate-sensitive diseases. The results of the quality assessment indicate that the combined application of advanced statistical methods, such as time-series analysis combined with Poisson regression, usually tends to provide more reliable results (higher quality ratings), since adjustments could be made for potential confounders, including long-term trends, seasonality and air pollution.

Impact of ambient humidity on child health

Because of their physiologic, metabolic and cognitive immaturity, and greater sensitivity to certain exposures, children are often the most vulnerable to adverse health effects from environmental hazards [14, 16]. In addition, more expected future years of life will expose them to newly developing or worsening environmental hazards [7]. In general, child vulnerability to environmental hazards (e.g. humidity) can be potentially explained by their unique modality of physiological, metabolic, behavioral, and self-care ability [60, 61]. Therefore, with global climate change, children are likely to suffer disproportionately from weather factors [60, 62]. It is thought that if children are adversely affected by meteorological factors (e.g. humidity), their long-term health may also be adversely impacted [63].

Findings from the present review suggest that the occurrence and prevalence of childhood climate-sensitive infectious diseases are significantly associated with ambient humidity. It is predicted that climate change will lead to more frequent and abundant rainfall, increasing temperature and higher concentrations of water vapor, which will cause favorable conditions of ambient humidity and concomitantly favor increases in the occurrence and development of infectious diseases [3, 4, 10]. For example, ambient humidity together with temperature can influence the population dynamics of vectors, persistence and survival of pathogens, seasonal activity of microorganisms, and duration of the life cycle of parasites, and therefore impact the occurrence and prevalence of various infectious diseases [10, 63, 64].

Ambient humidity can affect tick abundance and seasonal tick activity. It has been reported that the host seeking activity of *I. ricinus* depends on the relative humidity, and below a relative humidity threshold of 86%, the tick dehydrates and cannot continuously seek a host [65, 66]. In Sweden, a study found that the number of days with levels of relative humidity above 86% correlates positively with the incidence rate of erythema migrans [67].

For gastrointestinal infectious agents such as rotaviruses and EV71, changes in ambient humidity have been reported to facilitate viral resistance, thereby enhancing the virulence and increasing the efficiency of transmission through contaminated air, fomites and environmental surfaces [68, 69]. A laboratory-based study suggested that the stability of enteroviruses in external environmental conditions is dependent on temperature and humidity, and another study reported that raising the relative humidity to 80% results in a rapid loss of infectivity, suggesting that humidity might be an important environmental determinant of rotavirus infectivity [68, 70]. This perhaps can explain why the relative humidity has a linear inverse relationship with the number of cases of rotavirus diarrhea previously reported in a study of 3115 rotavirus diarrhoea cases in 0- to 2-year-old Bangladesh children [71]. However, a study performed in China suggested that the number of hand, foot, and mouth disease infections is positively correlated with ambient humidity [72].

Malaria is a climate-sensitive vector-borne illness. Meteorological factors (e.g. temperature, humidity) have considerable impact on *Anopheles* vector abundance

and the extrinsic cycles that the parasites perform inside mosquitoes. Thus, meteorological factors may affect malaria incidence and constitute driving forces for malaria epidemics [73]. A study in China suggested that moderate temperature and relative humidity increase the longevity of the adult mosquito so that it can transmit infection for a longer period of time [74]. In India, a study found a higher positive correlation between monthly malaria parasite incidence and ambient humidity [75].

Many studies demonstrate the effects of relative humidity on pediatric respiratory tract infections. In tropical and subtropical areas (e.g. Singapore, Malaysia), it has been suggested that high humidity and temperature prolong the activity and stability of microorganisms in large-particle aerosols, and permit year-round transmission of the microorganisms [5, 76]. A study reported that relative humidity is positively associated with RSV activity, with more RSV infection occurring when humidity increases [77]. However, a converse conclusion was found in an Argentinean study, which concluded that humidity provides a protective effect against respiratory infections [78].

The possible effects of ambient humidity on childhood asthma and other allergic diseases are of particular concern due to this population's greater susceptibility. Meteorological factors (humidity, temperature) can influence both biological and chemical components of air and might induce negative effects on respiratory allergic diseases. With climate change, ambient humidity is likely to impact asthma, hay fever and other allergic diseases via its influence on the concentration and distribution of pollens, mould spores, house dust mites, and other aeroallergens [79, 80]. Moreover, changes in the outdoor humidity, resulting from climate change, is important not only because of its own effects, but also because of its influence on indoor humidity, which results in infestation of homes with house dust mites, growth of fungal spores and home dampness, and is associated with the incidence of allergic diseases [12, 79, 81]. A study conducted among school children in Spain indicates that humidity significantly influences the occurrence of atopic eczema [82]. Youssefagha and colleagues indicate that upper-air relative humidity $\geq$50% and higher dew point (>-1.9) are significantly associated with exacerbation of asthma among children [83]. Another study performed in Japan also suggests that asthmatic children frequently visit the emergency department during early mornings with high absolute humidity [84].

However, in this review, some studies also report a negative association between ambient humidity and pediatric allergic diseases [52, 56]. The reasons for the inconsistencies among different studies are possibly due to regional differences and local characteristics, such as geographical environment, type of climate, vegetation condition, air quality, socio-economic status, and the acclimatization and adaptation of the local populations [63, 79, 80]. Additionally, study design, subgroups of children and method of analysis may also contribute to the controversies.

As mentioned above, different studies may present inconsistencies in the direction and magnitude of the effects of ambient humidity, with other studies even concluding that the occurrence of relevant climate-sensitive diseases appears

to be unrelated to humidity [36, 39, 85, 86]. This discrepancy can be explained by the following possible reasons: firstly, relative humidity can affect microorganisms in different ways. Some microorganisms tend to be more invasive in increased humidity, while others develop better in lower humidity [10]. Similar effects of ambient humidity on the concentration and distribution of aeroallergens have also been reported [87]. Secondly, there is a geographical, meteorological and temporal heterogeneity in the different studies. The occurrence of different effects suggests that geographical sites, regional variability and acclimatization of the local population may play a role in determining the exposure–response relationship. Thirdly, among various studies, whether or not one takes into account potential confounding factors and what kind of confounder is adjusted for existing differences, can make a difference in the conclusions. Moreover, even mutual confounding factors among different studies are likely to vary between regions, which implies that regional differences and local characteristics may modify the effects of weather factors [25, 27, 71]. Lastly, the date of the study conducted, the limited study duration and participants, and the different age groups of the study population may also play a role in the discrepancy. Future research taking these factors into account will be appreciated.

Strengths and limitations

This systematic review begins to address the current knowledge gap in the relationship between ambient humidity and child health. This is the first attempt to synthesize, using a systematic approach, the existing evidence of humidity-related health outcomes, across different countries, among children between 0–18 years of age. According to **Table 2**, almost all of the final included journal articles (34/37) were published after the year 2000, and were of relatively high reporting quality (the majority of records having a reporting quality above 70%). The findings in **Table 2** suggest that ambient humidity has been playing a significant role in weather-related health outcomes. Unfortunately, children are usually the most susceptible subpopulation. The present review is crucial because this literature provides details of the current state of studies that examine the effects of humidity on child health and proposes directions for the future research.

Despite targeting the reporting quality of observational studies, many items of the STROBE checklist were no doubt selected due to evidence of association with susceptibility to bias. Thus experts have suggested that the STROBE statement provides a suitable starting point for development of a quality assessment tool [20, 88]. Just as the MOOSE (Meta-analysis Of Observational Studies in Epidemiology) guidelines are being used to assess quality, although they were actually developed as reporting guidelines, in this review, we tried to describe the reporting quality of the final identified articles by using an adapted version of the STROBE checklist [18, 89]. After the quality assessments, studies that applied credible and convincing statistical methods and outcome measures often obtained higher quality scores at the same time (**Table 2**), indicating that the adapted STROBE checklist can describe the reporting quality of the final identified articles

well. This novel quality assessment tool is innovative and potentially ground-breaking in terms of its contribution to relevant environmental and meteorological literature reviews [22].

However, regarding the results of this systematic review, some limitations should be acknowledged. First, this review is limited by its emphasis on papers published in English in peer-reviewed journal databases, so we may have missed potentially useful studies. Second, despite the highly sensitive and comprehensive nature of the search strategy employed, it is unlikely that all existing studies have been identified, and publication bias cannot be entirely excluded. Third, the adapted version of the STROBE checklist was initially implemented to describe the reporting quality of weather-related studies, so the validity and reliability of the checklist for our purposes have not been completely tested and formally evaluated. However, in this review, the tool was used only to describe the reporting quality, and the quality scores were not included as part of the relevance criteria. Fourth, it has been reported that temperature and relative humidity are not independent of one another, so the effects of relative humidity may be confounded by temperature. However, in our review, the majority of studies adjusted for potential confounding factors (e.g. temperature) when analyzing the impact of humidity on child health, and studies that conducted no adjustments were given lower quality ratings. Additionally, relative humidity is a popular indicator that has been widely used in current research and meteorological monitoring. Therefore, it is helpful and of practical significance to choose relative humidity rather than absolute humidity or water vapor pressure as the exposure variable. Finally, the data extraction and quality assessment were not performed independently by more than one reviewer, which may have led to subjective errors and introduced bias. However, in the present review, due to the explicit inclusion criteria, specially pre-designed data extraction form, definite exposure variable and health outcome, and the adapted quality assessment tool, the authors were able to ensure the integrity of the review, and to be unbiased during the conduction of assessment.

Conclusion

In summary, this study demonstrates that due to various inherent and unique characteristics, children are often susceptible to ambient humidity. We find that with climate change, there is a significant impact of humidity on child health, especially for climate-sensitive infectious diseases, diarrhoeal diseases, respiratory system diseases, and pediatric allergic diseases. However, the humidity-related effects on child health are various and complex. Ambient humidity continues to impact children unequally and in different ways, with impacts ranging from direct and indirect, and negative and positive. In this review we find that the influence of humidity on child health involves heterogeneous and even converse effects among different study regions, research designs, health outcomes, adjustments of potential confounding factors (e.g. air pollution, seasonality, interaction with

other meteorological factors), and subgroups of children, which suggests that further studies focusing on the association between ambient humidity and child health are needed to deal with the aforementioned problems.

Current increasing interest in the relationship between climate change and child health may provide an ideal opportunity to employ various epidemiological and statistical methods to further explore the impact of ambient humidity on child health. Such research and epidemiologic evidence can inform the local health officials and policy-makers to make and implement necessary preparations (mitigation and adaptation), ultimately contributing to better health outcomes for a humidity-impacted population.

Supporting Information

S1 Checklist. PRISMA checklist.
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Author Contributions

Conceived and designed the experiments: JG LL. Performed the experiments: YS YL. Analyzed the data: YS YL. Wrote the paper: JG YS YL LL. Study selection, data extraction and quality assessment: JG YS YL. Development of methodology: LL.

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