Climate change and population health in Singapore: a systematic review

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Summary
Gaseous emissions have contributed to global warming, an increase in the frequency of extreme weather events and poorer air quality. The associated health impacts have been well reported in temperate regions. In Singapore, key climate change adaptation measures and activities include coastal and flood protection, and mitigating heat impacts. We systematically reviewed studies examining climate variability and air quality with population health in Singapore, a tropical city-state in South-East Asia (SEA), with the aim to identify evidence gaps for policymakers. We included 14 studies with respiratory illnesses, cardiovascular outcomes, foodborne disease and dengue. Absolute humidity (3 studies) and rainfall (2 studies) were positively associated with adverse health. Extreme heat (2 studies) was inversely associated with adverse health. The effects of mean ambient temperature and relative humidity on adverse health were inconsistent. Nitrogen dioxide and ozone were positively associated with adverse health. Climate variability and air quality may have disease-specific, differing directions of effect in Singapore. Additional high quality studies are required to strengthen the evidence for policymaking. Research on effective climate action advocacy and adaptation measures for community activities should be strengthened.

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Introduction
Increasing population density, urbanization, industrialization and emission of greenhouse gases, changes in precipitation, temperature, and increases in carbon dioxide levels have led to climate change globally.[1] Climate change has contributed to an increase in the frequency of extreme weather events such as heatwaves, wildfires, floods, and droughts which affects the food, air quality, water quality, and shelter that people depend on.[2]

Global average temperature has risen by 1.2 °C above pre-industrial times and this has increased the risk of heat driven mortality. Approximately 296,000 deaths due to high temperatures were reported in the year 2018.[2] Assessment reports from the Intergovernmental Panel on Climate Change (IPCC) in 2007 and 2023 concluded that human-induced global warming has spurred changes to the earth's climate which have severely impacted people as well as ecosystems over the years and future health risks are expected with every fraction of a degree of warming of the earth.[3,4]

Climate change impacts health through an increased risk of exposure to a higher frequency and intensity of heat waves, an increased frequency of floods and droughts, changes in the distribution of vector populations and thus vector-borne diseases and the adverse effects of disasters and malnutrition.[5] Globally, ambient temperature change was found to be associated with increased mortality risk from myocardial infarction, myocardial infarction hospitalization, and ischemic stroke.[6] Both heat exposure and cold exposure were

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associated with higher risk of myocardial infarction hospitalization while heat waves were associated with a higher risk of myocardial infarction mortality.[7] Acute temperature increase was associated with increased risk of ischemic stroke.[6] A systematic descriptive review on the impact of climate change on mental health found 163 studies that examined climate change and extreme weather and their association with classical psychiatric disorders such as anxiety, schizophrenia, mood disorder and depression, suicide, aggressive behaviours, and despair for the loss of usual landscape.[8]

Air pollution and climate change have a common driver—gaseous emissions from anthropogenic activities. Air pollution is estimated to cause 7 million premature deaths annually and a substantial loss in healthy years of life. In South-East Asia (SEA) where approximately 10% of the world's population resides, air pollution from transboundary haze as a result of land fires is a health concern. Rainfall, which is common in the tropics, may reduce the intensity of air pollution through wet deposition. During El Niño events however, air pollution from such fires are expected to exert worse outcomes because of drier weather conditions.

In SEA, increased average temperature has led to increased transmission of vector-, water-, and mosquito-borne diseases (such as malaria and dengue), heat stress, air pollution, and extreme weather events such as cyclones and floods that cause cholera and other diarrheal diseases,[9] and higher temperatures have been linked to an increased risk of mortality.[10] Dengue cases in the SEA region increased by 46% (from 451,442 to 658,301) from 2015 to 2019,[11] corresponding to an increase in average annual temperatures in the region from 26.2 °C to 26.4 °C over that time period.[12] The slight increase in temperature may have increased the biting frequency of *Aedes* mosquitoes, reduced the extrinsic incubation period of the dengue virus and partially contributed to the rise in cases.

Singapore is located in SEA near the southern tip of the Malay Peninsula. It has one of the highest population densities in the world with a land area of 700 km^2 and a population density of 8358 per km^2.[13] Singapore is a developed nation, with the highest Human Development Index (HDI) in Asia of 0.938 according to the United Nations Development Programme.[14] Climate extremes of high rainfall and hot weather characterize the climate of Singapore all year round.[15] The El Niño Southern Oscillation (ENSO) plays a significant role in influencing climate variability in Singapore. In the last 30 years, Singapore has lost 90% of its forest, 67% of its birds, and 40% of its mammals. This decline in natural areas, rapid and extensive urbanization, high humidity and the heavy reliance on air conditioning has resulted in the warmer temperatures across the country.[14,16]

From 1980 to 2020, the annual mean temperature in Singapore increased from 26.9 °C to 28.0 °C and rainfall has increased at an average rate of 67 mm per decade.[17] The increase in temperature and humidity spurred by climate change has led to an increase in incident cases of dengue,[18] salmonellosis,[19] diarrheal disease,[20] and heat-related illness[21] in the past two decades. Between 71 and 124 people in Singapore were admitted to hospital for heat-related illnesses each year from 2010 to 2020,[22] although the burden of such illnesses was likely underreported due to unrecognition and misclassification. The anticipated rise in ambient temperatures may result in a great number of such illnesses if present heat-mitigation measures remain the same.

A recent survey found that over 90% of Singapore residents were aware of climate change and its impact. Close to 80% were prepared to do more, including supporting Singapore's move to a low carbon economy even if they were expected to bear additional costs and inconvenience as consumers.[23] Another survey found that Singapore residents were found to be less aware about the carbon impact of food purchases.[24] Overall, climate action appears to be lacking in Singapore residents, adopting green practices only when it is convenient and affordable to them.

Singapore contributes to around 0.1% of global greenhouse gas emissions.[25] Since 2007, the Inter-Ministerial Committee on Climate Change (IMCCC) has coordinated policies and responses across government to tackle climate change. In 2008, the Singapore Index on Cities' Biodiversity was launched at the eighth Conference of the Parties to the Convention on Biological Diversity and has since been used by many cities around the globe to increase their capabilities in biodiversity conservation and for determining key priorities for conservation actions.[26] In 2019, Singapore formed the urban heat island (UHI) Workgroup (UHI WG) comprising infrastructure and public health agencies to coordinate whole-of-government efforts to study and mitigate UHI effects.[27] The multi–ministry Singapore Green Plan 2030, launched in 2021, is part of the government's continuous effort to set clear long-term directions for Singapore's sustainable development, and rally all parts of society to achieve the ambitious targets.

Under its Resilience Working Group (RWG), Singapore identified and reported seven key adaptation risk areas in its first Adaptation Communication in the 5th National Communication and Biennial Update Report: (i) sea level rise and flood resilience; (ii) water sustainability; (iii) safeguarding biodiversity and greenery; (iv) resilience in public health and food security; (v) keeping essential services running well; (vi) keeping buildings and infrastructure safe; and (vii) mitigating the UHI effect.[28] The Centre for Climate Research Singapore (CCRS), the Singapore Delft Water Alliance, the Tropical Maritime Science Institute and Earth

Observatory of Singapore provide scientific advice to the government and undertake climate modelling and research studies to contextualise the anticipated impacts for policy making and adaptation planning in Singapore.

The Second National Climate Change Study for Singapore published in 2015 projected that the average surface temperatures across Singapore would increase between 1.4 °C and 4.6 °C for the period of 2070–2099. These projections imply that the increasing frequency of warmer temperatures and record highs in Singapore could become the norm in the future.[29] An increase in climate change-driven mean temperatures and humidity may lead to increasing thermal discomfort and heat stress, and exacerbate adverse population health outcomes.

Although current literature suggests that climate change is likely to be associated with worse human health outcomes, the geographical contribution to the overall evidence is skewed, with the European region and the United States providing the most in climate change and health related literature.[30] In this paper, we aimed to conduct a systematic review to examine published literature on climate and air quality driven health outcomes in Singapore, and to discuss mitigating strategies.

Methods

Registration information

This systematic review and protocol was not registered.

Research question

Our systematic review, which follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines,[31] aimed to answer the question, "Among the general population in Singapore, what effect does exposure to climate and air quality variability have on population health?" We used the Population, Exposure, Comparator, and Outcomes (PECO) statement (Table 1) to guide our study inclusion criteria.

Search strategy

For this review, we conducted a comprehensive search of the literature in PubMed and Web of Science. The keywords were 'respiratory', 'cardiovascular', 'Salmonellosis', 'dengue', 'diarrheal', 'HFMD', 'vector-borne disease' or 'foodborne disease' for population health outcome terms, paired with the following exposure terms: 'climate', 'weather', 'temperature', 'heatwave', 'heat', 'rainfall', 'precipitation' or 'humidity, or with the following air quality terms: 'air quality', 'air pollution', 'particulate matter', '$PM_{2.5}$', 'PM_{10}', 'nitrogen dioxide', 'sulphur dioxide', 'carbon monoxide' or 'ozone'.

Inclusion and exclusion criteria, and data extraction

We restricted our research to human studies conducted in Singapore from 1 January 2000 to 23 July 2023. We considered only studies that were reported in English. We subsequently updated our search to 19 Sep 2023 in order to incorporate studies that were published before our article completed its final peer review. We only included original, peer reviewed studies that reported the quantitative association using epidemiological measures of effect (i.e. relative risk, odds ratio, hazard ratio or their equivalents) between population health outcomes and climate exposures or air pollutant exposures. We excluded studies that were reviews, research letters or commentaries. Details of each eligible study including author, publication year, location, study period, study design, measures of effects and their uncertainty intervals and study findings, were extracted and populated into Endnote. We included single-, multi-centre and national-level studies. Two reviewers (JA and LA), working independently, selected studies before reviewing them to obtain the penultimate list. All authors reviewed the final list of studies to be included. The studies were classified by exposures and full-text screening was conducted to confirm that the PECO statement, inclusion and exclusion criteria were met. Any discrepancies were resolved through a third reviewer (SWJ). We grouped the measure of effect from individual studies by category of exposure (climate variability or air pollution) and visualized them using forest plots.

Quality assessment

To assess the impact of study quality on our review conclusions, we conducted a risk of bias assessment (RoB) for each included study for the following domains: exposure assessment, outcome assessment, confounding, selection bias, incomplete data, selective reporting, conflict of interest, and other sources of bias. We rated the RoB using the following rating scale: *low,*

PECO element	Evidence
Population	Adults and/or children in the Singapore general population.
Exposure	Ambient temperature, heatwave metrics derived from ambient temperature, humidity, rainfall, PM_{10}, $PM_{2.5}$, sulphur dioxide, nitrogen dioxide, carbon monoxide and ozone.
Comparator	A reference population exposed to lower levels from the Singapore general population.
Outcomes	Any health outcome measured in the exposed population.

Table 1: **Population, Exposure, Comparator, and Outcomes (PECO) criteria.**

probably low, probably high and high. The risk bias assessment tool is in Appendix A1. We did not conduct an assessment of quality or strength of evidence across studies because this review included a wide range of different health outcomes and it was not possible to conduct a meta-analysis with limited studies across different health outcomes. We used Stata 17.0 (StataCorp LLC) and Microsoft Office to produce the figures in this article.

Role of the funding source
There was no funding source for this study.

Results

After removing duplicates, from a total of 1148 records, we reviewed 18 articles in full text and retained 14 (Appendix A2). All 14 were observational, epidemiological time-series or time stratified case-crossover studies that examined the short-term association between environmental stressors and population health outcomes. Study timescales ranged from daily to weekly while population segments included those at the national level as well as single-centre studies.

Health outcomes included respiratory illnesses [acute respiratory illness (ARI), respiratory syncytial virus (RSV), human influenza and human parainfluenza virus (HPIV)], foodborne disease (Salmonella and diarrheal illness), heat-related illnesses (HRI), dengue, hand, foot and mouth disease (HFMD), acute conjunctivitis, stroke and non-ST elevated myocardial infarction (NSTEMI) (Table 2). There was also a single-center study on the effect of air quality on emergency department (ED) admissions.

Environmental stressors included mean ambient temperature, maximum ambient temperature, heatwaves, absolute humidity, relative humidity, rainfall, and air pollutants [sulphur dioxide, nitrogen dioxide, particulate matter equals to or below 2.5 microns ($PM_{2.5}$), particulate matter equals to or below 10 microns (PM_{10}), carbon monoxide and ozone]. Studies which examined climate variability were more consistent in specifying the health-related effects using standard units of measurement (i.e. 1 °C, 1% or 10% relative humidity and 1 mm or 10 mm rainfall). Those which examined air quality had a mixture of different exposure unit measurements (i.e. every 10 $\mu g/m^3$ increase in exposure or exposure levels at specified air quality concentrations), likely owing to the non-linear effects.

Key climate-sensitive health risks

Mean temperature

There was clear evidence of an inverse association between mean temperature and respiratory illnesses such as ARI, HPIV and Influenza A (Fig. 1). However, mean temperature appeared to exhibit a positive relationship with Salmonellosis and diarrheal disease. Higher mean temperature appeared to exacerbate the number of HFMD infections and heat-related illnesses. Lower temperature was associated with an increased risk of NSTEMI episodes. Overall, there appeared to be an inconsistent direction of effect of mean ambient temperature on health outcomes.

Maximum temperature and heatwave

There was clear evidence of an inverse association between extreme heat and health outcomes. Two studies reported a decline for every unit rise in maximum temperature: RSV and dengue infections. Heatwaves were inversely associated with risk of dengue infections (RR: 0.717, 95% CI: 0.608–0.845).

Absolute humidity

There was clear evidence of an association between absolute humidity and health outcomes. Studies reported positive associations between absolute humidity and risk of dengue (RR: 1.206, 95% CI: 1.113–1.306), RSV (RR: 1.170, 95% CI: 1.102–1.242) as well as influenza B (RR: 4.799, 95% CI: 2.277–10.118).

Relative humidity

There were inconsistent associations of relative humidity across the included studies. Among enteric illnesses, relative humidity was positively associated with risk of diarrheal disease and the reverse was true for Salmonella infections. Among respiratory illnesses, ARI exhibited a positive association with relative humidity while HPIV exhibited an inverse association with relative humidity.

Rainfall

Three of four included studies reported a positive association between rainfall and melioidosis (RR_{100mm}: 1.400, 95% CI: 1.000–1.050), HPIV (RR_{10mm}: 1.021, 95% CI: 1.000–1.043), and influenza A (RR_{10mm}: 1.044, 95% CI: 1.017–1.071). One study reported an inverse association between rainfall and HFMD (RR_{10mm}: 0.996 (95% CI: 0.995–0.996), although the strength of association was comparatively small in relation to the effects of rainfall reported in the other included studies.

Key air quality related health risks

Carbon monoxide

Carbon monoxide (CO), which is a product of incomplete combustion that can be generated from sources such as industrial processes, combustion motor vehicles and forest fires, was reported in three separate studies. There were inconsistent effects of CO across included studies (Fig. 2). While CO exhibited a positive association with the risk of stroke (RR: 1.070, 95% CI: 1.040–1.110) and ED admissions (RR: 1.185, 95% CI: 1.170–1.199), an inverse association was observed for the risk of RSV (RR: 0.863, 95% CI: 0.801–0.929).

S/N	Article title	Author and year	Study design, study duration and study generalizability	Conclusions
1	Short term effects of weather on Hand, Foot and Mouth Disease[32]	Hii et al. (2011)	Time-series analysis; 2001–2008; National-level	A strong association between HFMD and weather was found. However, the exact reason for the association is yet to be studied. Information on maximum temperature above 32 °C and moderate rainfall precede HFMD incidence could help to control and curb the up-surging trend of HFMD.
2	Association of melioidosis incidence with rainfall and humidity, Singapore, 2003–2012[33]	Liu et al. (2015)	Time-series analysis; 2003–2012; National-level	Rainfall and humidity levels were associated with disease incidence in Singapore, where soil exposure is rare.
3	Climate variability and salmonellosis in Singapore—A time series analysis[19]	Aik et al. (2018)	Time-series analysis; 2005–2015; National-level	This study confirms the short-term influence of climatic conditions on *Salmonella* infections in Singapore and the potential impact of climate change on Salmonellosis in the tropics.
4	Weather impact on heat-related illness in a tropical city state, Singapore[21]	Xu et al. (2018)	Time-series analysis; 1991–2010; National-level	It is observed that the predicted occurrence rate is close to the observed one. The proposed combined model can be used to predict HRI cases for mitigating HRI occurrences and provide inputs for related public health policy considering climate change impact.
5	The burden of acute conjunctivitis attributable to ambient particulate matter pollution in Singapore and its exacerbation during South-East Asian haze episodes[34]	Aik et al. (2020)	Time-series analysis; 2009–2018; National-level	This study strengthens the evidence linking particulate matter exposure to an increased risk of conjunctival disease, with a disproportionately higher disease burden during South-East Asia transboundary haze episodes. These findings underscore the importance of reducing the health impact of indigenous and transboundary sources of ambient particulate matter pollution.
6	The effects of climate variability and seasonal influence on diarrheal disease in the tropical city-state of Singapore—A time-series analysis[20]	Aik et al. (2020)	Time-series analysis; 2005–2018; National-level	Diarrheal disease is highly seasonal and is associated with climate variability. Food safety and primary healthcare resource mitigation could be timed in anticipation of seasonal and climate driven increases in disease reports.
7	A time series analysis of the short-term association between climatic variables and acute respiratory infections in Singapore[35]	Mailepessov et al. (2021)	Time-series analysis; 2005–2019; National-level	Lower temperatures is associated with an increased risk of ARIs. Anticipated extreme weather events that reduce ambient temperature can be used to inform increased healthcare resource allocation for ARIs.
8	The effects of maximum ambient temperature and heatwaves on dengue infections in the tropical city-state of Singapore—A time series analysis[36]	Seah et al. (2021)	Time-series analysis; 2009–2018; National-level	Extreme heat was associated with decreased dengue incidence. Findings from this study highlight the importance of understanding the temperature dependency of vector-borne diseases in resource planning for an anticipated climate change scenario.
9	Association of air pollution with acute ischemic stroke risk in Singapore: a time-stratified case-crossover study[37]	Ho et al. (2022)	Time-stratified case-crossover study; 2009–2018; National-level	Air pollution increases the incidence of acute ischemic stroke, especially in those with atrial fibrillation and in those who are current or ex-smokers.
10	Ambient air quality and emergency hospital admissions in Singapore: A time-series analysis[38]	Ho et al. (2022)	Time-series analysis; 2009–2017; Single center study	Significant positive associations between respiratory disease- and cardiovascular disease-related emergency hospital admissions and ambient SO_2, $PM_{2.5}$, PM_{10}, NO_2, and CO concentrations were found. Age and sex were identified as effect modifiers of all-cause hospital admissions.
11	Ambient temperature and hospital admissions for non-ST segment elevation myocardial infarction in the tropics[39]	Seah et al. (2022)	Time-stratified case-crossover study; 2009–2018; National-level	Short-term temperature fluctuations were independently associated with NSTEMI incidence in the tropics, with age as a potential effect modifier of this association. An increase in the frequency of climate change driven temperature events may trigger more instances of NSTEMI in tropical cosmopolitan cities.
12	The influence of air quality and meteorological variations on influenza A and B virus infections in a paediatric population in Singapore[40]	Seah et al. (2022)	Time-series analysis; 2009–2019; Single-tertiary center study representing approximately 50% of hospital admissions for children	Different independent associations between air quality and meteorological variability with paediatric influenza A and B infections were observed. Anticipated seasonal infection peaks and variations in air quality and meteorological parameters can inform the timing of community measures aimed at reducing influenza infection risk.
13	Climate variability and seasonal patterns of paediatric parainfluenza infections in the tropics: An ecological study in Singapore[41]	Soh et al. (2022)	Time-series analysis; 2009–2019; Single-tertiary center study representing approximately 50% of hospital admissions for children	An association between human parainfluenza viruses (HPIV) infection risk and tropical climate variability was shown. The climate dependence and seasonal predictability of HPIV can inform the timing of community campaigns aimed at reducing infection risk and the development of hospital resources and climate adaption plans.
14	Air quality, meteorological variability and pediatric respiratory syncytial virus infections in Singapore[42]	Lee et al. (2023)	Time-series analysis; 2009–2019; Single-Tertiary center study representing approximately 50% of hospital admissions for children	A decrease in ambient temperature and increase in absolute humidity exacerbated pediatric RSV infection risk while increases in air pollutant concentrations were associated with lowered infection risk. These meteorological factors, together with the predictable seasonality of RSV infections, can inform the timing of mitigation measures aimed at reducing transmission.

Table 2: **Articles on the effects of weather and air quality on population health outcomes in Singapore.**

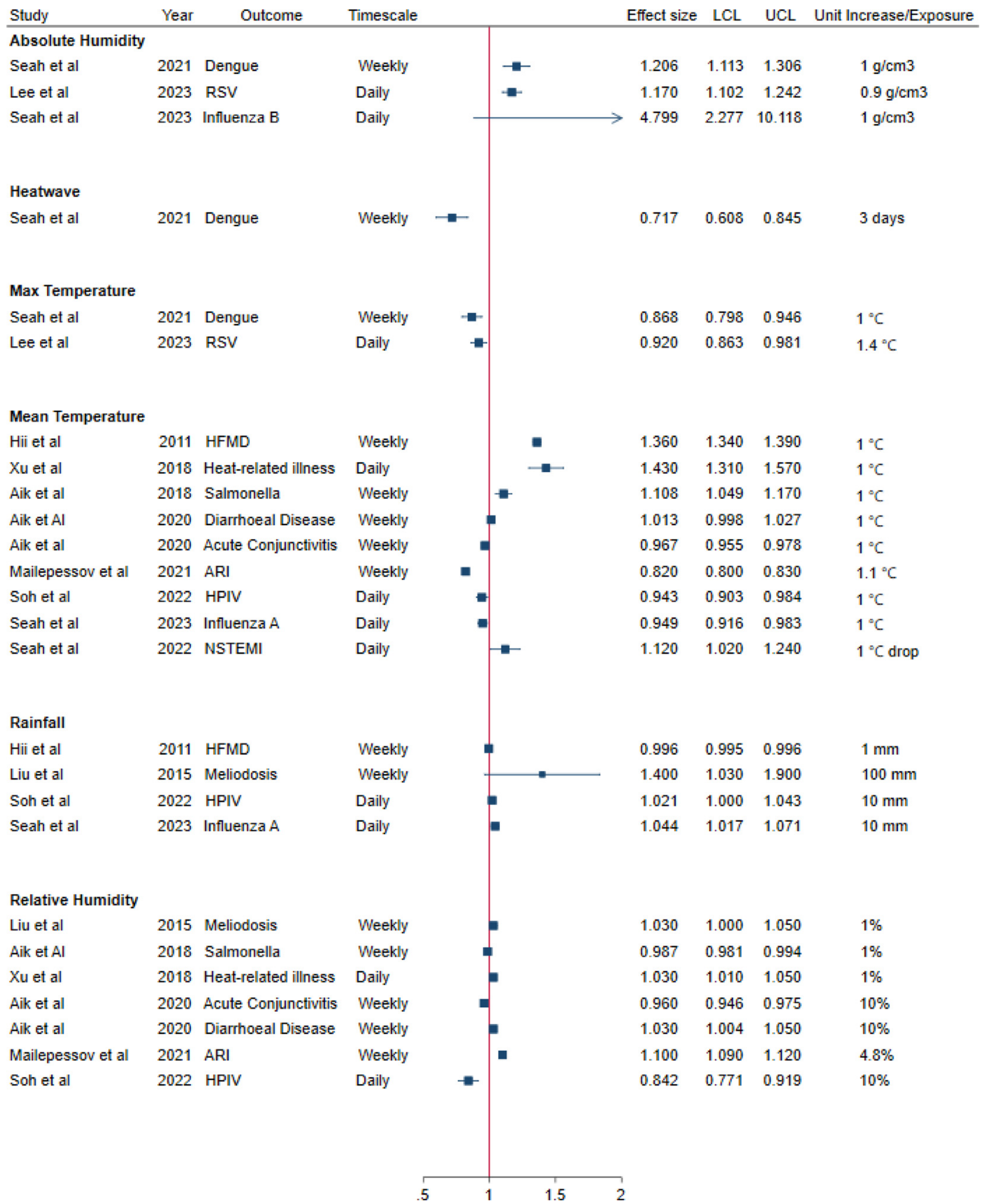

***Fig. 1:* Associations between climate variability and population health outcomes in Singapore, 2000–2023**. The solid navy squares represent the point estimates of the association between the climatic variable and the respective health outcome. The horizontal navy lines represent the 95% confidence intervals for those estimates. The vertical solid red line represents the null effect.

Nitrogen dioxide and ozone

Increases in nitrogen dioxide (NO_2) and ozone were each independently and positively associated with risk of Influenza B and stroke respectively. NO_2 exhibited a positive association while ozone exhibited an inverse association with ED admissions.

$PM_{2.5}$ and PM_{10}

Among all reported air quality effects, those related to particulate matter ($PM_{2.5}$ and PM_{10}) were relatively more common compared to other air pollutants. Particulate matter can be generated from sources such as industrial processes, internal combustion engine

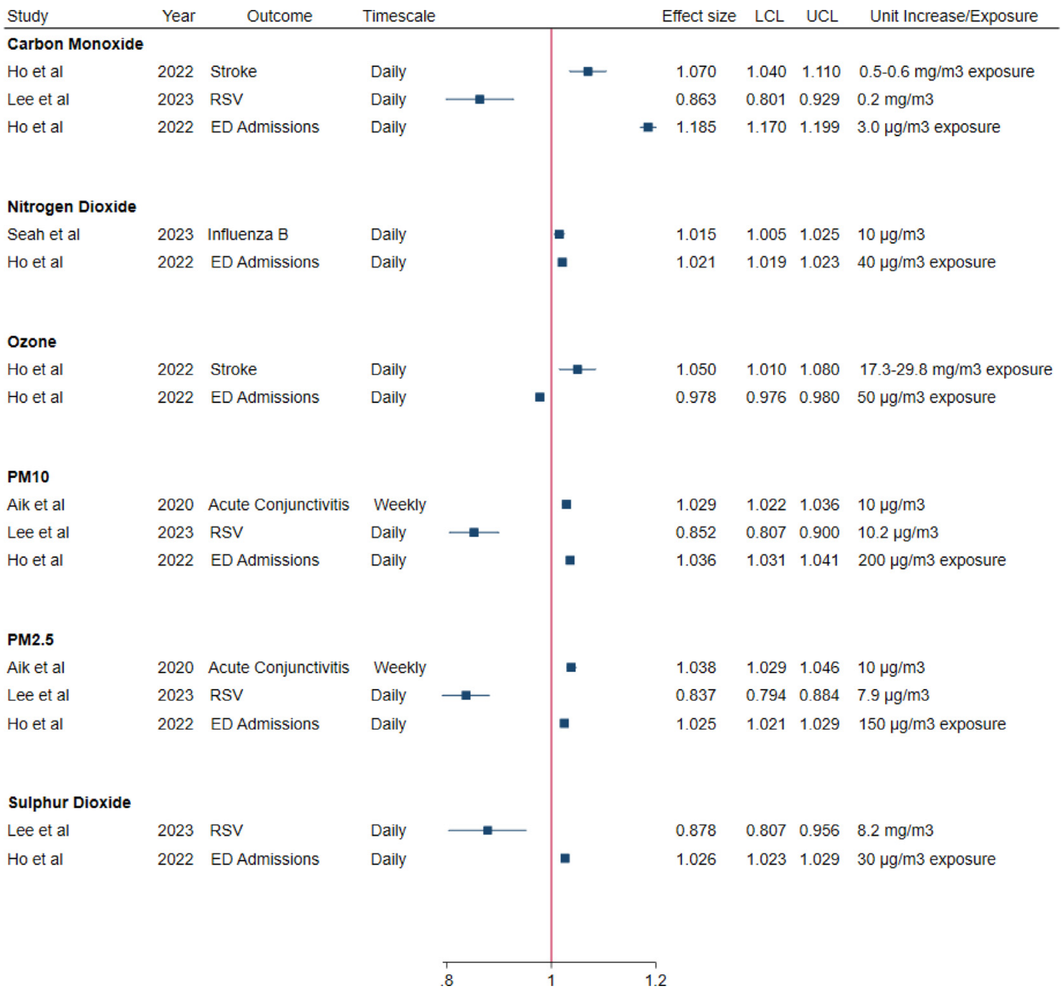

***Fig. 2:* Associations between air quality and population health outcomes in Singapore, 2000–2023**. The solid navy squares represent the point estimates of the association between the air pollutant and the respective health outcome. The horizontal navy lines represent the 95% confidence intervals for those estimates. The vertical solid red line represents the null effect.

vehicles and forest fires. Inconsistent effects of particulate matter on population health were reported. Increases in $PM_{2.5}$ and PM_{10} concentrations were positively associated with acute conjunctivitis, and ED admissions especially at extreme levels during the haze periods while being inversely associated with RSV risk.

Sulphur dioxide

Sulphur dioxide, which can be generated from sources such as petroleum refining, combustion of fossil fuels, industrial processes and volcanic activity, appeared to be positively associated with ED admissions (RR: 1.026, 95% CI: 1.023–1.029) and inversely associated with RSV risk (RR: 0.878, 95% CI: 0.807–0.956).

Risk of bias assessment

Fig. 3 summarises the risk of bias assessment for individual studies. The individual assessments are in Appendix A3. Included studies were rated as “probably low risk” or “low risk” in almost all areas of the assessment. One study was rated “high” for selection bias because it was a single-centre analysis with the majority of admissions likely from a single geographical area. Another study was rated “high” for confounding bias because there was no mention of long-term trend and seasonality being adjusted for.

Discussion

We reviewed evidence of associations between climate variability and air quality with population health in Singapore with the aim of identifying evidence gaps for policymakers. The positive associations between higher absolute humidity and infectious diseases such as dengue, RSV and Influenza B were clear, as were the positive associations between increased rainfall and

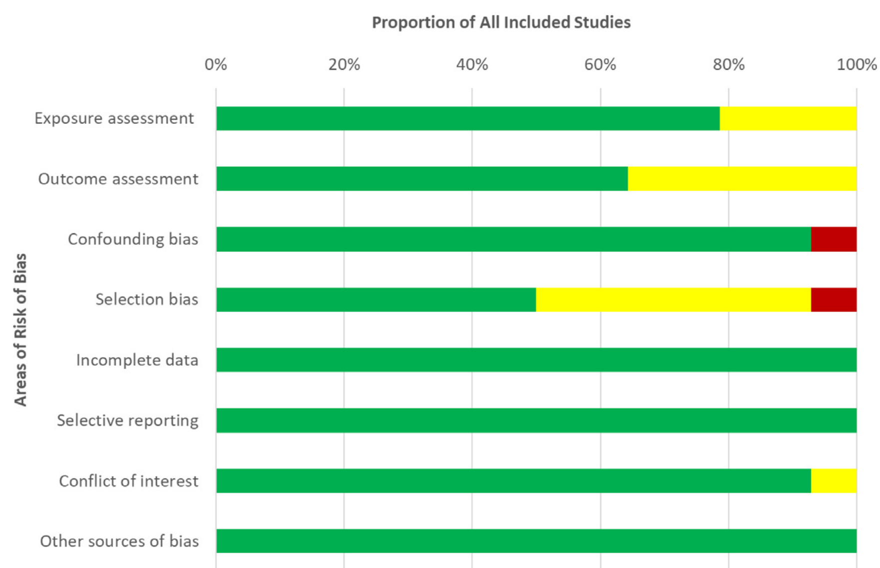

Fig. 3: **Risk of bias assessment summary for individual included studies.**

infectious disease such as melioidosis, HPIV and Influenza A, although the opposite was true for HFMD. We observed inconsistent effects of mean ambient temperature and relative humidity on different population health outcomes, with positive temperature associations related to heat- and enteric illnesses and inverse temperature associations for respiratory illnesses. Higher concentrations of nitrogen dioxide and ozone were associated with a greater risk of Influenza A and stroke respectively. However, inconsistent effects of higher $PM_{2.5}$ and PM_{10} concentrations on population health were reported, depending on the disease.

The associations between air pollutants and health in Singapore were found to be inconsistent. In particular, the protective effect of particulate matter, sulphur dioxide and carbon monoxide on paediatric RSV infections found by Lee et al. was unexpected.[42] One plausible reason cited by the authors was that parents (and consequently their children) might have adopted national guidance to reduce outdoor activities and thus increased their indoor dwelling time to minimise their exposure to higher concentrations of particulate matter. Reducing dwelling time in outdoor settings may have reduced the risk of RSV infections posed by other population segments who were present outdoors. Sulphur dioxide has a virucidal property and this may inactivate aerosolized viruses. Carbon monoxide was hypothesized by the authors to either have aided the resolution of inflammation quickly after viral clearance, thus reducing subsequent risk of infections to others. The mechanisms through which particulate matter, sulphur dioxide and carbon monoxide influences RSV infections may be better understood with more studies.

Despite contributing to about 0.1% of global fossil carbon emissions, the Singapore government has taken significant steps to reduce global warming. Carbon dioxide emissions in Singapore have declined from 9.5 metric tons of carbon dioxide per capita in 1990 to 7.7 metric tons per capita in 2020.[43] Since the early 2000s, Singapore recognised the importance of moving towards cleaner energy sources to reduce its carbon emissions and to improve air quality by shifting from crude oil/coal to natural gas. It signed on to the Powering Past Coal Alliance (PPCA) and has committed to continue phasing out the use of unabated coal by 2050. Even with its land limitations, it has deployed solar energy since 2009, which presently makes up 1% of Singapore's fuel mix. These are complemented sectoral decarbonisation efforts in industry, buildings and transport, such as through the National Hydrogen Strategy, and by ensuring all vehicles run on cleaner energy by 2040 through vehicle electrification that will reduce Singapore's land transport emissions by 80% from its 2016 peak of 7.7 million tonnes by 2050.[44]

Singapore announced in 2022 that it would target to achieve net zero emissions by 2050 as part of its Long-Term Low-Emissions Development Strategy (LEDS) and reduce emissions to around 60 MtCO2e in 2030 after peaking earlier, as part of the revised 2030 Nationally Determined Contribution (NDC).[45] This net zero target will be supported by a carbon tax–the first carbon pricing scheme in Southeast Asia–that will be progressively raised from S$5 in 2019 to S$45 per tonne in 2026–2027, with a view to reaching S$50–S$80 per tonne of CO2e by 2030.[46] Singapore's pathway to net zero will be contingent on the maturity of decarbonisation technologies and being able to effectively access regional and global mitigation opportunities. The Lao PDR-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP), a pathfinder to the ASEAN Power Grid, will allow Singapore to access renewable energy beyond its borders and lead demand in regional decarbonisation.[47]

In this review, temperature was positively associated with heat- and enteric illnesses and inversely associated with respiratory illnesses. The protective effect of maximum temperature and heatwaves on reported dengue infections by Seah et al. was slightly larger compared to other studies conducted in tropical regions.[36] According to the authors, while higher temperatures are associated with a reduction in extrinsic incubation period of the dengue virus (thus mosquitoes become infective more quickly), mosquito survival rates are also lower at higher temperatures, therefore limiting the transmission potential.

Government policies to help the population adapt better to heat effects had previously focused on building design, smart technology and intensifying urban greenery.[48] The Cooling Singapore Project, a research initiative first launched in 2017, provided 86 possible measures in the areas of greenery, urban geometry, water features, material and surfaces, shading, transport and energy to make Singapore's outdoor environment cooler.[49] According to a 2022 survey, the use of air-conditioning as the main mode of cooling homes for Singapore residents has increased.[24] As frequent use of air conditioning is likely to increase utility bills, there is a risk that socio-economically disadvantaged households may experience a higher risk of heat-driven adverse health outcomes if they have no other effective means to adapt to the rising heat. In 2023, the Ministry of Sustainability and the Environment released a Heat Stress Advisory framework based on Wet Bulb Globe Temperature (WBGT) readings to guide community actions during periods of extreme heat.[50] Future studies assessing community knowledge, attitudes and practices would improve the design and focus of community initiatives to reduce the risk of heat-driven adverse health outcomes.

Apart from community initiatives, other strategies to enhance thermal comfort and prevent heat injuries are already being undertaken by the National University of Singapore (NUS) in close collaboration with the Ministry of Manpower (MOM) and Singapore Armed Forces (SAF). One example is the recent inauguration, in January 2023, of the Heat Resilience and Performance Centre at NUS, which will incorporate findings from both laboratory-based and field studies to boost resilience to rising ambient heat in the wider community as well as in military settings. In terms of occupational health, heat stress management is a responsibility of employers under the Workplace Safety and Health (WSH) Act and employers are also required under the WSH (Risk Management) Regulation to conduct risk assessments to address heat stress on workers. Industry standards with regards to occupational heat stress are explicitly covered in the "WSH Council's 2020 Guidelines on Managing Heat Stress at the Workplace".[51] The MOM takes enforcement actions against errant employers through routine inspections of on-site measures and heat related workplace management systems and programmes.

The SAF implemented the WBGT Heat Stress Monitor in 2014 to enhance heat injury prevention. Sim and Lee identified the five pillars of SAF heat safety to be aerobic fitness and conditioning, heat acclimatisation, pre-activity cooling, work-rest cycles, and hydration.[52] These pillars are further supplemented by education of all new SAF recruits, as well as medical officers, commanders and trainers, to better identify the occurrence of heat illness; prohibition of excessive strenuous activities during the hottest part of the day; enforced liquid rehydration beyond the point of thirst; and introduction and development of rapid cooling technology, first in the form of Body Cooling Units (BCU) and later in the form of cooling pad technology.

Heat adaptation measures in Singapore have demonstrated reasonable success. Implementation of the educational, safety and training regulation, and BCU components, correlated with a decrease in exertional heat injury cases, from 200 cases per year on average in the 1990s to an average of 20 cases per year in the 2000s, in spite of increases in ambient temperatures over the same period. Subsequently, commercial cooling pads were introduced in 2016 and are now the routine rapid cooling regimen instituted by SAF. The use of ice slurry for pre-cooling and during-exercise cooling was implemented in 2022, and while its use was first reserved for implementation in specialised SAF groups, such as the commando unit, it has recently been authorised for use by general vocations. Project HeatSafe at the NUS was initiated to understand the complex threat that heat-exposure poses to human health, well-being, and work productivity in Singapore and other tropical countries such as Vietnam and Cambodia; and to identify sustainable preventive policies and population-specific actions that can reduce these impacts.[53]

The majority of studies included in this systematic review were published in the last 5 years while there were hardly any studies from 2000 to 2015. To the best of our knowledge, there were no studies examining the long term impact of climate change on population health. Overall, most studies were rated as low for our risk of bias assessment, although internal population generalisability of future studies ought to be improved. This systematic review which examined the associations between climate variability, air pollution and population health was the first for Singapore with no local antecedent review studies for comparison. The range and quality of published studies examining the effects of environmental stressors on cardiovascular, respiratory, and infectious diseases and other healthcare system-related outcomes such as emergency department visits, ambulance despatches and road traffic accidents at the national level can be expanded for greater generalisability. Greater focus on longer-term studies using population cohorts would also increase the evidence base to support policy implementation. Investigations of the interactive effects of higher temperatures and poorer air quality on population health were absent and are therefore well warranted in future studies.

Study limitations

We did not focus on larger multi-city/country studies which may have included data from Singapore. However, we did specify "Singapore" and the respective environmental exposures in our search terms but did not come across such wider studies that met our inclusion criteria. Our search was limited to the published peer review literature and the English language. This may have led to a degree of selection bias in our study findings. Due to insufficient studies, we were not able to carry out a meta-analysis. Future systematic reviews for Singapore can include this analysis when there is sufficient data.

Conclusion

In Singapore, environmental epidemiology research has increased in recent years and this has contributed to a better understanding of how climate change and air quality will influence population health. The influence of climate variability and air quality on population health in Singapore had different directions of effect that were specific to health outcomes. More high quality studies are required, especially those that utilize data with greater internal generalizability. While Singapore has a comprehensive set of climate mitigation and adaptation policies, these are typically targeted at mitigating direct impacts of climate change and its related economic costs. Many health outcomes are impacted by various factors in addition to climate change, therefore the development of meaningful indicators which directly correlate climate change to health outcomes to guide policy making remains difficult. The focus on policies to manage overall health indicators and outcomes as opposed to policies specifically targeting climate-induced health risks may be prudent. Research into effective adaptation measures for community activities in Singapore is still in its infancy, and more work must be done to determine effective adaptation strategies for diverse segments of the population.

Contributors

JA, SHG, CT and LA reviewed the literature. JA compiled the figures. JA and LA reviewed the search criteria and studies for inclusion, and completed the data extraction. JA and LA conducted the RoB assessment. JA, SHG, CT and LA wrote the first draft of this review. JA, JKWL and SWJ reviewed and edited the manuscript. All authors reviewed the final list of included studies, contributed to the structure and ideas presented in this manuscript, and reviewed and approved the final version. The corresponding author had final responsibility for the decision to submit for publication.

Data sharing statement

This study used pre-existing data from PubMed and Web of Science which is publicly accessible to anyone with internet access.

Declaration of interests

We declare no competing interests.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.lanwpc.2023.100947.

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