PLOS CLIMATE

RESEARCH ARTICLE

Lethal heatwaves are challenging India's sustainable development

Ramit Debnath[1,2]*, **Ronita Bardhan**[3], **Michelle L. Bell**[4]

1 Cambridge Zero, University of Cambridge, Cambridge, United Kingdom, **2** Division of Humanities and Social Science, California Institute of Technology, Pasadena, CA, United States of America, **3** Department of Architecture, University of Cambridge, Cambridge, United Kingdom, **4** School of the Environment, Yale University, New Haven, CT, United States of America

* rd545@cam.ac.uk

OPEN ACCESS

Citation: Debnath R, Bardhan R, Bell ML (2023) Lethal heatwaves are challenging India's sustainable development. PLOS Clim 2(4): e0000156. https://doi.org/10.1371/journal.pclm.0000156

Editor: Bidhubhusan Mahapatra, Norwegian Refugee Council, JORDAN

Received: September 1, 2022

Accepted: March 12, 2023

Published: April 19, 2023

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pclm.0000156

Data Availability Statement: The materials and data used in this paper are based on the Government of India's public repository, available at the National Data \& Analytics Platform (NDAP) {https://ndap.niti.gov.in/}.

Abstract

Due to the unprecedented burdens on public health, agriculture, and other socio-economic and cultural systems, climate change-induced heatwaves in India can hinder or reverse the country's progress in fulfilling the sustainable development goals (SDGs). Moreover, the Indian government's reliance on its Climate Vulnerability Index (CVI), which may underestimate the impact of heatwaves on the country's developmental efforts. An analytical evaluation of heat index (HI) with CVI shows that more than 90% of the country is at extremely cautious or dangerous levels of adversely impacting adaptive livelihood capacity, food grains yield, vector-borne disease spread and urban sustainability. The results also show by examining Delhi's urban heat risk that heatwaves will critically hamper SDG progress at the urban scale. Linking HI with CVI identifies more of India's vulnerability and provides an opportunity to rethink India's climate adaptation policies through international cooperation in designing holistic vulnerability assessment methodologies. The conclusion emphasizes the urgent need to improve extreme weather impact assessment by combining multiple layers of information within the existing climate vulnerability measurement frameworks that can account for the co-occurrence and collision of climate change events and non-climate structural SDG interventions.

Introduction

April 2022 in India was the hottest in 122 years and followed the hottest March on record, reportedly killing at least 25 people [1, 2]. The cumulative heatwave-related mortality in India is over 24,000 deaths since 1992 [3]. Moreover, the heatwave in the Indian subcontinent has had critical impacts on a broad range of interconnected systems of the built environment, health, etc., including frequent and more extended power outages, an increase in dust and ozone levels leading to spikes in air pollution and accelerated melting of glacier snow in the northern regions. At the same time, economic recovery from the Covid-19 pandemic is further hampering the response to the ongoing lethal heatwave [2, 4]. Thus, such heatwaves' public health and economic burdens are incredibly high.

Long-term projections indicate that Indian heatwaves could cross the survivability limit for a healthy human resting in the shade by 2050 [5, 6]. Moreover, they will impact the labour

Funding: This work was supported by the Bill and Melinda Gates Foundation (OPP1144 to RD), Laudes Foundation (G111269 to RD), the Quadrature Climate Foundation (01-21-000149 to RD), Keynes Fund, Faculty of Economics (JHVH to RD and RB), and the Africa Albarado Grant (G115009 to RB). RD received salary from the Quadrature Climate Foundation, the Laudes Foundation, and the Keynes Fund. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

productivity, economic growth, and quality of life of around 310–480 million people [6]. Estimates show a 15% decrease in outdoor working capacity (i.e., working outdoors in high temperatures, e.g., construction worker) during daylight hours due to extreme heat by 2050 [5]. Furthermore, a Lancet Report projected heatwaves will intensify from these 2050 baseline estimates, affecting around 600 million Indians by 2100 [7]. The increased heat is expected to cost India 2.8%, and 8.7% of its Gross Domestic Product (GDP) and depressed living standards by 2050 and 2100, respectively [5, 8]. Furthermore, a recent report by the World Meteorological Organization demonstrated the interconnections between lethal heatwaves and the Sustainable Development Goals (SDGs), implying that global mean surface temperature rise will affect all the 17 SDGs [9]. The impact of heatwaves on sustainability transition is especially concerning for India as the country is yet to achieve its developmental goals, despite recent strides in its self-reported SDG India Index (2020–21) [10].

India is currently facing a collision of multiple cumulative climate hazards co-occurring due to its size, urbanisation rate, and biophysical characteristics, significantly influencing the hydrological cycle and consequently affecting the behaviour of climate extremes [11]. In 2022 from January to October, India recorded 242 of 273 days of extreme weather events, making it nearly one extreme event daily. These include co-occurrence of extreme heatwaves and cold-waves in the north and western parts, drought in central India [12], and high flooding in the coastal plains along with landslides in north-eastern region [12, 13]. By 2100 India will have more frequent precipitation and consequent floods, cyclonic storms, warming, heatwaves, and sea-level rise concurrently. To comprehensively understand India's climate vulnerability, a cumulative representative index is imperative that accounts for the co-occurrence and collision of climate events. At present, India assesses its climate vulnerability through a national Climate Vulnerability Index (CVI), designed by the federal government's Department of Science and Technology [14], based on the Intergovernmental Panel on Climate Change (IPCC)'s SREX framework. The concept of vulnerability used by the Government of India is adopted from the IPCC AR5 [15] where it is conceptualised as an 'internal property of a system' that represents the propensity or predisposition of the system to be adversely affected, independent of hazard and exposure [15]. The CVI is a composite index that uses various indicators to account for India's socio-economic features and livelihood, biophysical, institutional and infrastructural characteristics (see Table 2, pp. 11–12 in [14]). These indicators were further mapped to related SDG indicators [16], as presented in Table 1. The mapping of the CVI indicators with the SDG was performed based on (i) key domain of impact, (ii) keywords that match the SDG, and (iii) based on the Government of India's SDG indicators. When all these criteria matched for a CVI indicator, it was assigned to the specific SDG. For example indicator–"Percentage of households below the poverty line as of 2011" is related to reducing poverty or SDG1- No Poverty.

While there are few methodological and sensitivity analyses for CVI [17–19], it is the only official federal measure available for the country's climate adaptation planning [14]. Therefore, we use it to analyse how lethal waves can challenge the progress in the nation's SDGs and the implications of heatwave impacts on India's climate vulnerability assessments—at the same time, examining the missed opportunity of not having heat-related policy measures in its current CVI-led assessment.

There is a knowledge gap in the literature evaluating the appropriateness of CVI as a holistic vulnerability measure [17–19]. Contributing to this measurement gap, Edmonds, Lovell and Lovell [20] proposed a multiple climate vulnerability index to make it a comprehensive measure for empirically estimating the exposure, mitigation and adaptive capacity [20]. However, the authors did not mention how such an index-based measure can be used as an effective decision-making tool to ensure that progress in SDGs is not reversed. This gap is persistent in

Table 1. India's Climate Vulnerability Index (CVI) indicators and its associated high-level United Nations Sustainable Development Goals (SDG).

Indicators used in CVI	UN SDG
Percentage of households below poverty line as per 2011	1 (No Poverty)
Coefficient of variation or yield variability of food grains	2 (Zero Hunger)
Proportion of area under Pradhan Mantri Fasal Bima Yojana (PMFBY) and restructured Weather Based Crop Insurance Scheme (WBICS)	2 (Zero Hunger)
Proportion of rainfed agriculture	2 (Zero Hunger)
Density of health care workers per 100,000 population	3 (Good Health and Wellbeing)
Vector borne diseases like dengue, chikungunya, acute encephalitis syndrome, japanese encephalitis, malaria per 1,000 population	3 (Good Health and Wellbeing)
Water borne diseases like cholera, typhoid, acute diarrhoea per 1,000 population	3 (Good Health and Wellbeing)
Women in the overall workforce (%)	5 (Gender Equality)
Proportion of income from natural resources like agriculture, forestry, livestock and fishery to gross domestic product	8 (Decent Work and Economic Growth)
Proportion of output from perennial trees to total value of agricultural and allied output	8 (Decent Work and Economic Growth)
Marginal and small operational land holding (%)	8 (Decent Work and Economic Growth)
Road and rail density	9 (Industry, Innovation and Infrastructure)
Average person day per household employed under Mahatma Gandhi National Rural Employment guarantee act (MGNREGA)	10 (Reduced Inequalities)
Forest land area in square kilometres per 1,000 rural population	15 (Life on Land)

(Source: [14, 16])

https://doi.org/10.1371/journal.pclm.0000156.t001

the current literature as climate vulnerability indices like India's CVI use socio-economic indicators to measure vulnerability, which links it with SDG indicators. Whereas, in the case of extreme weather events, the measures are primarily based on hazard probabilities (like the Heat Index (HI). Using these measures as overlapping information layers can improve the overall climate vulnerability assessment. This shapes the paper's motivation, which is not to compare CVI and HI for India, but instead to provide an empirical basis for evaluating and rethinking India's approach to vulnerability measurement, especially when the impact of an extreme weather event like heatwaves challenges its development goals and climate adaptation policies [3].

This paper uniquely contributes to the above gap by examining the following questions: (1) What does India's current climate vulnerability assessment miss in terms of identifying the vulnerability caused by the heatwaves? (2) To what extent is SDG progress impacted by the absence of a holistic vulnerability measurement? Furthermore, (3) How to co-design policies for improving climate vulnerability assessment in India?

Using the 2022 heatwaves across India as a case study, this paper analyses its vulnerability impact using Heat Index (HI). It discusses this impact assessment with the latest CVI-led SDG ranking across the Indian states and the national capital using publicly available federal data (see Methods section).

This study is designed in two stages to demonstrate that a holistic climate measurement is important across different spatial scales for India. Here, we set the scope of study at a state level and an urban scale. Due to a lack of data, we could not evaluate a more granular scale (like at the district level). The first stage analyses CVI in the country using the latest publicly available government data. The next step estimates the HI and temperature anomaly across

India for April 2022. It performs a normative heatwave impact assessment on India's SDG progress. In the second stage, a scaled-down analysis was performed at an urban scale for Delhi to evaluate its HI and assess its impact on the national capital's urban sustainability. This was done as a case study to show the severity of heatwaves at an urban scale, especially emphasising the need for contextualised heatwave impact studies.

The case of Delhi is interesting because it is the largest city and the capital of India, with a population of 32,065,760 [21], which is at high risk from heatwaves [22] and was the first to draft a State Action Plan on Climate Change (SAPCC). The SAPCC was recently updated with 17 climate risks (see Methods), including urban heat islands but without considering heatwaves. This paper argues that such state-level vulnerability assessment methodology can be improved by considering the heatwave impacts and upgrading its climate adaptation policies. Finally, broader implications were drawn from international efforts on heatwave adaptation at the national climate vulnerability scale and shaped the discussion on the urgency of similar policy action for India and its neighbouring nations.

Materials and methods

State-level CVI and HI estimation

This paper used a publicly available dataset on state-level climate vulnerability indicators from the Indian Government's National Data & Analytics Platform (NDAP) [23]. The first step was to reference this data with the National Climate Vulnerability Assessment Framework by the Department of Science and Technology [14] to classify the severity categories (Low, Moderate and High). Then, India's 2019 Climate Vulnerability Index (CVI) map was constructed using this dataset. In subsequent steps, we evaluated the Heat Index (HI) for April 2022 for India at a state level. Here we assume that exposure to a hazard like extreme heat (measured through HI) can significantly impact climate vulnerability. This impact measurement is currently missing in the Indian Government's vulnerability assessment through CVI.

HI measures how hot it feels when relative humidity is factored in with actual air temperature. It is a widely used heat exposure metric in environmental health research [24]. A similar approach was used for estimating district-level HI for Delhi to understand the effects of urbanisation on heat risks [25].

The United States NOAA National Weather Service's toolkit [26] (see Eq 1) was used to calculate the HI and estimate possible heat disorder severity (i.e., classifying HI into 'Low risk', 'Caution', 'Extreme caution', 'Danger' and 'Extreme danger').

$$HI = c_1 + c_2T + c_3R + c_4TR + c_5T^2 + c_6R^2 + c_7T^2R + c_8TR^2 + c_9T^2R^2 \quad (1)$$

where, HI = heat index (in degrees Celsius) T = ambient dry-bulb temperature (in degrees Celsius) and R = relative humidity (in % value between 0 and 100). And c_1 to c_9 are constant coefficients.

The T and R values were extracted from publicly available Indian Meteorological Department (IMD) April 2022 temperature profiles [27]. The temperature anomaly data for the same month was obtained from the IMD. The Sustainable Development Goal (SDG) interconnection with CVI is established as per the 'indicator rationale' presented in Table 2 (pages 11–12) of [14] and Government of India's SDG Index Dashboard 2020–21 [16]. The CVI indicators were mapped to the corresponding UN SDG. The resultant value of the indicator was then plotted using the colour of the SDG, where the colour gradient represents the rank of the CVI. Thus, the higher the value of an indicator, the deeper the colour of the box. For example, a deeper colour gradient was used if a CVI indicator conforms to a particular SDG and has a high value for a specific state. The colour was related to the corresponding SDG to which the

indicator belonged. CVI and HI spatial maps representing the state-wise severity levels were constructed through spatial analysis in ArcGIS v10.8.1. The GIS shapefiles were adapted from open repositories like github, respective licenses are mentioned in Figs 1 and 4.

The Government of India's classification [23] was used to rank the CVI scores across states as Low, Moderate and High. Low levels show less climate vulnerability. Moderate indicates medium and high levels indicate high levels of climate vulnerability. Similarly, for the HI, NOAA's classification standards [26] as Low Risk, Caution, Extreme Caution, Danger and Extreme Danger was used. This HI categorisation refers to the effects of heat on the human body, i.e., Caution: fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps; Extreme Caution: heat cramps and heat exhaustion are likely. Continuing activity could result in heat stroke; Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity; Extreme danger: heat stroke is imminent [26].

State-level CVI and HI impact on the UN SDGs

A trend analysis was conducted to map India's progress in UN SDGs over 20 years (2001–2021) using United Nation's SDG Index Score [28], with extreme weather-related mortality from 2001–2021. The trend data was taken from Mahapatra, Walia and Saggurti (2018) [29] and the Indian Government's National Crime Record Bureau data on accidental deaths by natural causes [30]. Next, the severity categories of the states for CVI and HI were mapped to judge the relative position of SDG vulnerability. For example, suppose a state receives a low rank in CVI but a high rank in HI. The relative positioning of the SDG vulnerability will imply that the SDG indicators respective to the low-CVI scores will not be prioritised. However, specific SDG indicators will be over-stressed due to a high HI-score, which needs to be highlighted in the state's vulnerability assessment. We present this contrasting analysis in the state-level CVI and HI analysis.

Urban-level CVI and HI estimation

In the next step, the case of heatwaves in New Delhi was studied as a scaled-down analysis to discuss heat risks on its urban sustainability. As a baseline, Delhi Government's latest vulnerability assessment measure through the State Action Plan on Climate Change (SAPCC) [31, 32] was used. The SAPCC also classifies vulnerability into three categories: Low, Medium and High. Finally, the vulnerability score is estimated based on 17 risks: migrant population, rate of urbanisation, disabled population, the area under forest cover, total vehicle, solid waste generation, water vulnerable areas, water bodies, parks and tree canopy, tap water connection, sewage treatment plants, effluent treatment plants, stormwater drainage, below-poverty-line families, rooftop solar power and registered electric vehicles and urban heat islands (source: [31, 32]).

Results

Increase in heatwave-related vulnerability

Fig 1 captures the extent of heatwave-related vulnerabilities in India, which is missed by the present CVI assessment. It shows the current status of India's climate vulnerability in Fig 1A; based on 2019 CVI estimates, the eastern states (except West Bengal) have high climate vulnerability. However, when CVI scores with the HI levels were compared, West Bengal and Andhra Pradesh (a southern state) fall in the 'extreme danger' category (see Fig 1B). Similarly, almost 45% of the country is at moderate CVI levels (see Fig 1A). However, HI estimates show

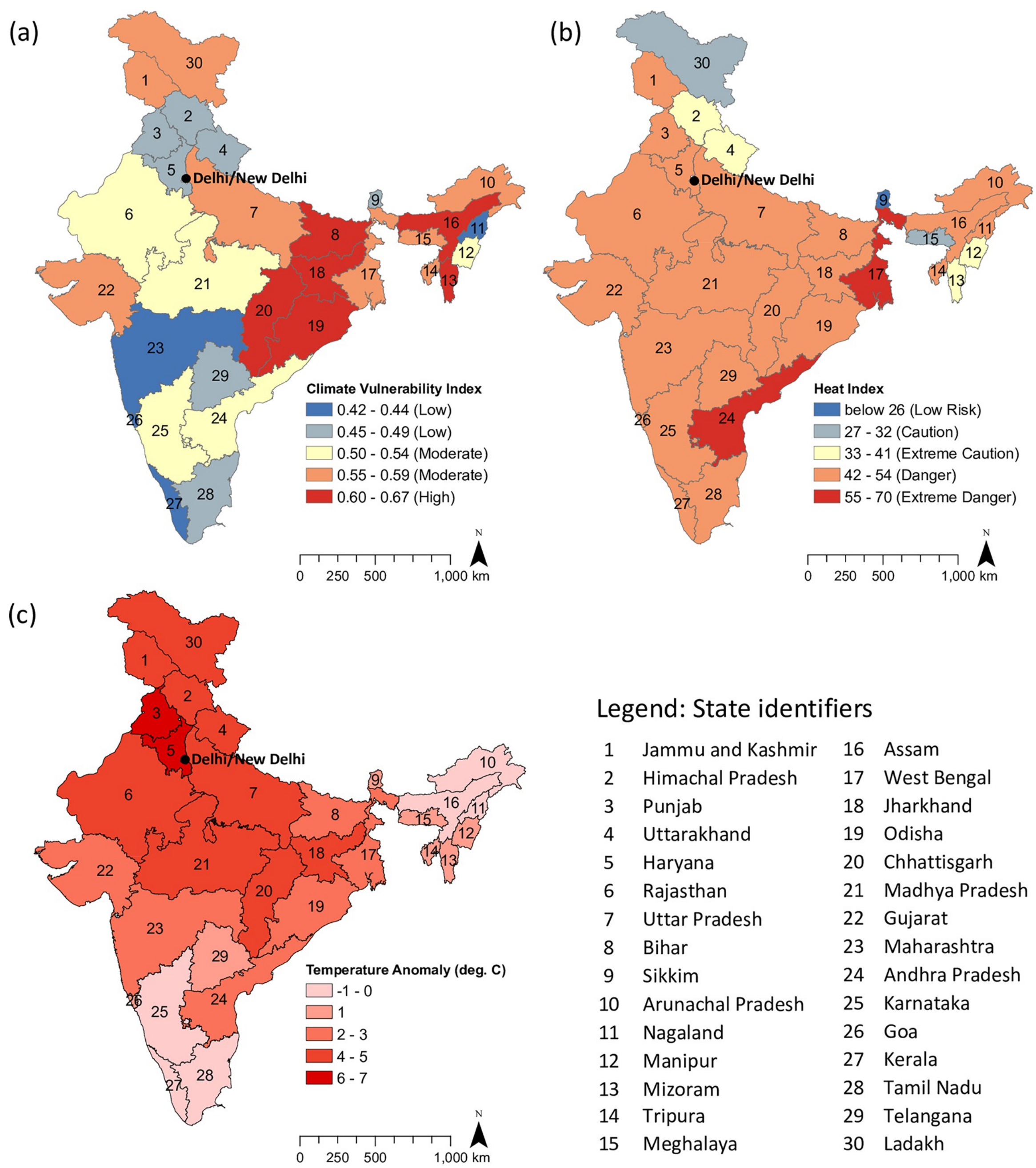

Fig 1. India's Climate Vulnerability Index (CVI) and Heat Index (HI) estimation. (A) CVI illustrated as Low, Moderate and High levels across states.; (B) Estimated heatwave impact (HI) in April 2022 using data from the India Meteorological Department (IMD) (data source: [27]). (C) Temperature anomaly caused in India due to heatwaves in April 2022, estimated using the IMD data (source: [27]) [Note: Due to lack of data, the Union Territories of India (except 30.Ladakh) are excluded from our analysis. The GIS shapefile for the spatial analysis is adopted from [33] under MIT License].

https://doi.org/10.1371/journal.pclm.0000156.g001

that more than 90% of India is in the 'extremely cautious' or 'danger' range (see Fig 1B for this categorisation). Furthermore, the states categorised as' low' in CVI rankings are in danger' Heat Index categories, demonstrating that heatwaves put more people at extreme climate risk across India than estimated by CVI.

Results also show that April 2022 temperature anomalies were exceptionally high (above 4˚C) in the northern regions classified as 'moderate' in the CVI scores. In addition, states like Punjab and Haryana have experienced a temperature anomaly of 6–7˚C, otherwise classified as 'low' CVI areas. This high-temperature anomaly zone also includes Delhi, making it most prone to future heatwaves (see Fig 1A and 1C).

Heatwaves weakening SDG progress across Indian states

The different implications of HI on India's SDG indicators are shown in Fig 2. Results indicate that the use of CVI may underestimate the actual burden of climate change concerning heat, suggesting India's need to reconsider its assessment of climate vulnerabilities to meet the SDGs. This is more so because a CVI that does not include measures of the primary climate change risks/threats (in this study, heatwaves) may fail to identify regions of greatest vulnerability to climate change at the intersection of climate extremes and non-climate, structural and social-economic factors that increase sensitivity. Missing the primary extreme events in conjunction with the contextual factors like differential adaptive capacity that fosters resilience may underestimate the vulnerability [34] and its subsequent undermining of the sustainable development goals.

Considering the multi-dimensional and cross-sectional nature of climate vulnerability, it is imperative to reflect on the social, cultural, economic, and structural development factors, their inter-relationships, and environmental vulnerabilities. For example, Andhra Pradesh is in extreme danger in HI, affecting SDG-3 (Good health and well-being) and SDG-15 (Life on land). However, these SDGs are considered moderate in the CVI classification (see [8] and Fig 1A). For West Bengal, in the same extreme danger HI range (see Fig 2), the SDGs that are most critical and will be severely affected are SDG-3 (Good health and well-being), SDG-5 (Gender equality), SDG-8 (Decent work and economic growth) and SDG-15 (Life on land). In this case, the CVI Range for these SDG were also in the high values indicating these SDGs were already stressed in the state. With heatwaves, their fulfilment can further get challenging. Apart from heatwaves, this state is highly vulnerable to flooding and tropical cyclones [35, 36].

The trend analysis of the last 20 years from 2001–2021 (see Fig 3) on the SDG progress with the mortality due to extreme weather events shows that while the effect of extreme weather events has intensified, the pace of SDG progress is slower. In the last three years (2019–2021), India's Global SDG rank has declined due to failure in achieving the targets for 11 of the 17 SDGs [28]. Most of the 11 SDGs India lags on are critically related to climate action. India's preparedness and performance on SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) has declined significantly [28]. This becomes severe due to the strong correlation between these SDGs [37, 38]. Thus, in terms of urban sustainability (SDG-11), the failure to develop appropriate low-income housing leaves a significant proportion of the population vulnerable to extreme weather events like heatwaves [39, 40].

The 'danger' HI range covers over 80% of Indian states (see Fig 1B). However, in Fig 2, many states are classified as moderate or low in the CVI ranking (see Fig 1A). Highlighting such measurement discrepancies is especially important as the lack of HI accountability in vulnerability mapping can slow down SDG progress and climate adaptation capabilities (supporting the conclusion of [41, 42]). For example, Tamil Nadu is assigned a low CVI score reflected across its SDG targets (SDG-2, 8 and 15), implying that even though it has a low climate vulnerability across this sector, heatwaves can significantly impact its socio-economic, livelihood and biophysical quality.

As shown in Fig 1C, northern states are particularly prone to higher temperature anomalies, which supports the latest heatwave pattern across the Indian subcontinent [43, 44]. While

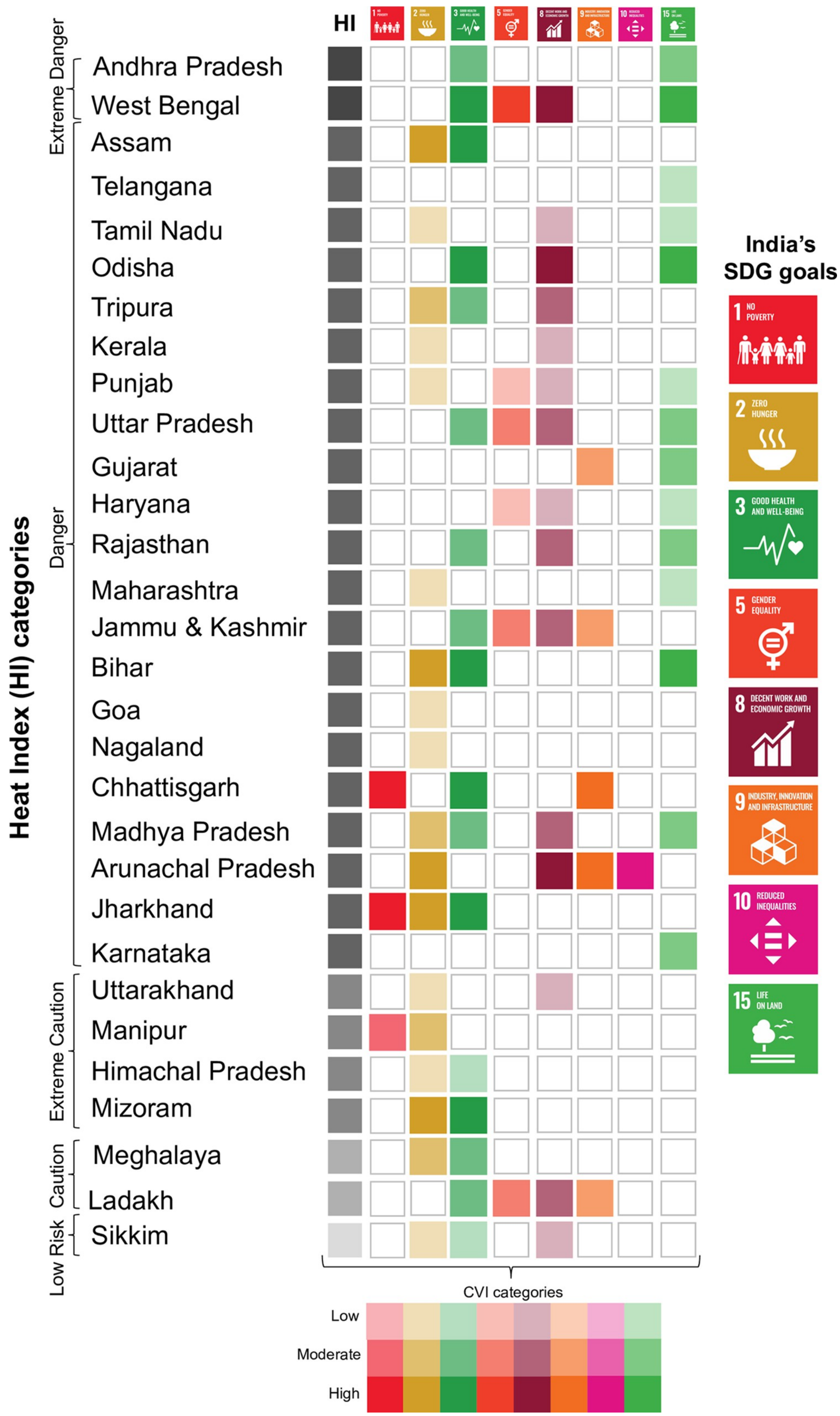
Heat Index (HI) categories
HI
Extreme Danger
Andhra Pradesh
West Bengal
Danger
Assam
Telangana
Tamil Nadu
Odisha
Tripura
Kerala
Punjab
Uttar Pradesh
Gujarat
Haryana
Rajasthan
Maharashtra
Jammu & Kashmir
Bihar
Goa
Nagaland
Chhattisgarh
Madhya Pradesh
Arunachal Pradesh
Jharkhand
Karnataka
Extreme Caution
Uttarakhand
Manipur
Himachal Pradesh
Mizoram
Caution
Meghalaya
Ladakh
Low Risk
Sikkim
India's SDG goals
1 NO POVERTY
2 ZERO HUNGER
3 GOOD HEALTH AND WELL-BEING
5 GENDER EQUALITY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
15 LIFE ON LAND
CVI categories
Low
Moderate
High

Fig 2. The Heat Index (HI) identifies more of India's vulnerabilities than the Climate Vulnerability Index (CVI). The y-axis represents the state-wise HI categories (extreme danger, danger, extreme caution, caution and low risk). The x-axis represents the state-wise CVI categories per UN SDGs. States with blank CVI scores for corresponding SDGs is due to missing data (source: [16]).

https://doi.org/10.1371/journal.pclm.0000156.g002

almost 95% of northern India is under extreme caution and danger HI ranges, ensuring SDG progress becomes even more critical. For example, the most common factors under high climate vulnerability in these states are associated with SDG-2,3, 8 and 15 (see Fig 2), which includes agricultural production, employment security and health (as per the Government of India's CVI estimation, see [14]). In addition, its sub-indicators include income shares from natural resources, marginal and small landholdings, adaptive livelihood capacity through the MGNREGA program, yield variability of food grains, vector-borne diseases and water-borne diseases (see Table 2 in [14]). Our findings show that heatwaves will impact all of the above at a grander scale than previously estimated with CVI.

Low HI-risk states also have climate vulnerabilities that will not be affected by heatwaves as much as the states mentioned above. However, Ladakh has a high CVI range impacting SDG-3,5, 8 and 9, implying that the government must continue progress on these SDGs to mitigate its climate vulnerability.

Heatwaves threatening national capital's urban sustainability

Delhi government's latest iteration of the State Action Plan on Climate Change (SAPCC) [31] found high inter-district variability among the standard critical drivers of vulnerability (discussed in Methods) in Delhi, as shown in Fig 4A.

The Delhi government's assessment shows that the South and North-East Delhi are most vulnerable to climate change impacts (see Fig 4A), which are also the most affluent areas [32]. However, our estimation shows that 100% of the city is at 'Danger' HI levels (see Fig 1B and 1C). In addition, by downscaling the HI to the district level in Fig 4C, results show that even the 'low' climate-vulnerable areas in Delhi are at high heatwave risks. This is concerning as the current heat-action plans [46] are designed and implemented per the Delhi government's vulnerability assessment, which does not include HI estimations. In addition, the high intensity of

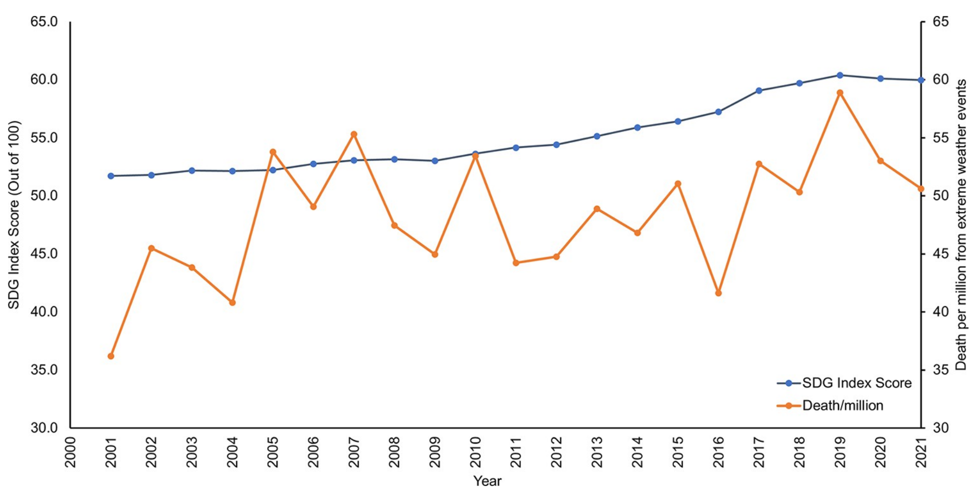

Fig 3. India's progress in SDGs with deaths due to extreme weather events in the last two decades (2001–2021). (source: SDG Index score [28], Death: [29, 30]).

https://doi.org/10.1371/journal.pclm.0000156.g003

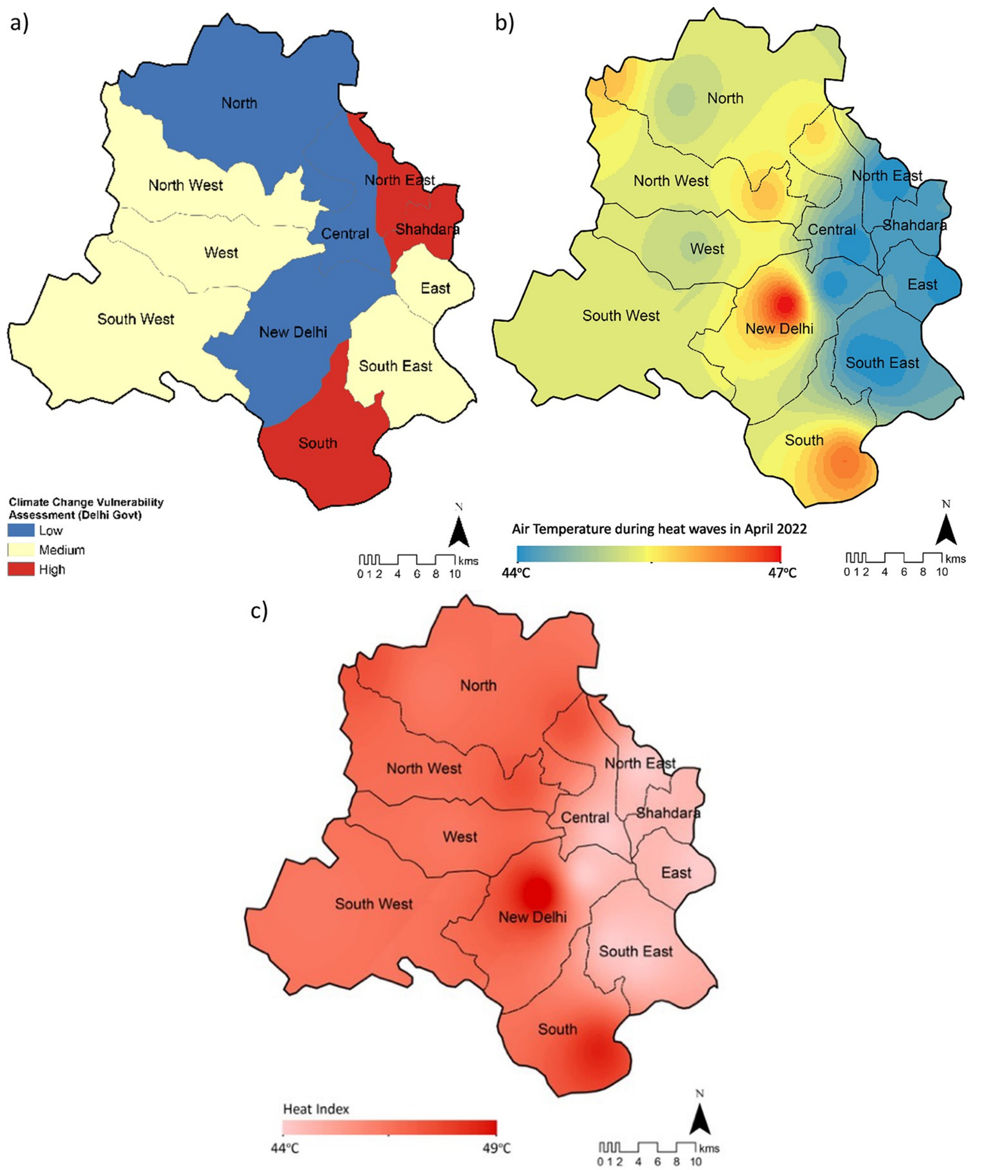

Fig 4. Delhi's heatwave impact for April 2022. (A) District-level climate change vulnerability assessment as per the Delhi Government classification.; (B) Air temperature during heatwaves, and (C) Estimated heat index (HI) at district-level. The GIS shapefile for the spatial analysis is adopted from [45] under the CC BY-SA 2.5 IN license.

https://doi.org/10.1371/journal.pclm.0000156.g004

development in Central, East, West and North-East districts (i.e., the old Delhi area) can further elevate the HI risks through heat island formation. (supporting the findings of [47, 48]).

Discussion

Lack of holistic vulnerability measurements impact India's SDGs

This study shows that heatwaves make more Indian states vulnerable to climate change than previously estimated with the CVI. Our results show that more than 90% of India is in the 'extremely cautious' or 'danger' range of heatwave impacts through Heat Index (HI), which is otherwise considered as 'low' or 'moderate' vulnerability (through CVI, see Figs 1 and 2). As

the heatwaves in India and the Indian subcontinent become recurrent and long-lasting, it is high time that climate experts and policymakers reevaluate the metrics for assessing the country's climate vulnerability.

In addition, the findings uniquely reveal that the state-level SDGs in India, considered the basis for CVI, suffer extensive vulnerability due to a lack of consideration of heat impacts at the policy level. It is to be noted that India is already very selective of SDGs in its CVI estimation (see Table 1). Such extreme weather events can have spillover effects on SDGs that are not considered. For example, urban India is already very vulnerable to climate change impacts due to its proximity to coastal areas and topological factors in general, resource dependence and existing environmental risks [49]. By 2025, 70 Indian cities are expected to have more than 1 million inhabitants [50]. A lack of a holistic climate vulnerability assessment process will slow progress towards meeting SDG-11 (sustainable cities and communities). Such under-reporting of legacy vulnerabilities can severely affect its urban sustainability, as more than 70% of India's building stock is yet to be built [51].

Heatwave challenging India's urban sustainability

In Fig 3, a trend analysis showed India's preparedness and performance of SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) had declined significantly [28]. Furthermore, regional analysis in the SDG-11 context showed that Delhi's urban sustainability is severely challenged as its current district-level climate change vulnerability measurements (through SAPCC) do not factor in heatwave impacts (see Fig 4). The results emphasise that Delhi's vulnerability assessment does not consider the variables the national CVI estimation considers, supporting our argument that there needs to be more standardisation for vulnerability assessment in India across federal, state and local levels. Additionally, CVI does not account for the structural sustainable development interventions that are not often related to climate but might impact the coping capacity thresholds for the population. For example, affordable housing is mainly developed to close the housing deficit in the low-income population. However, it can act as a coping mechanism to climate-related heat stress if it is designed to allow better ventilation for heat removal or provides open spaces that encourage community networking. Such networks can then act as mechanisms to build climate resilience. Thus, fulfilling the SDG-11 and SDG-13 agendas. Therefore, vulnerability assessments must account for the interaction between primary climate events and non-climate interventions to progress interdependent SDG goals.

Our results showed that Delhi lies in the 6–7˚C temperature anomaly zone, with HI in the danger category (see Figs 1 and 4). Some of the critical variables in Delhi that will aggravate heat-related vulnerabilities are like concentration of slum population and overcrowding in high HI areas, lack of access to basic amenities like electricity, water and sanitation, non-availability of immediate healthcare and health insurance, poor condition of housing and dirty cooking fuel (traditional biomass, kerosene and coal). Reducing these vulnerabilities needs structural interventions through the fulfilment of SDG 3, 9, 11 and 10, which are currently missing in India's SDG focus areas (see Fig 2). While some of these variables are considered by the Delhi government in their vulnerability assessment of a small sample of slum households (n = 392) in high-temperature hotspot zones [52], a significant gap remains in scaling and implementation as heat-action policy frameworks do not exist in practice. The HI analysis for Delhi also supports the existing SAPCC's vulnerability assessment that affluent areas are at high risk (see Fig 4). Since in Delhi, most of the slum settlements co-exist near affluent neighbourhoods [47], it will have unprecedented consequences on the low-income population. It will pose a threat to energy security (SDG—7), public health and well-being (SDG—3) and

reverse progress in reduced inequality (SDG—10) and poverty action (SDG—1). Furthermore, as a rapidly urbanising city, Delhi has a high level of construction activities, mostly involving a low-income labour force, who are also at severe risk from heatwave impacts.

India ranks Delhi as the second-best performer in terms of UN-SDG progress [16]. It ranks highest in SDG-7 (clean and affordable energy) and has made positive progress towards SDG-1 (no poverty), SDG-3 (good health and well-being), SDG-4 (quality education), SDG-8 (decent work and growth), SDG-10 (reduced inequality), and SDG-11 (sustainable cities and communities) [16]. However, with the unaccounted HI risk, this ranking is threatened even with its bespoke climate vulnerability assessment using the 17 risk indicators (see Fig 4A). Moreover, it pressures the adaptive capacity of the migrant population, below-poverty-line families, disabled people, and slum population, severely challenging Delhi's urban sustainability.

The case of Delhi emphasises that heat is an urban killer and can be modulated through artificial interventions. How we design our cities strongly determines heatwave impacts, eventually affecting the SDGs. Therefore, most urgently, upcoming heat-action policies need to standardise and streamline vulnerability assessments in India.

Emphasizing the multidimensional nature of CVI and its policy

Impacts. India has demonstrated tremendous leadership in scaling up heat action plans in the last five years by declaring heatwaves a natural disaster and mobilising appropriate relief resources [53]. In addition, the states have begun adopting the newly launched national guidelines for prevention and management of heatwave [54], a one-of-a-kind heat action plan in practice only for the city of Ahmedabad since 2013. There are also plans to improve heatwave nowcasting and vulnerability mapping [3]. However, it is high time that due attention is given to how India assesses its climate vulnerabilities while progressing in its SDGs in the recurring extreme weather context.

The United Nations Framework Convention on Climate Change (UNFCCC) has long recognised the importance of international cooperation and knowledge transfer to improve climate vulnerability assessment while fulfilling global climate objectives [55]. The results further emphasise the need for India to rethink its vulnerability assessment strategies at a national sustainability policy scale with the increasing severity of heatwaves. International lessons can help in its reevaluation as well [56]. While there is yet to be a globally accepted universal climate vulnerability index, this study showed the need to incorporate the multidimensional aspects of vulnerability while capturing the co-occurrence and interactions of the climate events capturing the co-occurrence and interactions of the climate events with economic and structural development changes primarily related to SDGs. It further emphasises UN SDG-17 (Partnership for the goals), which is not present in its current CVI methodologies. For example, Bhutan aims to integrate heat risk in an all-hazards risk management system with specific emphasis on improving SDG-4 (Quality Education) through a climate-resilient education system [57]; however, at present, no information exists on heat vulnerability for Bhutan [3].

Similarly, Pakistan plans to strengthen extreme heat risk management in the southern region close to India's highest temperature anomaly zones (see Fig 1C). Nonetheless, it lacks risk sensitisation and local heat health action plans [3]. Bangladesh has limited knowledge of heat hotspots and vulnerability mapping across areas within Indian borders. There is a real opportunity for regional partnerships across the Indian subcontinent.

Lessons can also be learnt from global heat preparedness leaders like Australia, the US, the UK and the European Union (EU). For example, the Australian government is set to use the Integrated Heat Vulnerability Assessment Toolkit to measure heat sensitivity and heat

adaptive capability indicators at national, regional and city scales [58]. It is built on the successful Heat Vulnerability Index (HVI), already in use across Melbourne, Dandenong, and Bendigo [59]. The UK Health Security Agency (UKHSA) and Met Office have recently launched their comprehensive Heatwave plan for England with detailed heatwave alert levels (see pp 13 in [60]). As a policy, it is designed to work with UK's existing climate vulnerability measurements [60]. In the US, the Centre for Disease Control (CDC) releases guides for health departments to assess health vulnerabilities to climate change through a federal Climate and Health program that helps local authorities holistically track climate-related health vulnerabilities (along with heat effects) [61]. The EU has strategically identified that long-term intersectoral cooperation, surveillance, and plan evaluation can build resilience towards heatwave impacts [62].

This paper consistently emphasises that there are opportunities for upgrading existing vulnerability assessments for future lethal heatwaves, which is critical to preventing the reversal of India's SDG progress.

Conclusion

Heatwaves around the globe are getting recurrent, intense and lethal due to climate change. The 2022 Indian heatwave was severe. This paper shows that for India, a vulnerability index (CVI) that does not include measures of the primary climate change risks/threats (like heatwaves) may fail to identify regions of greatest vulnerability to climate change, especially those at the intersection of climate extremes and non-climate, structural and social-economic factors (indicated through SDGs) that increase sensitivity. Results showed that combining HI with CVI can identify practical climate vulnerability impacts that account for extreme weather events at the state level. This, in turn, aids in developing a better understanding of India's SDG progress. This paper advocates the urgency of improving India's extreme weather vulnerability assessment while supporting its developmental needs. The same empirical viewpoint can be valid for other weather-related parameters like temperature, precipitation, humidity, etc., to cover extreme weather events, which remain a future work, along with the need for standardization of India's climate vulnerability assessment at a granular level.

The analysis presented in this paper is limited in its scope to prescribe methods for improving India's (or any nation's) CVI estimations across the spectrum of extreme weather events. Due to a lack of data, there was a time lag between the CVI (2019–2020) and HI (2022) estimates that affected the accuracy of CVI vs HI categorization in Figs 1 and 2. A more updated CVI dataset could provide a more realistic state vulnerability ranking to the HI scores. This study assumed that the hazard probability measured through HI could represent the climate vulnerability measured through CVI. The vulnerability paradox suggests that long-term exposure to elevated levels of climate extremes generate asymmetry in coping capacity and can foster short-term resilience [34]. Hence, future work would need to derive a composite index with its vulnerability, hazard, adaptive/coping capacity of the population and exposure level at a national and urban scale to compare CVI with heatwave risks for assessing SDG progress.

Further studies should be conducted to evaluate the sensitivity of indices like CVI and HI across different climatic conditions across local, national and international scales to understand their usefulness in the climate change context. Moreover, the two scales presented in this study pave the way for India's district-level heatwave impact analysis. Small area estimation results can help gross root-level climate change preparedness planning.

This paper shows evidence from the 2022 incidences of severe heatwaves in India (based on April 2022) that abnormal temperature rises from climate change could severely impact over 90% of the country. More accurate estimates can be derived with more data points and macro

trend analysis. This lack of data infrastructure must be mitigated for better climate vulnerability assessment. However, the core implication of this paper is that such extreme weather events will intensify the adverse effects on productivity, health, and well-being, potentially slowing down SDG progress. While India can gain from global partnerships on mitigation and adaptation to heatwave impacts, the neighbouring nations can learn from India's capacity building to a holistic climate vulnerability assessment. India can begin appropriate adaptation planning only with a whole-system treatment of its climate vulnerabilities.

Author Contributions

Conceptualization: Ramit Debnath, Ronita Bardhan, Michelle L. Bell.

Formal analysis: Ramit Debnath, Ronita Bardhan.

Funding acquisition: Ramit Debnath, Ronita Bardhan.

Methodology: Ramit Debnath.

Project administration: Ronita Bardhan.

Software: Ramit Debnath.

Validation: Michelle L. Bell.

Visualization: Ramit Debnath, Ronita Bardhan.

Writing – original draft: Ramit Debnath, Ronita Bardhan, Michelle L. Bell.

Writing – review & editing: Ramit Debnath, Ronita Bardhan, Michelle L. Bell.

References

1. Jain Y, Jain R. India and Pakistan emerge as early victims of extreme heat conditions due to climate injustice. BMJ. 2022; https://doi.org/10.1136/bmj.o1207 PMID: 35562114
2. Irfan U. The extraordinary heat wave in India and Pakistan, explained; 2022. Available from: https://www.vox.com/23057267/india-pakistan-heat-wave-climate-change-coal-south-asia.
3. Kotharkar R, Ghosh A. Review of heat wave studies and related urban policies in South Asia. Urban Climate. 2021; 36:100777. https://doi.org/10.1016/j.uclim.2021.100777
4. Golechha M, Panigrahy RK. Covid-19 and Heatwaves: A double whammy for Indian cities. The Lancet Planetary Health. 2020; 4(8). https://doi.org/10.1016/S2542-5196(20)30170-4 PMID: 32730749
5. Woetzel J, Pinner D, Samandari H, Gupta R, Engel H, Krishnan M, et al. Will india get too hot to work?; 2020. Available from: https://www.mckinsey.com/business-functions/sustainability/our-insights/will-india-get-too-hot-to-work.
6. Mani M, Bandyopadhyay S, Chonabayashi S, Markandya A, Mosier T. South Asia's hotspots; 2018. Available from: https://openknowledge.worldbank.org/handle/10986/28723.
7. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Belesova K, Berry H, et al. The 2018 report of The lancet countdown on health and climate change: Shaping the health of nations for centuries to come. The Lancet. 2018; 392(10163):2479–2514. https://doi.org/10.1016/S0140-6736(18)32594-7 PMID: 30503045
8. Ahmed M, Suphachalasai S. Assessing the costs of climate change and adaptation in South Asia; 2019. Available from: https://www.adb.org/publications/assessing-costs-climate-change-and-adaptation-south-asia.
9. WMO. WMO: Climate change threatens sustainable development; 2021. Available from: https://public.wmo.int/en/media/press-release/wmo-climate-change-threatens-sustainable-development.
10. Khalid AM, Sharma S, Dubey AK. Concerns of developing countries and the Sustainable Development Goals—Case for India. International Journal of Sustainable Development & World Ecology. 2020; 28 (4):303–315. https://doi.org/10.1080/13504509.2020.1795744
11. Kumar N, Kumar Goyal M, Kumar Gupta A, Jha S, Das J, Madramootoo CA. Joint behaviour of climate extremes across India: Past and future. Journal of Hydrology. 2021; 597:126185. https://doi.org/10.1016/j.jhydrol.2021.126185

12. Pandey K, Sengupta R. Climate India Report 2022—An assessment of extreme weather events: January—September. Centre for Science and Environment; 2022. Available from: http://www.indiaenvironmentportal.org.
13. Kumar A, Mondal S, Lal P. Analysing frequent extreme flood incidences in Brahmaputra basin, South Asia. PLOS ONE. 2022; 17(8). https://doi.org/10.1371/journal.pone.0273384 PMID: 35994487
14. DST. Climate Vulnerability Assessment for Adaptation Planning in India using a Common Framework; 2021. Available from: https://dst.gov.in/sites/default/files/Full%20Report%20%281%29.pdf.
15. IPCC. Fifth assessment report; 2014. Available from: https://www.ipcc.ch/assessment-report/ar5/.
16. Aayog N. SDG India Index; 2022. Available from: https://sdgindiaindex.niti.gov.in/.
17. Raghavan Sathyan A, Funk C, Aenis T, Winker P, Breuer L. Sensitivity analysis of a climate vulnerability index—a case study from Indian Watershed Development Programmes. Climate Change Responses. 2018; 5(1). https://doi.org/10.1186/s40665-018-0037-z
18. Singh C, Deshpande T, Basu R. How do we assess vulnerability to climate change in India? A systematic review of literature. Regional Environmental Change. 2016; 17(2):527–538. https://doi.org/10.1007/s10113-016-1043-y
19. Wolf T, Chuang WC, McGregor G. On the Science-Policy Bridge: Do Spatial Heat Vulnerability Assessment Studies Influence Policy? International Journal of Environmental Research and Public Health. 2015; 12(10):13321–13349. https://doi.org/10.3390/ijerph121013321 PMID: 26512681
20. Edmonds HK, Lovell JE, Lovell CAK. A new composite climate change vulnerability index. Ecological Indicators. 2020; 117:106529. https://doi.org/10.1016/j.ecolind.2020.106529
21. WPR. Delhi Population 2022; 2022. Available from: https://worldpopulationreview.com/world-cities/delhi-population.
22. Dubey AK, Lal P, Kumar P, Kumar A, Dvornikov AY. Present and future projections of Heatwave Hazard-risk over India: A regional earth system model assessment. Environmental Research. 2021; 201:111573. https://doi.org/10.1016/j.envres.2021.111573 PMID: 34174254
23. NDAP. State Level Climate Vulnerability Indicators; 2022. Available from: https://ndap.niti.gov.in/dataset/7159.
24. Anderson GB, Bell ML, Peng RD. Methods to calculate the heat index as an exposure metric in environmental health research. Environmental Health Perspectives. 2013; 121(10):1111–1119. https://doi.org/10.1289/ehp.1206273 PMID: 23934704
25. Sharma R, Hooyberghs H, Lauwaet D, De Ridder K. Urban heat island and future climate change—implications for delhi's heat. Journal of Urban Health. 2018; 96(2):235–251. https://doi.org/10.1007/s11524-018-0322-y PMID: 30353483
26. NOAA. NOAA National Weather Service: Weather Prediction Center; 2022. Available from: https://www.wpc.ncep.noaa.gov/html/heatindex.shtml.
27. IMD. Monthly Weather and Climate Summary for April 2022; 2022. Available from: https://internal.imd.gov.in/press_release/20220502_pr_1604.pdf.
28. Sachs J, Kroll C, Lafortune G, Fuller G, Woelm F. From Crisis to Sustainable Development: the SDGs as Roadmap to 2030 and Beyond: Sustainable Development Report 2022. Cambridge University Press. 2022; https://doi.org/10.1017/9781009210058
29. Mahapatra B, Walia M, Saggurti N. Extreme weather events induced deaths in India 2001–2014: Trends and differentials by region, sex and age group. Weather and Climate Extremes. 2018; 21:110–116. https://doi.org/10.1016/j.wace.2018.08.001
30. GoI. National Crime Records Bureau; 2020. Available from: https://ncrb.gov.in/en/adsi-reports-of-previous-years.
31. Government D. Delhi State Action Plan on Climate Change; 2022. Available from: http://environment.delhigovt.nic.in/wps/wcm/connect/58632d00420a6bb5a265b328c2355f02/Delhi%2BSAPCC_06022019.pdf?MOD=AJPERES&lmod=-331427138.
32. Dixit K. It's going south! How Delhi's affluent district is most vulnerable to climate impact & pollution; 2022. Available from: http://timesofindia.indiatimes.com/articleshow/90038252.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst.
33. Bhatia A. Merging updated district-level shapefiles for India; 2020. https://github.com/abhatia08/india_shp_2020.
34. Kennedy MD, Kopyciok S, Korhonen J. The paradox of vulnerability: States, nationalism, and the financial crisis. Contemporary Sociology: A Journal of Reviews. 2019; 48(2):151–153. https://doi.org/10.1177/0094306119828696b

35. Saranya JS, Roxy MK, Dasgupta P, Anand A. Genesis and trends in marine heatwaves over the tropical Indian Ocean and their interaction with the Indian summer monsoon. Journal of Geophysical Research: Oceans. 2022; 127(2). https://doi.org/10.1029/2021jc017427

36. Ratnam JV, Behera SK, Ratna SB, Rajeevan M, Yamagata T. Anatomy of Indian heatwaves. Scientific Reports. 2016; 6(1). https://doi.org/10.1038/srep24395 PMID: 27079921

37. Nilsson M, Griggs D, Visbeck M. Policy: Map the interactions between sustainable development goals. Nature. 2016; 534(7607):320–322. https://doi.org/10.1038/534320a PMID: 27306173

38. Stapleton SO, Nadin R, Watson C, Kellett J. Climate change, migration and displacement -The need for a risk-informed and coherent approach. Shaping Policy for Development by Overseas Development Institute, United Nations Development Programme. 2017;.

39. Bardhan R, Debnath R, Malik J, Sarkar A. Low-income housing layouts under socio-architectural complexities: A parametric study for sustainable slum rehabilitation. Sustainable Cities and Society. 2018; 41:126–138. https://doi.org/10.1016/j.scs.2018.04.038

40. Malik J, Bardhan R, Hong T, Piette MA. Contextualising adaptive comfort behaviour within low-income housing of Mumbai, India. Building and Environment. 2020; 177:106877. https://doi.org/10.1016/j.buildenv.2020.106877

41. Rathi SK, Chakraborty S, Mishra SK, Dutta A, Nanda L. A heat vulnerability index: Spatial patterns of exposure, sensitivity and adaptive capacity for urbanites of four cities of India. International Journal of Environmental Research and Public Health. 2021; 19(1):283. https://doi.org/10.3390/ijerph19010283 PMID: 35010542

42. Kumar A, Singh DP. Heat stroke-related deaths in India: An analysis of natural causes of deaths, associated with the Regional Heatwave. Journal of Thermal Biology. 2021; 95:102792. https://doi.org/10.1016/j.jtherbio.2020.102792 PMID: 33454033

43. Thiagarajan K. Heatwaves in India and Pakistan are lasting longer than previously seen. BMJ. 2022; https://doi.org/10.1136/bmj.o1143 PMID: 35512797

44. Pratt SE. Early Season Heat Waves Strike India. NASA Earth Observatory. 2022;.

45. DataMeet. Spatial Data of Municipalities; 2018. https://github.com/datameet/Municipal_Spatial_Data/tree/master/Delhi.

46. IRADe. Heat wave action plan—Delhi city; 2020. Available from: http://climateandcities.org/reports/.

47. Sharma M, Abhay RK. Urban growth and quality of life: inter-district and intra-district analysis of housing in NCT-Delhi, 2001–2011–2020. GeoJournal. 2022; https://doi.org/10.1007/s10708-021-10570-8 PMID: 35017786

48. Kumari P, Garg V, Kumar R, Kumar K. Impact of urban heat island formation on energy consumption in Delhi. Urban Climate. 2021; 36:100763. https://doi.org/10.1016/j.uclim.2020.100763.

49. Egerer M, Haase D, McPhearson T, Frantzeskaki N, Andersson E, Nagendra H, et al. Urban change as an untapped opportunity for climate adaptation. npj Urban Sustainability. 2021; 1(1). https://doi.org/10.1038/s42949-021-00024-y

50. Revi A. Climate change risk: An adaptation and Mitigation Agenda for Indian cities. Environment and Urbanization. 2008; 20(1):207–229. https://doi.org/10.1177/0956247808089157

51. Debnath R, Bardhan R, Sunikka-Blank M. How does slum rehabilitation influence appliance ownership? A structural model of non-income drivers. Energy Policy. 2019; 132:418–428. https://doi.org/10.1016/j.enpol.2019.06.005 PMID: 31481823

52. IRADe. Vulnerability Assessment of Households in Delhi to Heat Stress; 2020. Available from: http://climateandcities.org/reports/.

53. NDMA. Beating the heat: How India successfully reduced mortality due to heat waves; 2020. Available from: https://ndma.gov.in/sites/default/files/IEC/Booklets/HeatWave%20A5%20BOOK%20Final.pdf.

54. NDMA. National Guidelines for Preparation of Action Plan—Prevention and Management of Heat Wave; 2019. Available from: https://ghhin.org/wp-content/uploads/heatwaveguidelines.pdf.

55. UNFCCC. Article 10.1 of the Paris Agreement on Climate Change; 2015.

56. Khosla R, Sagar A, Mathur A. Deploying low-carbon technologies in developing countries: A view from India's buildings sector. Environmental Policy and Governance. 2017; 27(2):149–162. https://doi.org/10.1002/eet.1750

57. Kagawa F. The Heat is On: Towards a climate resilient education system in Bhutan; 2022.

58. Rice C. The Integrated Heat Vulnerability Assessment Toolkit; 2022. Available from: https://aurin.org.au/high-impact-project-update-the-integrated-heat-vulnerability-assessment-

59. Bao J, Li X, Yu C. The Construction and Validation of the Heat Vulnerability Index, a Review. International Journal of Environmental Research and Public Health. 2015; 12(7):7220–7234. https://doi.org/10.3390/ijerph120707220 PMID: 26132476

60. NHS. Heatwave plan for England: Protecting health and reducing harm from severe heat and heatwaves; 2022. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1074023/Heatwave_Plan_for_Engand_2022_May-2022-v2.pdf.

61. CDC. Assessing Health Vulnerability to Climate Change: A Guide for Health Departments; 2018. Available from: https://www.cdc.gov/climateandhealth/docs/assessinghealthvulnerabilitytoclimatechange_508.pdf.

62. Bittner MI, Matthies EF, Dalbokova D, Menne B. Are European countries prepared for the next big heatwave? European Journal of Public Health. 2013; 24(4):615–619. https://doi.org/10.1093/eurpub/ckt121 PMID: 24097031