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Review

How climate change degrades child health: A systematic review and meta-analysis

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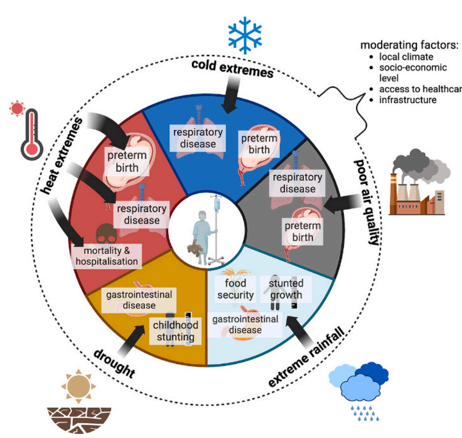
HIGHLIGHTS

- Climate change poses a great threat to child health globally.
- The strongest effects were temperature extremes increasing preterm birth.
- Respiratory disease, mortality, and morbidity are also affected by climate.
- Low- and low-middle income nations are under-represented in the published evidence.
- Socio-economic status, quality health-care, and climate together determine disease severity.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Children are more vulnerable than adults to climate-related health threats, but reviews examining how climate change affects human health have been mainly descriptive and lack an assessment of the magnitude of health effects children face. This is the first systematic review and meta-analysis that identifies which climate-health relationships pose the greatest threats to children.

Objectives: We reviewed epidemiologic studies to analyse various child health outcomes due to climate change and identify the relationships with the largest effect size. We identify population-specific risks and provide recommendations for future research.

Methods: We searched four large online databases for observational studies published up to 5 January 2023 following PRISMA (systematic review) guidelines. We evaluated each included study individually and

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Respiratory disease
Stunting
Birth weight
Pregnancy

aggregated relevant quantitative data. We used quantitative data in our meta-analysis, where we standardised effect sizes and compared them among different groupings of climate variables and health outcomes.
Results: Of 1301 articles we identified, 163 studies were eligible for analysis. We identified many relationships between climate change and child health, the strongest of which was increasing risk (60 % on average) of preterm birth from exposure to temperature extremes. Respiratory disease, mortality, and morbidity, among others, were also influenced by climate changes. The effects of different air pollutants on health outcomes were considerably smaller compared to temperature effects, but with most (16/20 = 80 %) pollutant studies indicating at least a weak effect. Most studies occurred in high-income regions, but we found no geographical clustering according to health outcome, climate variable, or magnitude of risk. The following factors were protective of climate-related child-health threats: (*i*) economic stability and strength, (*ii*) access to quality healthcare, (*iii*) adequate infrastructure, and (*iv*) food security. Threats to these services vary by local geographical, climate, and socio-economic conditions. Children will have increased prevalence of disease due to anthropogenic climate change, and our quantification of the impact of various aspects of climate change on child health can contribute to the planning of mitigation that will improve the health of current and future generations.

1. Introduction

Climate change has moved progressively towards the centre of global political and public interest over the past 20 years (Arpin et al., 2021; Bradley et al., 2020; Clayton, 2020; Ebi and Paulson, 2007; Lee et al., 2020; McMichael et al., 2006; Pearce et al., 2018; Perera and Nadeau, 2022; Xie et al., 2019). Of the real and potential risks, there is a large and growing body of literature examining the child-health impacts of climate change (Arpin et al., 2021; Ebi and Paulson, 2007; Helldén et al., 2021; Perera and Nadeau, 2022). Climate change has already displaced 600 million people outside of the 'human climate niche', with our current trajectory warning that as many as 3 billion people will fall outside of this ideal temperature range by the end of the century (Lenton et al., 2023). Of the vulnerable among us, children are the most affected, with 88 % of the climate-change health burden carried by this demographic (Horton, 2023; Philipsborn and Chan, 2018).

An appreciation of climate change as a health issue is essential for initiating meaningful action and mitigation, with the health profession being one of the first sectors needing to adapt (Romanello et al., 2022; Romanello et al., 2021; Watts et al., 2018). Meaningful action has been suggested to take the form of reviewing health-service planning and allocation of resources, preparing clinical practice to deal with climate-related increases in hospital presentations, and recognising the importance of primary health care in responding to climate-related health risks (Blashki et al., 2011; Burton et al., 2014; McMichael et al., 2007). Among health professionals, the perception that climate change is damaging health is widespread, although self-assessed knowledge of these health impacts is poor (Hathaway and Maibach, 2018). Likewise, health policy makers recognise that climates change will challenge the healthcare system in the future (Tong and Ebi, 2019), considering that most healthcare systems are unprepared for increased incidence of specific diseases and burden on both primary and tertiary care (Blashki et al., 2011; Burton et al., 2014; Friel, 2020; Patel et al., 2022; Sheehan and Fox, 2020).

Existing reviews provide valuable insights and perspectives on climate change-related health effects (Ebi and Paulson, 2007; Helldén et al., 2021; Perera and Nadeau, 2022). These reviews have explored how climate change affects child health in terms of specific disease and broader health outcomes. However, there is still a lack of a quantitative comparisons of the detrimental impacts of climate change on child health across multiple climate and health variables (Helldén et al., 2021). No current systematic review compares risk across climate variables and child health outcomes. Our systematic review and meta-analysis is the first to compare the relative risk of specific health outcomes across multiple climate variables. Our review is limited by the availability of adequate data published in primary resources. As such, the relationships between climate change and child health explored in greatest detail are those with the largest body of evidence available, while several other relationships lack adequate data required for meta-analysis.

The world is sitting on the precipice of an ecological and health crisis (World Meteorological Association, 2022; Friel, 2020), with temperature, extreme events, and pollution (Eyring et al., 2021; Trancoso et al., 2020) continuing to increase as climate change progresses; therefore, quantifying the extent to which these phenomena will affect child health will stimulate better future health policies and clinical protocols. In this systematic review, we (*i*) synthesise the current evidence on how climate change affects child health outcomes, (*ii*) quantify the extent to which climate change affects child health, (*iii*) identify which areas of child health pose the greatest risk of climate-related disease based on current evidence, (*iv*) provide a framework for identifying population-specific risks, and (*v*) identify knowledge gaps and suggest future research direction.

2. Methods

2.1. Systematic literature review

Our systematic review and meta-analysis addresses the main question: which climate variables pose the greatest disease burden for children? We compared all previously examined climate variables and child health outcomes using a systematic-review and meta-analysis approach. This approach provides a means to appraise study quality and standardises different child health outcomes as responses to various climate variables (*e.g.*, temperature, precipitation, air quality). We followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; prisma-statement.org) recommendations for our systematic review and meta-analysis (PRISMA checklist; Appendix 1). We did a systematic literature search on 5 January 2023 in the databases *Pubmed*, *Medline*, *Embase*, and *Web of Science* (search string provided in Appendix 2). We designed the search string to encompass a broad range of climate variables and health outcomes with no restrictions on the database search engines regarding study type or year of publication (studies *versus* year of publication; Appendix 3, Fig. A1). Our aim was to include the largest number of climate variables and health outcomes feasible to provide a comprehensive review of the field and identify all available peer-reviewed data for our meta-analysis. The lead author (LW) then screened the identified studies and reviewed them following the process outlined in Fig. 1. Our criteria selected studies based on broader definitions of climate and health (Table 1) (Masson-Delmotte et al., 2018). These criteria align with our research question and ensure that we did not omit any climate or health variables identified in the database searches. We excluded studies based on their respective study type, climate event/change metric explored, health outcome measured, age of

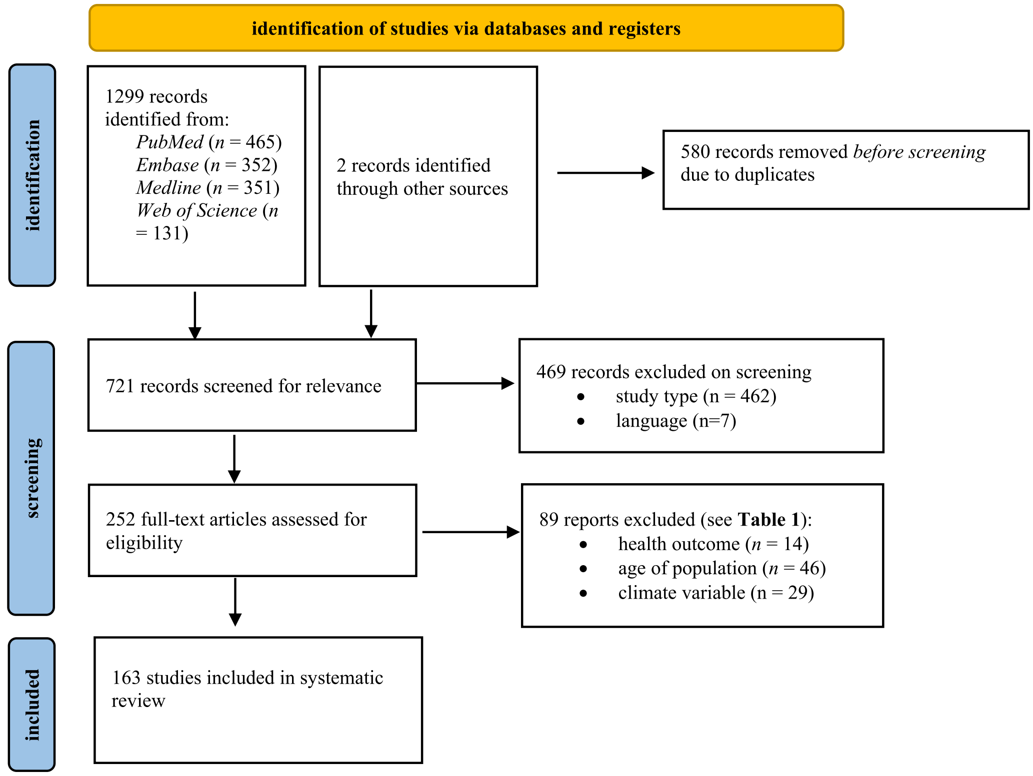

Fig. 1. Screening and review process following the literature search. Reason for study exclusion are described in terms of the "criteria topic" of the eligibility criteria.

Table 1
Eligibility criteria.

Criteria topic	Inclusion criteria	Exclusion criteria
study type	cross-sectional, longitudinal, time-series, or cohort	other
climate event	clear climate extremes or climate change as per IPCC glossary (Masson-Delmotte et al., 2018)	other – climate events / extremes that do not fit IPCC definitions
health outcome	clear health outcome (pathology or disease) related to a human body system	other
age group of population	0–18 years	other
study language	English, Indonesian, Dutch	other

the population studied, and language (studies excluded; Appendix 4).

We identified 721 unique studies after removing duplicates, and after exclusion we retained 163 unique studies measuring a change in a particular climate variable within a population and presenting a measured health outcome. Two authors (CB and LW) extracted and analysed the data.

2.2. *Risk of bias assessment*

We applied the U.S. National Toxicology Program's Office of Health Assessment and Translation (OHAT) risk of bias rating tool to each included study. OHAT can assesses the risk of bias across the following five domains: (*i*) *selection* (Are participants representative of the population and are appropriate comparison groups allocated?), (*ii*) *confounding* (Did the study design or analysis account for confounding and modifying variables?), (*iii*) *attrition* (Were outcome data complete without attrition or exclusion from analysis?), (*iv*) *exposure characterisation* (Were definitions and methods of exposure measurement appropriate?), and (*v*) *outcome assessment* (Was the outcome assessed using well-established methods?). We provide the ratings given to each included study across all these domains in Appendix 5.

The assessment of bias highlighted the need to adjust our analytical methods to accommodate high attrition bias among the cohort of studies. We found no relationship between the magnitude of a study's standardised metric (see Section 2.4) and a study's risk of bias (Appendix 5, Fig. A2).

2.3. *Metrics*

We recorded the climate and health metrics in each study, along with the relationships observed between them. We provide all included studies in Appendix 6 with their descriptive data. We then identified

Table 2
Common climate variables examined in relation to health impacts.

Climate variable	Metric	Type of measurement
temperature	temperature extremes	• > 90th, > 95th, > 99th percentile of average temperature • < 10th, < 5th, < 1st of average temperature
	average temperature increases	• increase of 1° C • increase of 10° F
	diurnal temperature	• increase of 1° C, 5 °C, 10 °C
air pollution	particulate matter – PM_1, $PM_{2.5}$, PM_{10} O_3 NO_2 SO_4	• increase of 1 μg m^{-3}, 10 μg m^{-3} • increase in interquartile range
rainfall	drought	• unclear – often drought is specific to local climate
	average rainfall changes	• increase/decrease in rainfall (mm) daily average

Table 3
Common health outcomes examined as a function of climate variables.

Health outcome	Metric	Type of measurement
mortality/ morbidity	mortality admissions to emergency department / hospitalisations	• increase in percentage, risk ratio, odds ratio (including control group risk if present)
perinatal outcomes	preterm birth birth weight pregnancy loss	• increase in percentage, risk ratio, odds ratio (including control group risk if present)
respiratory outcomes	asthma hospital presentations respiratory tract infections admissions to emergency department / hospitalisations	• increase in percentage, risk ratio, odds ratio (including control group risk if present)
nutritional status	height-for age middle-upper-arm circumference	• *z* score
gastrointestinal	diarrhoeal disease admissions to emergency department / hospitalisations	• increase in percentage, risk ratio, odds ratio (including control group risk if present)

common climate and health variables and tabled the quantitative relationships (Table 2 and Table 3: *type of measurement* column) reported in studies examining these variables.

2.4. Metric standardisation

Of the studies we included, relative changes in health outcome metrics due to a change in temperature or air quality above or below an arbitrary baseline were given in various forms, including percentage change (p), relative risk (r), hazard ratio (h), or odds ratio (o). We converted each of these different risk metrics into a standard unit for comparison across studies. Because the most common risk was expressed as an odds ratio, we chose to standardise all other metrics to odds ratios (*i.e.*, the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure) using the following conversions:

$$o = 1 + \left(\frac{p/100}{1 - p/100}\right) \tag{1}$$

where p = percentage change;

$$o = \frac{r(1-b)}{1-rb} \tag{2}$$

where r = relative risk, and b = the expected or 'baseline' probability of the event occurring; and

$$r = \frac{1 - e^{h\log_e(1-b)}}{b} \tag{3}$$

where h = hazard ratio, from which an odds ratio can be calculated following eq. 2.

However, one problem was that most studies did not provide an estimate of b necessary to convert r or h to o; we therefore calculated a least-squares linear regression between r and o for the studies providing an estimate of b (Appendix 7, Fig. A3), the resulting slope and intercept coefficients of which we used to correct r to the appropriate scale of o in studies without an estimate for b:

$$o = 1.115r - 0.129 \tag{4}$$

The standardisation procedure allowed us to synthesise the results according to the climate and health variables the studies examined. We then tabulated, ranked (in descending order of mean odds ratio), and graphed these results according to health metric and climate variable. We could not standardise or analyse all studies included due to a lack of data, an important aspect of assessing bias. When an article presented insufficient data for inclusion in the meta-analysis, we present and examine the results of individual studies in the context of the wider literature. The number of articles exploring the relationships between climate change and child health outcomes has increased over recent years (studies *versus* year of publication; Appendix 3), and these new data provide an opportunity for meta-analysis.

3. Results

3.1. Morbidity and mortality

Thirty-three studies measured morbidity or mortality as an outcome due to various climate events. Twenty-eight of the 33 (85 %) studies examined the relationship between temperature extremes, either defined as a heatwave or within a certain percentile of mean ambient temperature, or temperature changes and morbidity/mortality. The remaining five studies investigated the relationship between air pollutants or river water levels and morbidity/mortality.

Sixteen studies examined how exposure to temperature extremes influences presentations and admissions to hospital, presenting results either as (*i*) exposure to a temperature extreme and the risk of admission to hospital, or (*ii*) the impact on admissions to hospital due to an increase in ambient temperature. While highly variable among studies, exposure to a temperature extreme >95th percentile of average daily temperature increased the odds ratio of paediatric hospital admission from 1.17 (95 % confidence interval: 1.12–1.21) to 1.27 (1.12–1.44) (Bernstein et al., 2022; Xu et al., 2014a, b), and 3.6 (1.4–9.5) for paediatric renal admission to hospital (Wang et al., 2014). A 1.011–1.013 odds ratio of paediatric emergency-department presentations was reported after exposure to a temperature extreme >99th percentile of average daily temperature (Wilk et al., 2021).

Measuring a health outcome based on an absolute increase in temperature, often during a predefined 'hot season', was adopted by many studies (Zhao et al., 2019). A 7^{o} C increase in consecutive maximum daily temperatures raised the odds ratio of paediatric admissions to hospital to 1.022–1.031, and all-causes emergency department visits to 1.004–1.022 for a 5.5^{o} C increase (Kingsley et al., 2016; Sheffield et al., 2018). Socio-economic status is an important moderating factor for the impact of temperature changes on child morbidity, with a 1.095–1.125 odds ratio increase *versus* 1.043–1.067 increase in risk of hospitalisation for children in low- and middle-income cities *versus* high-income cities (Xu et al., 2020). Increased temperature variability is also associated with increased hospitalisations (Zhao et al., 2018).

Exposure to temperatures <5th percentile of average daily temperature increased (O'Neill et al., 2005) the all-causes mortality odd ratio to 1.117–1.17, and 1.03–1.78 increase in 18+ only/all-causes mortality upon exposure to temperatures >95th percentile (Ma et al., 2015). An increase of 1^{o} C during hot periods in Chinese cities raised the odds ratio of all-causes mortality anywhere from 1.009–1.056 to 1.015–1.097 (Li et al., 2014). Children <5 years of age are generally more sensitive than the rest of the population to high temperatures, but not to low extremes (Scovronick et al., 2018). Five studies (Green et al., 2015; Ingole et al., 2012; Li et al., 2014; Scovronick et al., 2018; Sheffield et al., 2018) identified children as a vulnerable group to temperature extremes and increases in average temperature, while one study (Son et al., 2012) found children were the least vulnerable group.

3.2. Perinatal outcomes

Forty-nine studies explored the impacts of climate changes on various perinatal outcomes, of which 39 examined temperature changes, and 10 examined air pollutants. The main health outcome measured was preterm birth, followed by changes in birth weight and pregnancy loss. Of the 39 studies examining the impact of temperature changes on perinatal outcomes, preterm birth (births occurring up to week 37 of gestation) was the most common health outcome (29 studies), followed by low birth weight, gestational age changes, premature rupture of membranes, and pregnancy loss. Of the 29 preterm-birth studies, 21 examined exposure to extreme temperature, and the remaining 8 investigated increases in ambient temperature.

Exposure to a temperature extreme >90th percentile of maximum daily temperature results in an odds ratio of preterm birth of 1.25 (Vicedo-Cabrera et al., 2014). Exposure to a temperature extreme >95th percentile also resulted in large range of increased risk of preterm birth (1.028 to 3.171) (Cox et al., 2016; Guo et al., 2018; Guo et al., 2017; Hough et al., 2023; Jegasothy et al., 2022; Ren et al., 2022; Sun et al., 2019). Exposure to a temperature extreme >97.5th percentile increased the odds ratio of preterm birth (Huang et al., 2021) to 1.014–1.039, and to 1.290–1.586 after exposure to a temperature extreme >99th percentile (Cushing et al., 2022; Mohammadi et al., 2019; Nyadanu et al., 2022).

Some studies reported risk after exposure to extremes of cold. One cohort study reported a 1.187–2.493 odds ratio of preterm birth when exposed to a temperature extreme <1st percentile of mean daily temperature (Cheng et al., 2021a, b), and another reported a maximum preterm birth odds ratio of 1.192–1.744 following the 2008 cold spell in two sub-tropical cities in Guangdong Province, China (Liang et al., 2018). Nineteen studies concluded that exposure to temperature extremes (with assorted definitions) was associated with an increased risk of preterm birth (Cheng et al., 2021a, b; Cox et al., 2016; Cushing et al., 2022; Guo et al., 2018; Hough et al., 2023; Huang et al., 2021; Jegasothy et al., 2022; Liang et al., 2018; Mathew et al., 2017; Mohammadi et al., 2019; Nyadanu et al., 2022; Ren et al., 2022; Smith and Hardeman, 2020; Son et al., 2019; Spolter et al., 2020; Sun et al., 2019; Vicedo-Cabrera et al., 2014; Vicedo-Cabrera et al., 2015; Wang et al., 2013; Wang et al., 2020). In terms of absolute increases in temperature, the odds ratio of preterm births was 1.043–1.246 following an increase of 5.5^{o} C in weekly mean temperature (Avalos et al., 2017; Basu et al., 2017; Basu et al., 2010), similar to other studies (McElroy et al., 2022; Muresan et al., 2017; Ward et al., 2019; Zheng et al., 2018; Zhong et al., 2018) identifying a positive relationship between increases in mean ambient temperature and preterm birth.

Exposure to temperatures >97th percentile of maximum daily temperature over two consecutive days at any point during gestation increased the risk of low birth weight (< 2500 g) by 1.023–1.106, with the first trimester of pregnancy being the most vulnerable (Lawrence et al., 2021). In Queensland, Australia, exposure to a daily maximum temperature > 30^{o} C during the last week of gestation reduced birth weight (Li et al., 2018). But other studies suggest an opposite relationship, with a 41.8 g (0.6–82.9 g) increase in birth weight occurring with every 1^{o} C rise in daily average temperature during the third trimester in Uganda (MacVicar et al., 2017). A cohort study in Ethiopia found that higher temperatures *in utero* during the first and third trimesters and greater rainfall during the third trimester were positively associated with severe stunting (Randell et al., 2020), and another from South Asia observed that precipitation extremes of both wetness and dryness decreased height-for-age *z* scores (McMahon and Gray, 2021). Stunting due to interactions between rainfall and temperature extremes might be mediated by the role rainfall plays in food security and infectious disease prevalence. Lower rainfall (15th compared to the 50th percentile) increased the risk (1.097–1.543) of diarrhoea in Uganda (Epstein et al., 2020), while higher rainwater runoff concomitantly decreased the risk (0.54) of diarrhoeal disease in Rwanda (Mukabutera et al., 2016). Flooding also increased the risk of acute gastroenteritis in the Netherlands and Peru (Colston et al., 2020; Mulder et al., 2019). In Tuvalu, household water-tank reserves <20 % increased the risk (1.16–4.60) of diarrhoeal disease (Emont et al., 2017).

Ten studies explored relationships between airborne pollutants and various perinatal outcomes (preterm births [n = 7] and birth weight [n = 3]), all using various measures of particulate matter in ambient air: PM_1, $PM_{2.5}$, PM_{10}. One cross-sectional study in Africa found that an interquartile range increase (33.9 μg m^{-3}) in the concentration of $PM_{2.5}$ in ambient air measurements was associated with an odds ratio of preterm birth of 1.01–1.16 (Bachwenkizi et al., 2022), and another in China observed an increased risk of preterm birth (1.094–1.105) with an increase PM_1 concentration of 10 μg m^{-3} during the entire pregnancy (Wang et al., 2018). Others (Dibben and Clemens, 2015; Wang et al., 2020) reported no relationship between $PM_{2.5}$ or PM_{10} and the risk of preterm birth. A 1.014–1.018 increase in the odds ratio of preterm birth was observed after exposure to a 10 mg m^{-3} rise in SO_2 (Xiong et al., 2019).

The three studies examining reductions in birth weight (Dibben and Clemens, 2015; Li et al., 2021; Wang et al., 2019) found that airborne pollutants due to fire exposure reduced birth weight by 0.56–3.77 g per 1 μg m^{-3} increase and a 1.01–1.049 odds ratio of low birth weight (Li et al., 2021), a 1.01–1.12 increase in the odds ratio of low birth weight with a 1 μg m^{-3} increase (Dibben and Clemens, 2015) in ambient PM_{10}, but the magnitude of the effect depends on temperature (Wang et al., 2019). One study in South Asia found different increases in the risk of stillbirth per 1 μg m^{-3} rise in average $PM_{2.5}$ depending on the source of the pollutant (Xue et al., 2021). A 1 μg m^{-3} increase in fire-sourced $PM_{2.5}$ increased the stillbirth odds ratio (Xue et al., 2021) by 1.035–1.067, but non-fire $PM_{2.5}$ by 1.011–1.016.

3.3. Respiratory outcomes

Forty-three studies examined the way in which various climate variables influence child respiratory health (mainly, emergency-department presentations, asthma incidence, and risk of infectious respiratory disease), 26 of which explored the deleterious impacts of temperature and 16 of which focussed on air quality and air pollution. Five studies measured the influences of temperature changes on rates of admission to hospital for generalised respiratory paediatric illnesses. One cohort study (n = 796,125) in Fuzhou, China found that lower mean temperatures (< 25th percentile of the mean) had a higher risk (0.998–1.045) of admission due to respiratory disease among children (Wu et al., 2022). Similar impacts were reported in Beijing, China, were cold extremes increased child respiratory presentations to the emergency department, but the impacts on respiratory health had a longer period of influence for children (< 15 years) than for older people (> 65 years) (Ma et al., 2019). Another study in China (Cangnan) found children <4 years of age did not experience greater respiratory disease due to heatwaves (Zhang et al., 2019).

Exposure to temperature extremes >95th percentile of the mean results in an odds ratio of 1.287–2.737 for childhood asthma emergency-department presentations (Soneja et al., 2016; Xu et al., 2013a), whereas an increase in temperature from the 25th to 75th percentiles results in an odds ratio of 1.019–1.086 (O'Lenick et al., 2017; Winquist et al., 2016). The risk for childhood asthma emergency department presentations following a 5^{o} C rise in diurnal temperature range (Xu et al., 2013b) increased to 1.124–2.381, and there was a 0.986–1.009 greater risk following a 1^{o} C increase in lower daily mean temperature during thunderstorm days. The consensus is that exposure to increased temperatures and/or high temperature extremes is associated with a variable increased risk of childhood asthma (Figgs, 2019; O'Lenick et al., 2017; Park et al., 2022; Soneja et al., 2016; Winquist et al., 2016; Xu et al., 2013a; Xu et al., 2014a).

Thirteen studies examined the influences of temperature changes on infection-related respiratory disease, with ten exploring respiratory viruses. Exposure to lower temperatures is associated with an increase in risk of human parainfluenza virus, respiratory syncytial virus, influenza A virus, coronavirus, and viral-induced childhood bronchitis/bronchiolitis (Chen et al., 2022; Du Prel et al., 2009; Kim et al., 2017; Lim et al., 2021; Lim et al., 2022; Lim et al., 2020; Nichols et al., 2021; Oh et al., 2020), but 'lower temperatures' are defined differently among studies. An increase in 10^{o} C in diurnal temperature range was

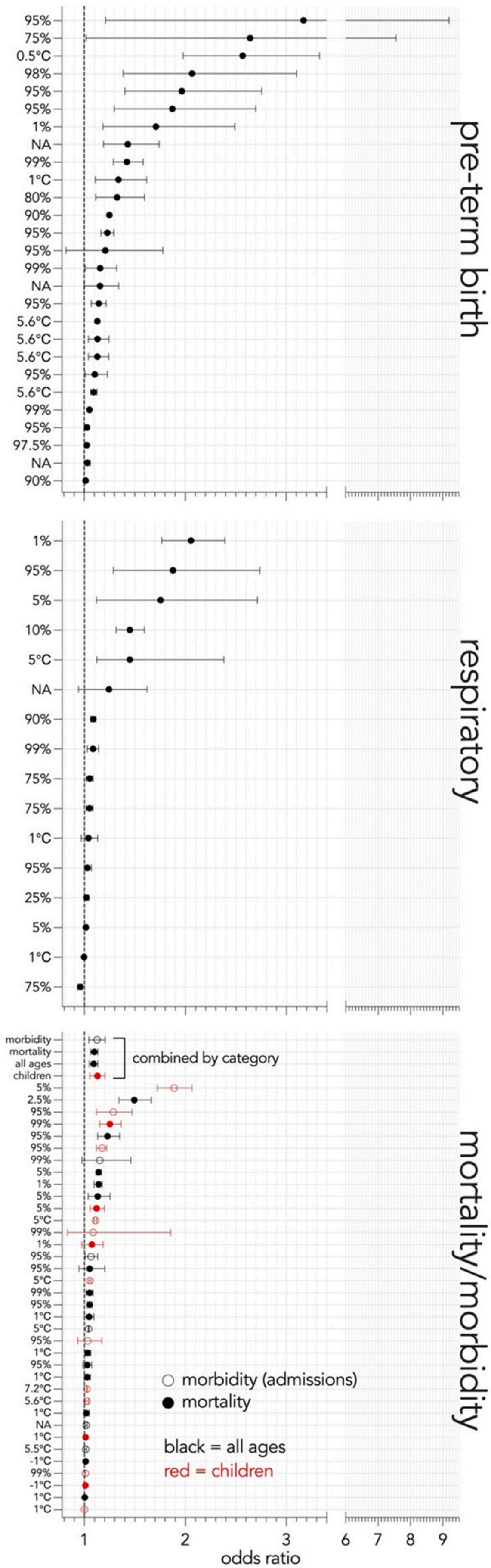

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Fig. 2. Impact of temperature extremes (defined by the percentage of average temperature) on preterm birth, respiratory disease, and mortality/morbidity. Aggregated mortality morbidity results are included for children and all ages. Studies are ranked by effect size (median odds ratio) from largest to smallest in each panel.

associated with an odds ratio of 1.012–1.103 for upper respiratory tract infections in children ≤5 years old (Carreras et al., 2015), and 1.004–1.131 for lower respiratory tract infections among children aged 6–18 years (Carreras et al., 2015). Every 1^{o} C increase in weekly average diurnal temperature range results in an odds ratio of respiratory syncytial virus infection of 1.71–7.23 (Onozuka, 2015). However, variation in diurnal temperature range did not affect the risk of influenza A virus (Lim et al., 2022) or childhood pneumonia (Xu et al., 2014a, b). Likewise, weather conditions did not affect the risk of paediatric intensive care unit admission due to respiratory syncytial virus infection (Linssen et al., 2021).

Sixteen studies explored the relationship between air quality or aeroallergens and childhood respiratory health (mainly, risk of asthma), with $PM_{2.5}$ being the most studied airborne pollutant, followed by aeroallergens, PM_{10}, O_3, and NO_2. The risk of asthma can increase by 1.058–1.105 when $PM_{2.5}$ (due to fire smoke) increases 1 μg m^{-3} (Stowell et al., 2019), although this result is not consistent across studies (To T et al., 2021). An ambient air increase of 1 μg m^{-3} $PM_{2.5}$ also raises the risk of combined respiratory disease (1.012–1.031) (Stowell et al., 2019). An interquartile range increase in SO_4 concentration was associated with a greater risk (1.343–4.365) of all-cause hospitalisations among children with asthma (To et al., 2021), and other studies (Pepper et al., 2020; Sheffield et al., 2011; To et al., 2020) report a greater risk of childhood asthma from increased O_3 and NO_2, but not $PM_{2.5}$. A 10 grains m^{-3} increase in total aeroallergen concentration also raised the incidence of hospitalisation due to asthma (1.011–1.098) (Darrow et al., 2012; Di Cicco et al., 2022; Héguy et al., 2008). $PM_{2.5}$ also increases the risk of childhood pneumonia presentations to hospital (Cheng et al., 2019; Howard et al., 2021). Respiratory outcomes due to air pollution increases are worse when temperature decreases (Song et al., 2021).

Increased $PM_{2.5}$ and PM_{10} concentration can also increase the risk of all-cause childhood respiratory presentations to the emergency department (Cheng et al., 2021a; Leibel et al., 2020; Stowell et al., 2019; Zhang et al., 2015). For example, fires associated with drought conditions in the Brazilian Amazon increase childhood respiratory hospitalisations (Smith et al., 2014), whereas another study in the same region observed an odds ratio of 1.266 for childhood respiratory disease during the dry season compared to the wet season (Rosa et al., 2008). Fire-related air pollution also increases the risk of hospitalisations (Hutchinson et al., 2018).

3.4. *Quantitative comparison among health outcomes*

Standardisation was not possible for all climate and health variables due to a lack of studies available. For those variables with adequate data, the standardisation procedure allowed us to compare different categories directly to assess the relative magnitude of effect sizes. Overall, there was a higher effect of temperature extremes on the risk of preterm birth (Fig. 2a) compared to the risk of respiratory disease (Fig. 2b) or mortality/morbidity (Fig. 2c). Temperature changes caused an average increase in preterm birth of 60 % but this belies high uncertainty and variability across studies.

However, 8 of the 27 (30 %) studies for which an odds ratio of effect of temperature change on preterm birth risk could be calculated indicated no effect (lower confidence limit overlapping or near 1; Fig. 2a). For the risk of respiratory disease from exposure to temperature extremes, at least 6 of the 14 (43 %) studies with comparable data indicated no effect (Fig. 2b), and 18 of the 32 (56 %) studies assessing the effects of temperature extremes on the risk of morbidity/mortality

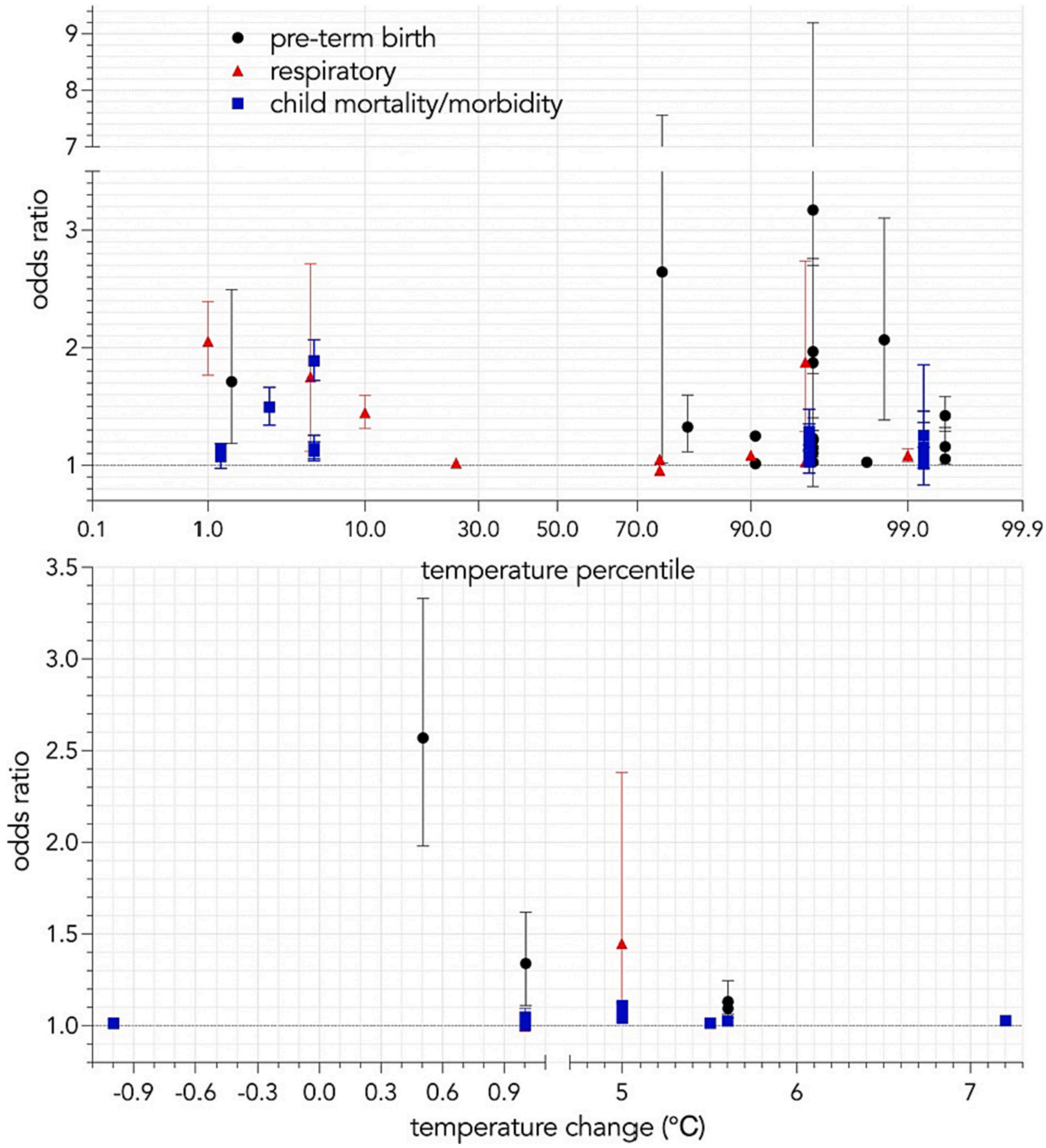

Fig. 3. Odds ratios of preterm birth, respiratory disease and mortality/morbidity against temperature percentiles and average temperature increases.

indicated no effect (Fig. 2c). For the latter, there was no discernible difference in the odds ratio combined for different categories of age (children *versus* all ages) or outcome (mortality *versus* morbidity) (Fig. 2c, 4 category combinations at the top of the graph).

When we examined the relationship between effect size (odds ratio) and either the percentile change (Fig. 3, top panel) or absolute magnitude (Fig. 3, bottom panel) of temperature change, there was no discernible relationship for any health outcome category (Fig. 3). One might expect a U-shaped relationship for the temperature percentile relationships, where extreme cold or extreme heat would be expected to increase the risk of the health outcome in question, but the data were too variable and there were not enough results available for mid-range temperatures to test this hypothesis (Fig. 3a). Neither did increasing magnitudes of temperature increase effect sizes, mainly given the lack of sufficient sample size to detect a trend (Fig. 3b). This might suggest that either the data are currently insufficient to explore this relationship adequately, or that the severity of temperature extremes, such as a 99th *versus* 97th percentile extreme, does not affect the severity of disease.

The odds ratios for the effects of different air pollutants on health outcomes were smaller than for temperature effects, but with most (16/20 = 80 %) studies indicating at least a weak effect (Fig. 4).

While the odds ratios were on average slightly higher for respiratory disease compared to perinatal outcomes, the range of effect sizes were approximately the same for both categories (Fig. 4). When we combined the different outcomes by air pollution variable (irrespective of health outcome measured), there was a higher impact of NO_x pollution on health compared to any particulate matter- or SO_x-focussed studies, although sample sizes were consistently small (Fig. 5). More studies examining the impact of specific air pollution species on health outcomes are needed to determine which air pollution species pose the greatest threat to child health and which sources of air pollutants are most dangerous. Appendix 8 and Fig. A4 provide additional details of studies examining other health outcomes not summarised above.

Local climate and socioeconomic factors are important to consider when exploring health-climate relationships. Most studies included in the meta-analysis explore populations in the Northern Hemisphere (84.5 %). Fifty-six percent of these studies were done in high-income nations/regions, 39 % in upper-middle income nations/regions, 2 % in lower-middle income nations/regions, and 2 % in low-income nations/regions. There is no obvious clustering of studies geographically by intensity of effect (odds ratio) or health measure (Fig. 6).

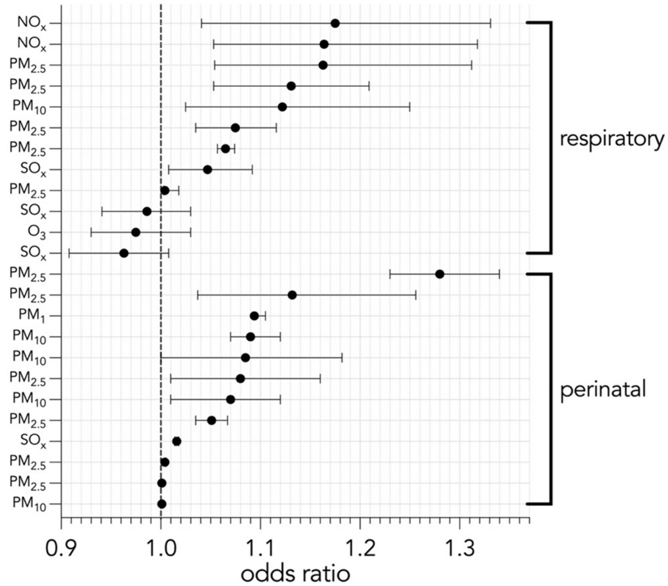

Fig. 4. Air pollution studies and their main measured variable ranked by median odds ratio for the health outcomes of increased risk of respiratory disease or perinatal outcomes.

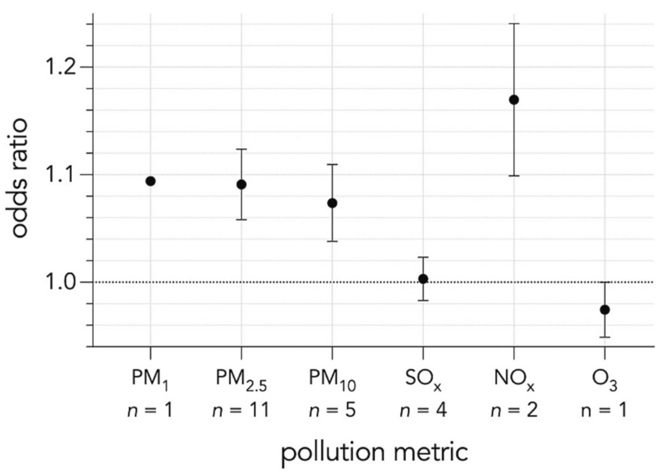

Fig. 5. Studies examining the influence of air pollution on respiratory and perinatal outcomes combined by pollutant type (pooled odds ratios). n = number of studies.

4. Discussion

We found clear evidence for many relationships between various climate-change variables and different measures of child health in our review, despite considerable variation and inconsistences among the studies we assessed (summary of relationships; Appendix 9). Most studies examined climate effects on perinatal (largely preterm birth), respiratory, and mortality/morbidity child health outcomes, with temperature and airborne pollutant most explored. After standardisation, the effects of temperature changes on preterm birth were strongest, followed by respiratory outcomes, and then mortality/morbidity (Fig. 2). However, we did not observe any relationship between the magnitude of temperature changes and health outcomes given the high variability among studies and the low sample sizes. The impact of air pollution on both respiratory and perinatal disease was substantial. Temperature extremes and air pollution had the largest effect on child disease. This is important to consider in the broader literature, where several studies have explored the synergistic effects of these two variables on diseases (Xiao et al., 2023). While the synergies between temperature and air pollution, among other climate variables, can worsen health outcomes such as preterm birth, more research is needed to quantify the breadth of interactions between multiple climate variables and how this manifests as human disease (Anenberg et al., 2020; Sun et al., 2020; Xiao et al., 2023).

Several general patterns emerge: (*i*) the degree to which climate affects child health is highly variable, with many idiosyncrasies among studies complicating direct comparison, (*ii*) studies often omit the raw data from which their reported results were derived, (*iii*) the variables examined were not consistent among studies in the same field, (*iv*) despite the high variance, child health will worsen as climate change progresses.

We identified several limitations rendering among-study comparisons difficult or impossible. Among the 110 studies examining temperature effects on health outcomes, the most common (n = 15) climate metric was exposure to a temperature extreme >95th percentile of average temperature. To increase comparability, we recommend that studies should present as many different climate metrics as possible, including absolute magnitude of change, percentiles, and baseline (control) probabilities of the health outcome under study. To illustrate, a cohort study examining the impact of heatwaves/temperature extremes on preterm birth should ideally define the 90th, 95th and 99th percentiles of average temperature, and what these percentiles equate to in terms of degree-increase above the mean. This not only expands the scope and applicability of the study, it strengthens the review and meta-analysis. Studies should also present their raw data in the final publication or make them otherwise accessible (Aguinis et al., 2021). We recommend that future studies select their variables so that they align with other published studies; this would strengthen the meta-analysis and form a stronger and more cohesive body of evidence. Tables 2 and 3 presents the commonly examined variables for both climate and health measurements for reference.

We faced limitations in this systematic review regarding how studies reported their methodology and results. Large variability in reporting standards made it difficult to extract and standardise data from many of the studies. Well-established recommendations and guidelines for reporting observational studies already exist (Ghaferi et al., 2021). Our risk of bias assessment using the OHAT risk-of-bias tool identified that the domains with the largest risk were attrition and confounding biases. However, there was no relationship between a study's odds ratio and the relative risk (Appendix 5, Fig. A2), despite many studies not clearly reporting the number of participants and outcome data (as in STROBE checklist items 13–16) (STROBE statement, 2023). Data used to adjust for confounders were also often not reported. As such, we recommend clear publication of data (within the ethical boundaries) used for analysis in observational studies or at least a basic description of the cohort characteristics, because this would facilitate more comprehensive and meaningful comparison and meta-analysis. We provide a modified STROBE checklist for observational studies examining climate-health relationships in Appendix 10. Delineating the difference between climate change and extreme weather events is important for devising how the health impacts of climate change are studied. Because the frequency of extreme weather events is influenced by climate change (Stott, 2016), cross-sectional studies examining the health outcomes of these extreme weather events, alongside longitudinal studies, are therefore important for exploring how climate change might influence child health over time. Another limitation we faced was the lack of adequate data for several relationships, such as the impact of air pollution on child mental health, required for inclusion in the meta-analysis. These relationships have been explored more broadly by other reviews (Arpin et al., 2021).

Our review covers a broad scope of both climate changes and child health outcomes, but different elements of the global human population will face unique climate challenges that will be expressed in different ways. Considering the specific climate threats that a society will face

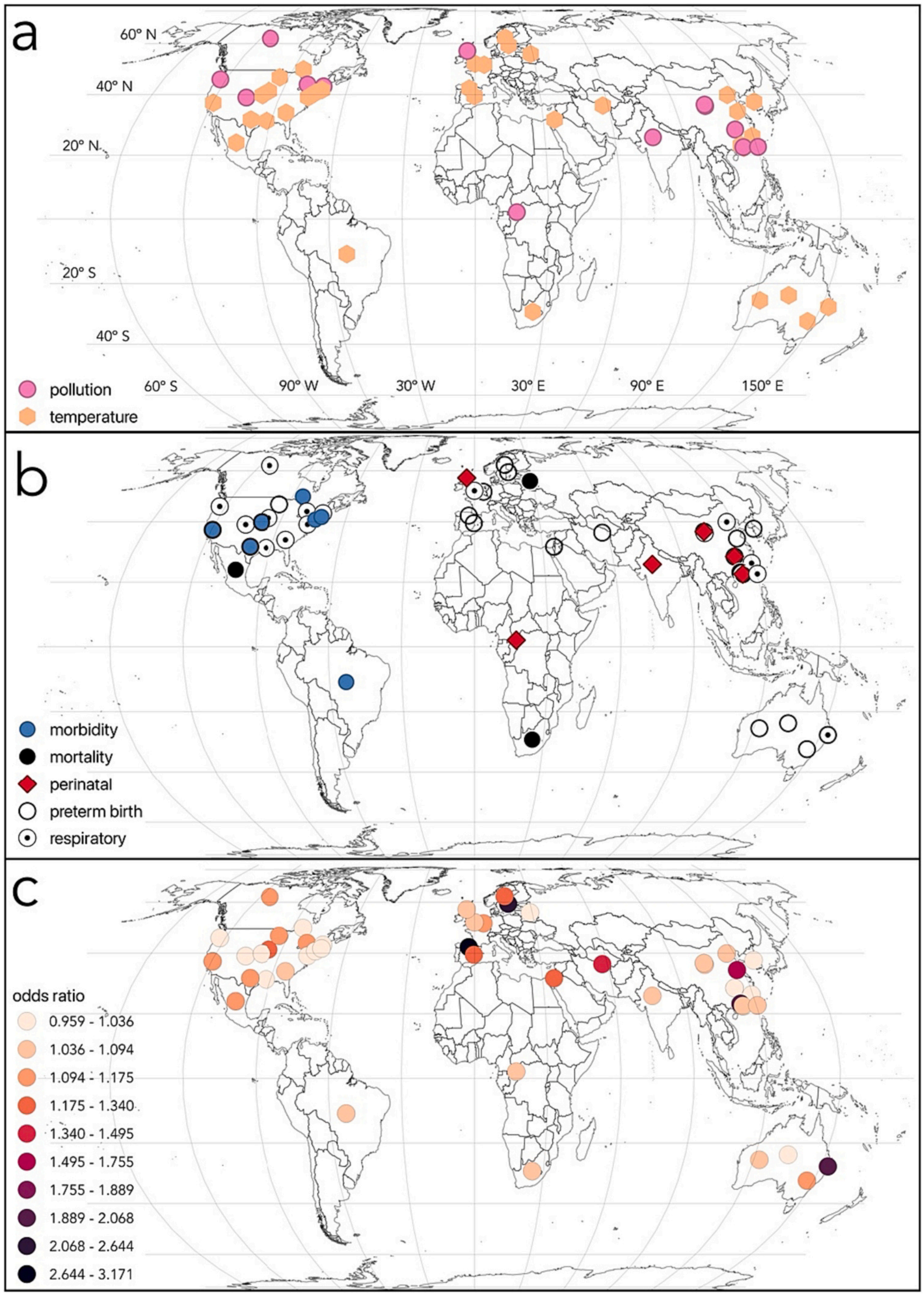

Fig. 6. Distribution of results of studies included in the meta-analysis. Studies graphed by (a) climate variable, (b) health outcome, and (c) odds ratio.

should lie at the crux of how policies are created to improve healthcare, infrastructure, and environmental sustainability. Fig. 7 outlines the major threats climate changes pose to child health based on the evidence we report here. The severity of child disease is influenced by the moderating factors described in Fig. 7 — socio-economics, local climate, access to healthcare, quality infrastructure, and local geography, among other broader determinants of health, play an integral role in determining how a child's health will react to a climate stressor. The spatial analysis in the Results (Fig. 6) identifies that lower-middle- and low-income nations/regions only contribute to 4 % of the studies in the meta-analysis. This biased spatial coverage limits the generalisability of the meta-analysis in these nations, but concomitantly highlights that more studies are needed to determine the impacts of climate change on child health in low-income nations. Population- and climate-specific studies are therefore required to quantify and predict the magnitude of these threats, which will enable health authorities to identify the most relevant current and future health threats their populations face. Several climate variables can work synergistically to worsen or alleviate the severity of diseases (Anenberg et al., 2020; Sun et al., 2020). As such, the impacts of changing climate variables should not be evaluated in isolation.

The high variability in results across studies coupled with a lack of research in many fields of climate-related threats to child health exposes gaps in the literature. Future research that provides more accurate insight into these areas (*e.g.*, nutritional status, atopic diseases, renal disease, and diabetes) is therefore needed, with studies identifying modifiable confounding factors that alter how specific climate changes affect child health valuable for informing realistic change.

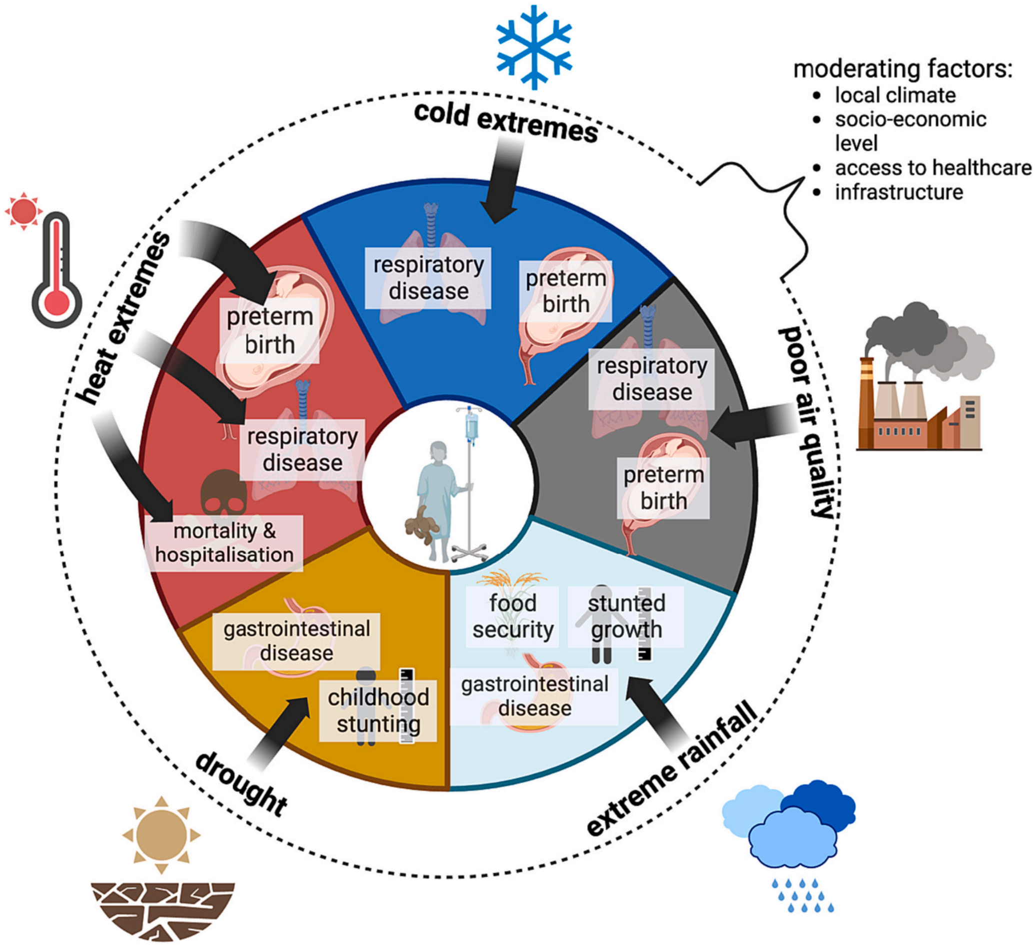

Fig. 7. Main findings of the systematic review regarding relationships between climate change and child health with pertinent, but not exhaustive, moderating factors. Arrow width indicates relative effect size. There are many additional relationships explored in this systematic review and meta-analysis beyond those depicted.

Action is required to protect children from climate-related disease burden, and our review recognises some important areas where children are most vulnerable to climate change. Children in lower- and middle-income countries and those without access to healthcare, adequate infrastructure, and a stable food network are the most vulnerable, yet most studies have been done in wealthy nations and regions. The severity of impacts we determined from our meta-analysis should therefore be considered conservative. Health inequity will also worsen as climate change progresses unless global responsibility for climate mitigation increases over the next decade or so. Actions needed to support vulnerable children align with many of the United Nations Sustainable Development Goals, such as zero hunger, good health and well-being, clean water and sanitation, decent work and economic growth, sustainable cities and communities, responsible consumption and production, and climate action (United Nations Sustainable Development Goals 2, 3, 6, 8, 11, 12, 13) (United Nations Development Programme, 2023). Global partnerships for these goals are therefore essential in ensuring the current and future health of children.

Children are the most vulnerable demographic facing the sequelae of climate change (Philipsborn and Chan, 2018). Our systematic review summarises and synthesises the current evidence regarding the impacts of a broad range of climate changes on child health. Despite the high variability among studies in this field, our study shows that children are already affected by climate change. Increased preterm birth, more respiratory disease, higher mortality, and more children in hospital are but a few of the health problems societies will face as climate change worsens. Some health outcomes, such as preterm birth, will result in lifelong complications and costs. Several studies have shown that diseases that are affect by climate change, such as preterm birth and asthma, can incur financial costs to the health sector (Nørgaard et al., 2021; Shea et al., 2020; Stowell et al., 2022). The cost of wildfire-associated smoke on asthma has been estimated to as much as US$1.5 billion due to a single fire season in the future (Stowell et al., 2022). Another study (Shea et al., 2020) estimated costs of a single case of childhood asthma up to US$23,573. Given that climate influences childhood disease, the social and financial costs will continue to rise as climate change worsens, placing increasing pressure on families and health services.

Progress in research into protecting current and future children from climate change's adverse effects must be made. Better standardisation of variables and consideration of confounders will enable more accurate climate- and population-specific projections of climate-related child health threats. Generation of successful counter measures to protect children will also require knowledge of the causal pathways and mechanisms that underpin relationships between climate change and child health. Little is known of these at present. The development of public health policies to counter these climate-related diseases, alongside efforts to reduce anthropogenic climate change, must be addressed if we are to protect current and future children. Finding solutions and implementing climate adaptation and mitigation policies would positively impact multiple United Nations Sustainable Development Goals (United Nations Development Programme, 2023). Climate change is universal and adversely affecting all countries and people, and thus local and global partnerships must be formed to prepare societies for current and future child health threats.

CRediT authorship contribution statement

Lewis J.Z. Weeda: Writing – review & editing, Writing – original draft, Visualisation, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation. **Corey J.A. Bradshaw:** Writing – review & editing, Visualisation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Melinda A. Judge:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualisation. **Chitra M. Saraswati:** Supervision, Methodology, Investigation, Data curation, Conceptualisation. **Peter N. Le Souëf:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualisation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170944.

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