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ORIGINAL PAPER

The nexus between climate change and public health: a global overview with perspectives for Indian cities

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Abstract

Climate change is widely recognized as a major threat to public health. The Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6), assessing different Shared Socioeconomic Pathway scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), projects that relative to 1850–1900, the global temperature is rising and would exceed 2 °C during the twenty-first century under the high (SSP3-7.0) and very high (SSP5-8.5) greenhouse gas (GHG) emission scenarios considered. Populations within tropical and subtropical regions are more likely to experience increased vulnerability towards heat stress. In this study, a summary of some of the important aspects of climate change and human health has been presented. The effects of climate change on India's energy demand, employment, labor market and benefits have also been highlighted. Finally, we have discussed the national policies implemented or action underway to mitigate climate change and improve public health and have also provided some recommendations to carry forward. The current study overviewing the nexus between climate change and public health has a major aim to provide a perspective towards strengthening the health system in Indian cities.

Keywords Climate change · Public health · Mitigation · Adaptation · Co-benefits

Introduction

Climate change affects males and females differently due to various factors and is expected to widen the existing gender-based health disparities in the future (WHO 2021a). Females are biologically more vulnerable to climate change impacts such as extreme heat (PAHO 2021). In addition, nutritional deficiencies due to increased needs during menstruation and pregnancy and spending more time in kitchen around chulhas make them more sensitive to heat stress. Climate change negatively impacts children's health too (American Academy of Pediatrics 2021). Climate-related extreme events such as floods and droughts have been found to harm the mental health of children (UNICEF 2021). For instance, a previous study has found that children exposed in utero to drought have significantly lower scores on math and reading tests (Shah and Steinberg 2014). Their study showed that in utero exposure of children to drought was associated with their 2.6% points less likely able to recognize numbers from 1 to 10 and 1.2% points less likely to do a simple subtraction problem (as compared to baseline of 53.9% and 61.6%, respectively). The child survivors from Kashmir 2014 floods showed that boys as well as girls exhibited from moderate-to-severe psychological impact on CRIES-8 domains (Children's Revised Impact of Event Scale) (Hassan et al. 2018). The inclusion of gender-specific actions among decision-makers for various climate action plans for public health is further limited due to the dearth of data segregated by gender on climate change-related health impacts (UN Women-Watch 2009; UN Women 2015; World Bank 2021a). In addition to women and children, other populations may also be adversely affected by climate change like the elderly, poor, migrants and sections of low socioeconomic status (SES) around the world (PAHO 2021).

To build on past achievements and pave the way for future ambition, Egypt will hosted the 27th session of the

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Conference of the Parties to the UNFCCC (COP 27) in Sharm El-Sheikh in November 2022 (UN News 2022). This session addressed the framework for monitoring and implementing actions to avoid a climate crisis. The main objective was to talk about ways to reduce carbon emissions and save the planet's future. It was signed by 197 different parties. Mitigation, adaptation and financing for climate action were among COP 27's main goals. The COP 27 was about moving beyond discussions and "planning for implementation" for all these commitments made, according to the Presidential vision statement (UN News 2022). The 26th Conference of the Parties (COP 26) to the UNFCCC (United Nations Framework Convention on Climate Change) was held from 31 October−13 November 2021, in Glasgow, UK (COP26 2021). COP 26 was a key moment for countries, cities, businesses and more to keep on track the Paris Agreement on climate change and put forward fairly practical and reasonable solutions for a zero-carbon future. Looking back in time, the Paris Agreement under the UNFCCC was adopted in Dec. 2015 in Paris (France), at the COP 21 to the UNFCCC (UNFCCC 2015). As part of the Paris Agreement, one of the objectives is to substantially reduce the risks and effects of global climate change by limiting global average temperatures to 1.5 °C wrt. pre-industrial levels (UNFCCC 2015). In addition, the agreement seeks at strengthening the capacity of countries and therefore the whole world to cope with the impacts of climate change.

Background on global climate change

In its AR6 report, the IPCC revisits with high confidence the findings from the AR5 report which indicates that cumulative anthropogenic CO_2 emissions are directly linked to global warming (IPCC 2021). For every 1000 Gt CO_2 of the cumulative CO_2 emissions is likely to cause a 0.45 °C (Uncertainty interval 0.27−0.63 °C) increase in the global mean surface temperature (IPCC 2021). Climate response to cumulative CO_2 emissions is commonly referred to as "TCRE" or transient climate response to cumulative CO_2 emissions. The historical trend of observed global surface temperature increase in °C with the cumulative carbon dioxide (CO_2) emissions in Gt CO_2 from 1850 to 2019 is shown by a thin black line (Fig. 1). Anthropogenic (human-induced)

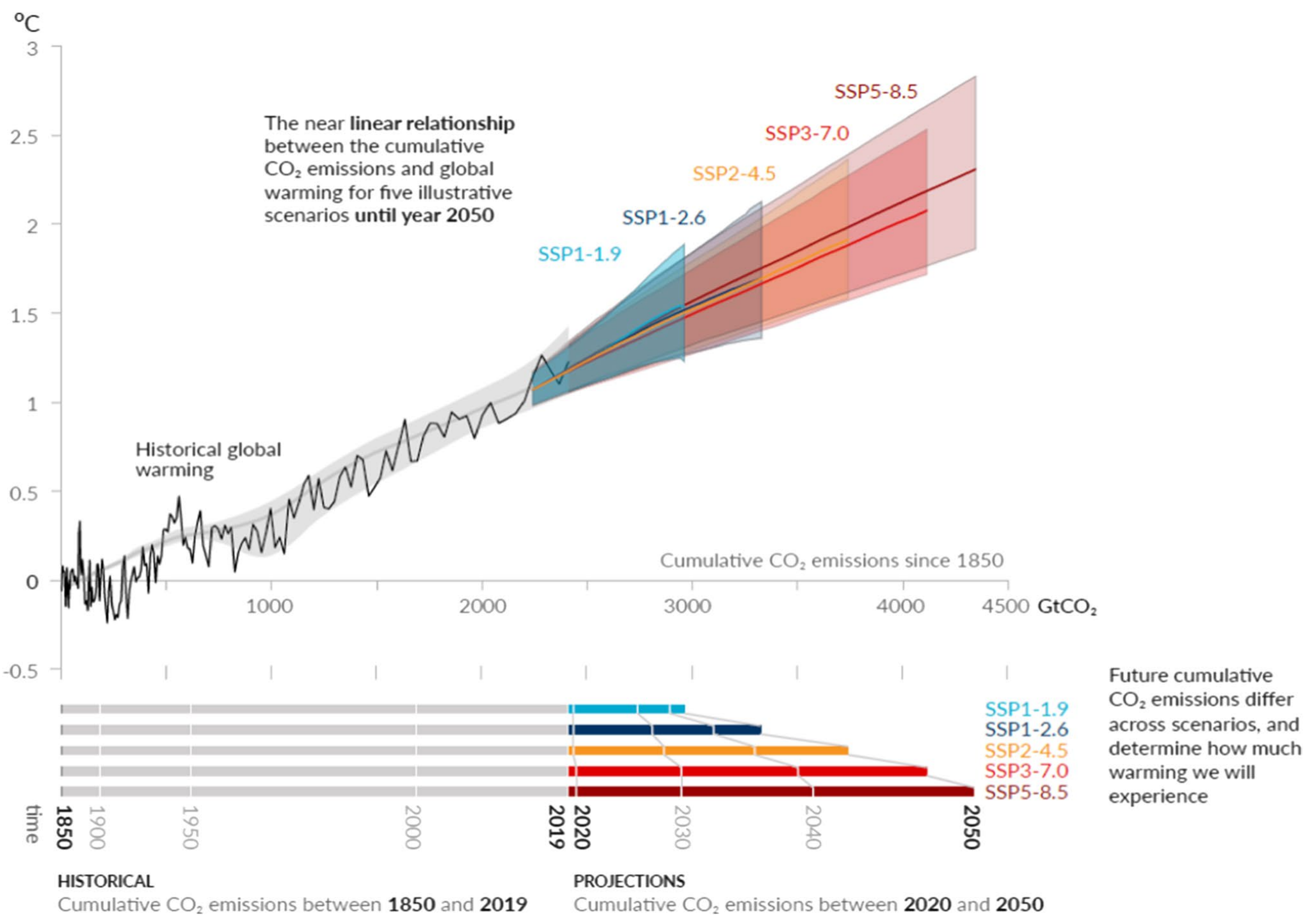

Fig. 1 Cumulative CO_2 emissions and the rise in global surface temperature since 1850−1900 (Gt $CO.^2$; source: IPCC 2021)

global surface warming estimate is represented in the grey range along with a central estimate. The very likely projections in the range of global surface temperature from 2020 through 2050, for the set of illustrative Shared Socioeconomic Pathway scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), are shown as colored areas, and the median estimates are shown by thick colored central lines (Fig. 1). The projected magnitude of global warming has effect contributions from all anthropogenic forcers. There is a limited evidence supporting the quantitative application of TCRE to estimate temperature evolution under net negative CO_2 emissions under the period from 1850 through 2050.

In the IPCC AR6 report, the estimated changes in global surface temperature for selected 20-year periods and five emission scenarios (SSPs) are provided in Table 1 (IPCC 2021). Accordingly, based on the current understanding, the global warming, relative to 1850–1900, would exceed 2 °C during the twenty-first century under the considered high (SSP3-7.0) and very high (SSP5-8.5) greenhouse gas (GHG) emission scenarios (IPCC 2021). As far as the intermediate scenario (SSP2-4.5) is concerned, global warming would likely exceed 2 °C too. However, in the very low (SSP1-1.9) and low GHG emission scenarios (SSP1-2.6), it appears extremely unlikely that global warming would exceed 2 °C. Under the very high GHG emission scenario (SSP5-8.5), it is very likely that global warming would surpass 2 °C levels. In the near term period (2021–2040), it is very likely that we are going to experience global warming of 1.5 °C (relative to 1850−1900) even under SSP1-1.9 (a very low GHG emission scenario). So, no matter how best now we control emissions through mitigation and adaptation, the global surface temperature would increase by 1.5 °C in 2030 (in near term period: 2021−2040) relative to that of 1850–1900. These aspects of global warming under different SSPs until the end of this century are shown in Fig. 2 (IPCC 2021).

United Nations Sustainable Development Goals (UN SDGs)

Among the 17 SDGs, Goal 13 represents Climate Action and it is all about taking urgent actions to combat climate change and its impact globally, whereas Goal 3 represents Good Health and Well-Being (UN SDGs 2022). Salient features of SDGs 3 and 13 (Public Health & Climate Action) are as follows:

- Boost global resilience and capability for natural disasters and hazards related to the climate.

Table 1 Summary of changes in global surface temperature for selected 20-year periods and considered five illustrative emissions scenarios (source: IPCC 2021)

Scenario	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

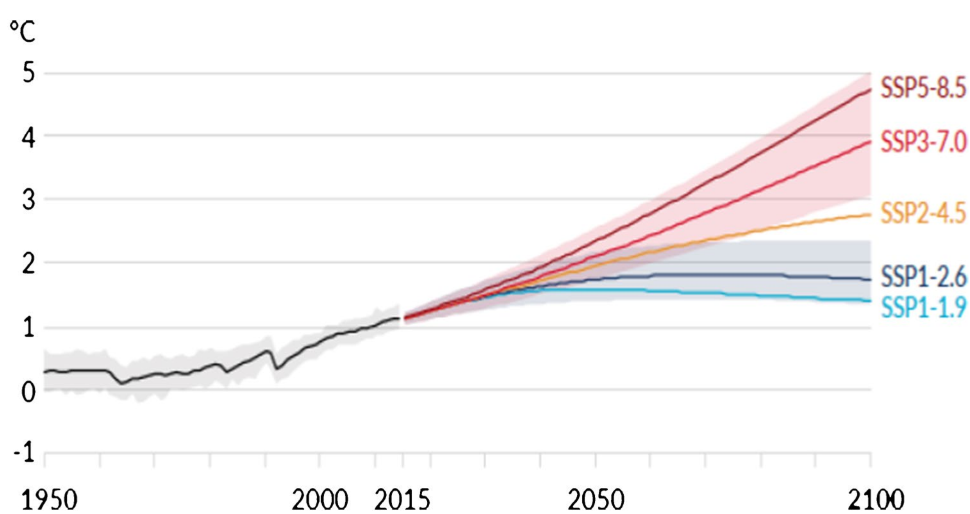

Fig. 2 The change in global surface temperature, relative to 1850−1900, for the set of five illustrative Shared Socio-economic Pathway scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) (source: IPCC 2021)

- Ensure healthy lives and promote well-being for all across all ages.
- COVID-19 continues to pose challenges to people's health and well-being globally and is impeding progress in meeting Goal 3 targets.
- Include climate change mitigation measures in national planning, strategy and policies.
- Boost human and institutional capacity for mitigation, adaptation, impact reduction and early warning of climate change impact.

Climate change and public health: a broader perspective

Climate change events, both short-term extreme events (such as heatwaves, floods, cyclones) as well as slow-onset events (such as gradually rising average temperatures, the increasing CO_2 levels and sea-level rise), have negative impacts on human health (WMO 2020). This can occur via multiple pathways, including environmental degradation, threatened food and water security, deteriorating air (aggravating air pollution), water (exploiting the linkages between water scarcity and quality) and land (desertification) quality, changing vector ecology and degrading living conditions that further exacerbate the existing inequalities (Fig. 3) (CDC 2021). In addition to direct health impacts, slow-onset events such as gradually rising temperatures will also increase forced migration, civil conflicts, loss of productive labor hours and adversely impact mental health (Singh et al. 2020a). Climate change would impact both the water quantity as well as its quality that would exacerbate the existing social and health inequities and vulnerabilities (Singh et al. 2021a, b; CDC 2021).

Climate change poses great challenges for public health across the world. During 2030−2050, climate change could result into an additional 250,000 deaths/year globally, from malnutrition (95,000), malaria (60,000), diarrhea (48,000) and heat stress (38,000). By 2030, direct health damage costs will reach USD 2−4 billion/year (excluding costs in health-determinating sectors like agriculture and water and sanitation) (WHO 2021a). Additionally, weather-related disasters kill over 60,000 people every year, mostly in developing countries. Although climate change will affect all populations, some are more vulnerable than others based on their age, gender, geography, economic status, and technological capacity (Mall et al. 2019). Thus, in developing countries including India, building a stronger health system will lead to potentially more health benefits in general.

Urban heat island impacts

Elevated temperatures from heat islands can have a variety of effects on a community's environment and standard of living (Singh et al. 2020b; USEPA 2022). Important ones are listed below and discussed in detail in subsequent sections.

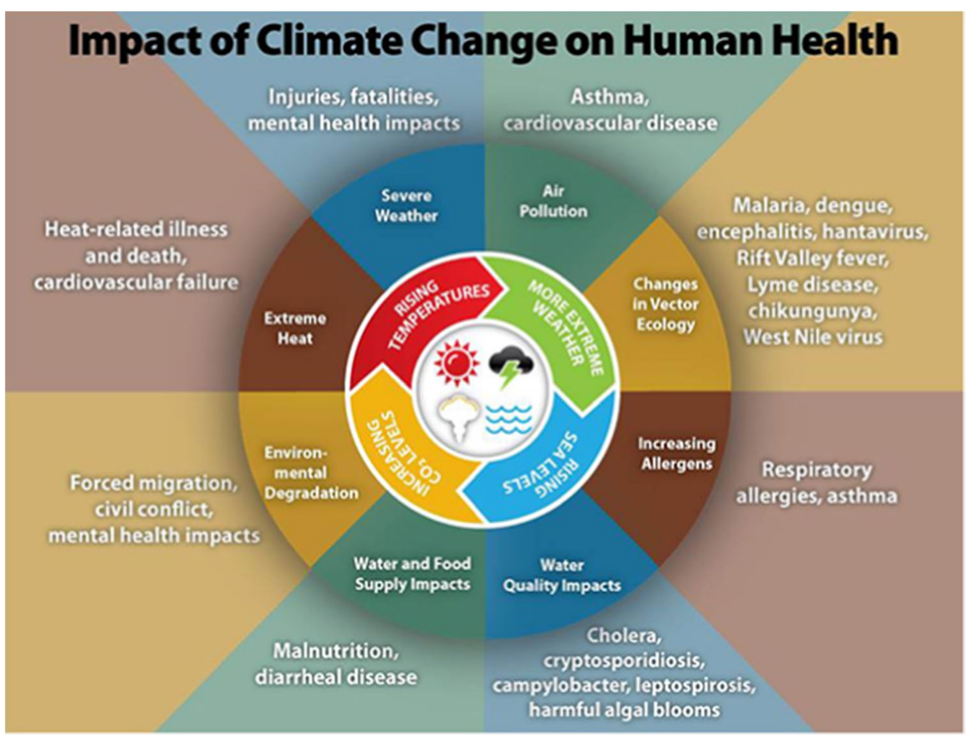

Fig. 3 Likely nexus between climate change and human health (source: CDC 2021)

Increased energy consumption

In several countries, it was found that for every 2°F rise in temperature, the electricity consumption for air conditioning rose by between 1 and 9%.

Elevated emissions of air pollutants and greenhouse gases

Heat islands, as previously mentioned, increase summertime electricity demand. The use of fossil fuels more frequently results in higher emissions of greenhouse gases like carbon dioxide resulting in rapid climate change on a global scale.

Compromised human health and comfort

The group of those most at risk from extreme heat occurrences is *older folks*. Due to early-life exposure and other factors, *young children* are typically more vulnerable to high heat. Because of poor housing conditions, such as a lack of air conditioning and cramped living quarters, and a lack of money to locate alternate refuge during a heat wave, *low-income populations* are more likely to suffer from heat-related illnesses. *People who work outside* are more vulnerable to illnesses including heat exhaustion and heat stroke. Extreme temperature exposure puts persons in poor health at risk, including *those with chronic diseases*, disabilities, mobility issues and those taking specific drugs. During heat waves, *those who have diabetes*, physical limitations or cognitive deficiencies are particularly at risk. Extreme heat events or sudden, sharp temperature spikes, can cause above-average mortality rates and are particularly harmful. Ten thousand five hundred twenty-seven heat-related fatalities, or an average of 702 per year, were reported in the USA from 2004 to 2018, according to the Centers for Disease Control and Prevention.

Climate change and elevating incidence of heat stress

Here, we have discussed an overall scenario of heat stress and the regions/countries under risk (ILO 2019). In occupational health, the incidence of heat stress is widely gauged through the wet bulb globe temperature index (WBGT, in °C). The WBGT is calculated using ambient temperature, relative humidity, wind speed and radiated heat (Parsons 2014). The heat levels and trends presented here show two periods of/about 30 years (1981–2010 and 2071–2099). There is a consensus among the climate science community that the trend observed for a minimum of 30 years represents a good signal to capture long-term climate trends (WMO 2021). The global heat stress scenario gauged by the WBGT index for the estimated climate is shown for 1995 covering the years 1981–2010 (Fig. 4). On Fig. 4, one can see the 30-year average (from 1981 to 2010) of estimated daily maximum WBGT (based on afternoon values in the shade) during the month with the highest temperatures in the region

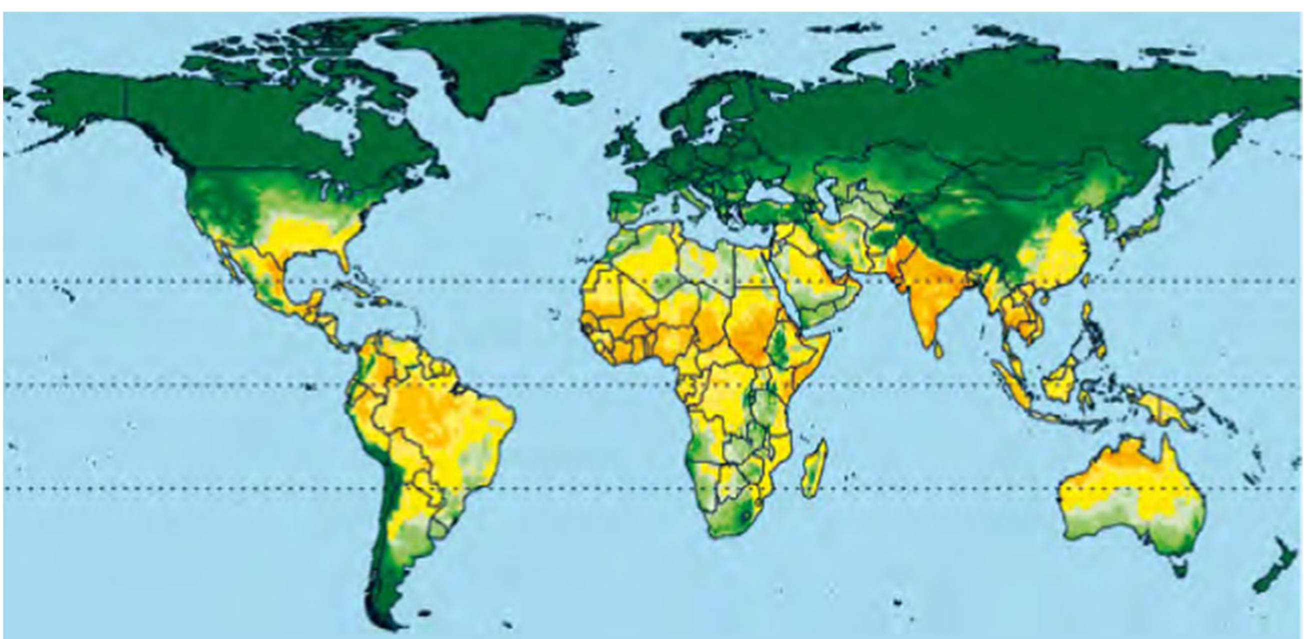

Fig. 4 Estimated global scenario for incidence of heat stress in 1995 (source: ILO 2019). This figure has been reproduced after kind permission from the Rights & Licensing, ILO Publishing, Department of Communication

(grid cell resolution: 50 km × 50 km at the equator) (ILO 2019). It is very obvious from Fig. 4 that the distribution of heat stress is non-homogeneous across the globe with the hottest areas situated within the tropical and subtropical regions. The wind patterns and monsoons, among others, decide the hottest month in different areas. To help workers in hot areas reduce heat strain on their bodies, work re-schedule adjustments need to be made which will eventually lead towards higher workforce output in tropical and subtropical regions (Gallup et al. 1999).

Furthermore, the WBGT for the projected climate is shown for 2085 (2071–2099) (Fig. 5). In the hottest month locally, the 29-year average of projected daily maximum WBGT (afternoon values in shade) (2071–2099) is shown in a map (Fig. 5) with a grid cell resolution of 50 km × 50 km at the equator (ILO 2019). Global temperatures are expected to rise by 2.7 °C above pre-industrial levels by the end of the century, according to climate projections based on RCP6.0. The most populous places, such as sub-Saharan Africa, southern India, northern Australia and Southeast Asia, tend to be the most vulnerable. Figure 5 depicts the expected incidence of heat stress in 2085 based on RCP6.0, in which global mean temperature rises by 2.7 °C over pre-industrial levels by the end of the century (ILO 2019). Focusing on the near-term projection of heat stress climate change in Asia and the Pacific (Fig. 6), it is obvious that the magnitude of heat stress in populated areas particularly during the hottest month is expected to increase in India, South-East Asia and North Australia.

Employment and labor market at a glance

As per the International Labor Organization (ILO), some of the vulnerable countries to heat stress (mainly situated in Africa and Asia) have limited resources and adaptability to protect their workers from the multiple negative health and work outcomes of the rising temperatures (ILO 2019). A similar effect can be seen through working hours lost due to heat stress by region worldwide in 1995 and 2030 (Fig. 7) (Statista 2021). Particularly focusing on South Asia, it appears that working hours loss in 2030 would be around 5.3% which is substantially higher as compared to that of 4% in 1995 (Fig. 7). Unforeseen migration could be one of the consequences if no planning and action is framed and worked out which would eventually lead to overcrowding in some cities of these regions/countries.

The other side of climate change's influence is that heat-sensitive workers may be forced out of agriculture/field work into more productive sectors——a kind of first order practical solution towards structural transformation for these countries. However, demographic and economic projections do not mimic the same. The sectorally segregated employment scenario in 1995 and projection for 2030 across the globe are shown in Fig. 8. It can be seen from the figure that in Africa and Asia, the agriculture sector serves as bread-and-butter for a large number of the countrymen (including dependents, Fig. 8). As per the International Labor Organization (ILO 2019), due to heat

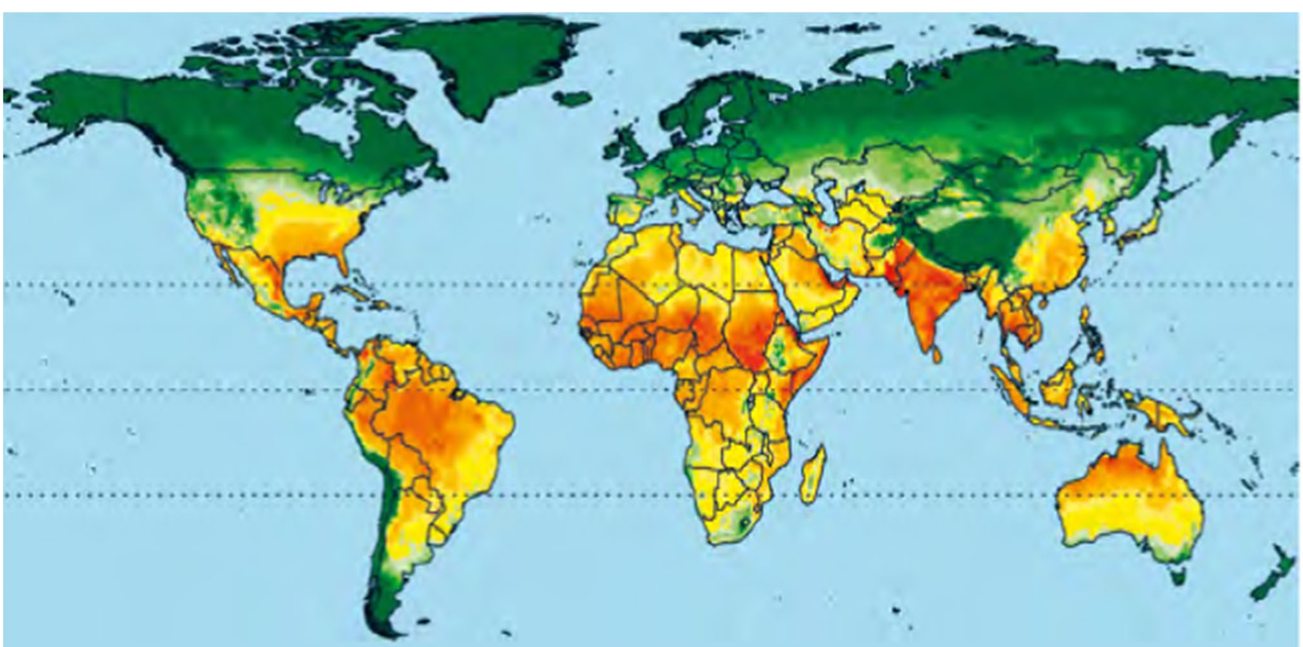

Fig. 5 Global projection of heat stress incidence in 2085 based on HadGEM2 and GFDL-ESM2M climate models (source: ILO 2019). This figure has been reproduced after kind permission from the Rights & Licensing, ILO Publishing, Department of Communication

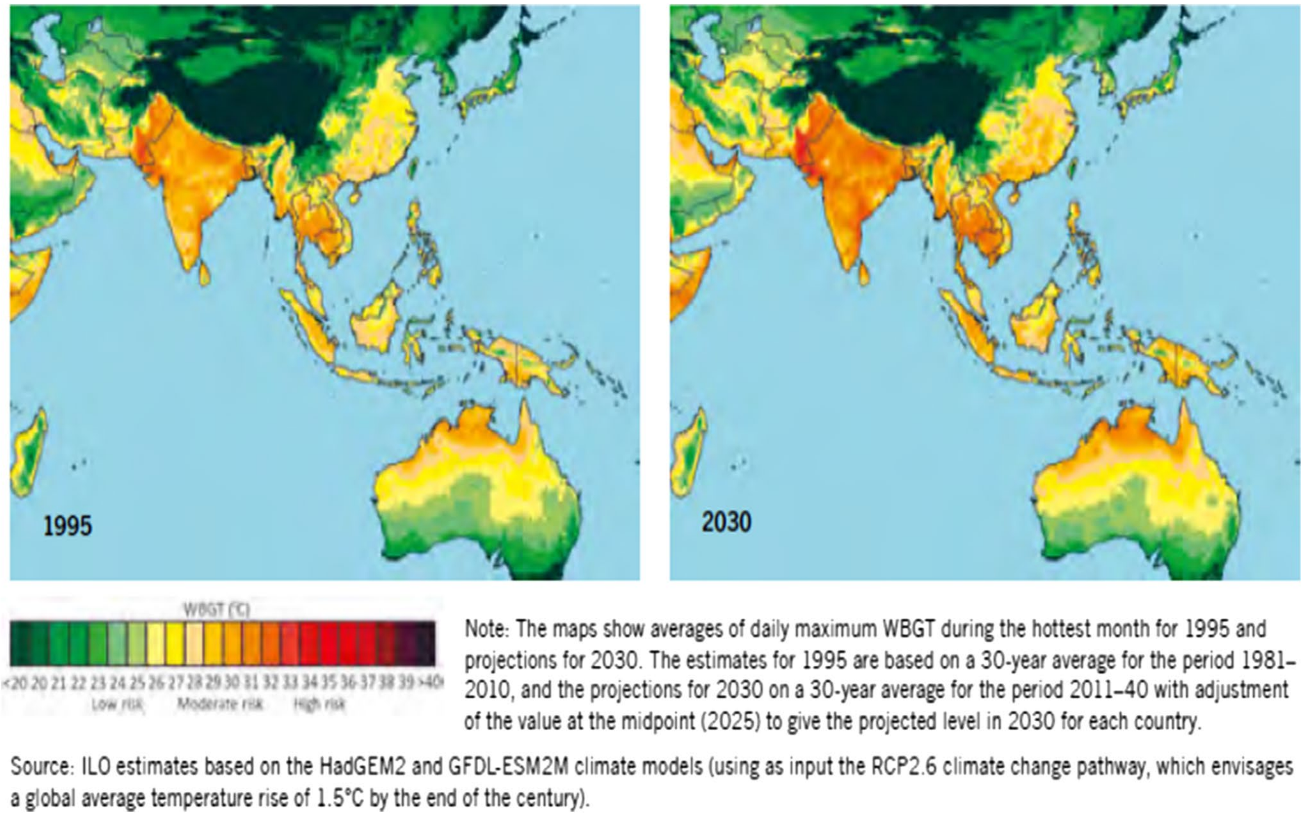

Fig. 6 Heat stress incidence in the hottest month over Asia and the Pacific for estimated (1995) and projected year (2030) (source: ILO 2019). This figure has been reproduced after kind permission from the Rights & Licensing, ILO Publishing, Department of Communication

stress, India in 1995 witnessed a productive loss equivalent to 15 million full-time jobs and is expected to lose 34 million full-time jobs by 2030. About half of these lost hours will be from the agriculture sector.

India's cooling challenge: energy demand, adaptation and co-benefits

In the present-day scenario, about 40% of the global population resides in hot and humid tropical regions wherein many people get around 20 days of extreme temperatures (heatwaves and cold waves) (SEforALL 2021). Extreme weather events often affect the most vulnerable populations. Current global estimates reveal that approx. 12,000 people die annually due to heatwaves (SEforALL 2021). According to WHO estimates, extreme heatwaves might kill over 255,000 people each year by 2050 (RMI 2019). Easy access to cooling, unavailable to a large body mass in tropical/sub-tropical regions, can prevent mortality due to heat stress. Access to cooling, particularly to vulnerable groups, should be considered as a justice and equity issue. The cooling enhances work productivity, improves the health and well-being of people, and is also necessary for survival. Only around 8% of the 2.8 million people living in the world's hottest regions (Fig. 9) have access to air conditioners (IEA 2018). However, in the USA and Japan, close to 90% of people have easy access to cooling.

An unprecedented elevating cooling energy demand in the residential sector would contribute over 25% of global annual emissions from room ACs under business-as-usual (BAU) scenario by 2050; currently, this figure is only ~ 5% (RMI 2018). By the year 2100, the direct as well as indirect emissions from room ACs could alone be responsible for a 0.5 °C rise in global warming. With a caution, it should be noted that utilization of low-cost equipments with highly potent refrigerants and less energy-efficient would ultimately be among the largest risk factors to climate and public health. During summers, the northern and western parts of the country experience extremely hot climatic condition (average temperatures range from 32 to > 45 °C). By 2100, the temperature projections are showing a rise of up to 3 °C in many cities which would likely result in increasing the number of deaths by a factor of 2 due to extreme heatwaves (SEforALL 2021). By 2030, exposure to heatwaves alone has been shown to result in an economic burden of more than $450 billion due to productivity loss (Kjellstrom 2016). Towards this, development of and reliance on Heat Action

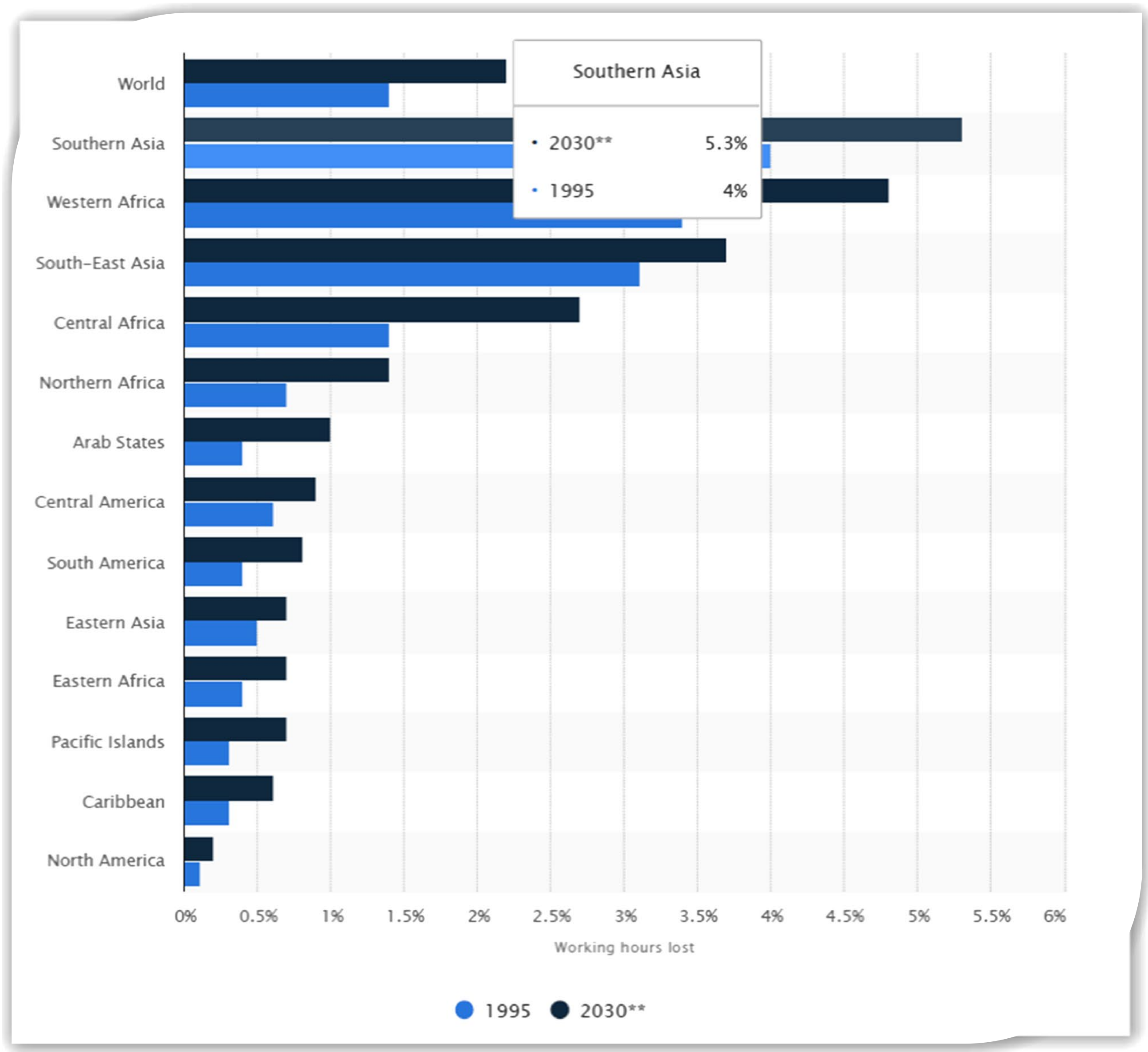

Fig. 7 A global trend in heat stress-induced-working hours lost during 1995 and 2030 (source: Statista 2021)

Plan (HAP) for each city/state would create public awareness about extreme climates save lives. The first HAP in South Asia was formulated in Ahmedabad (India) in 2010. By June 2017, HAP had been developed in 17 cities and 11 states across India (SEforALL 2021). The India Cooling Action Plan (ICAP) was developed in 2019, and it provides a 20-year plan for India's sustainable strategy to meeting future energy demand and providing thermal comfort (MOEFCC 2019).

Furthermore, the Government of India's energy services conglomerate, Energy Efficiency Services Limited (EESL), recently announced a 12-month pilot programme with Bombay Suburban Electric Supply (BSES), a utility in Delhi, that will include the deployment of superefficient air conditioners that are 40% more efficient than 3-star currently available ACs in the market, but are priced similarly. In Delhi, the pilot initiative seeks to reach around 2.5 million residential and institutional customers (The Hindu BussinessLine 2019). India could avoid paying for around 400 GW of additional power generation capacity by 2050 by adopting a superefficient cum climate-friendly cooling technology solution, saving nearly $380 billion or 15% of India's GDP in 2021 (World Bank 2021b). To summarise, India and the rest of the globe will be able to deliver cooling to all without overheating the planet by

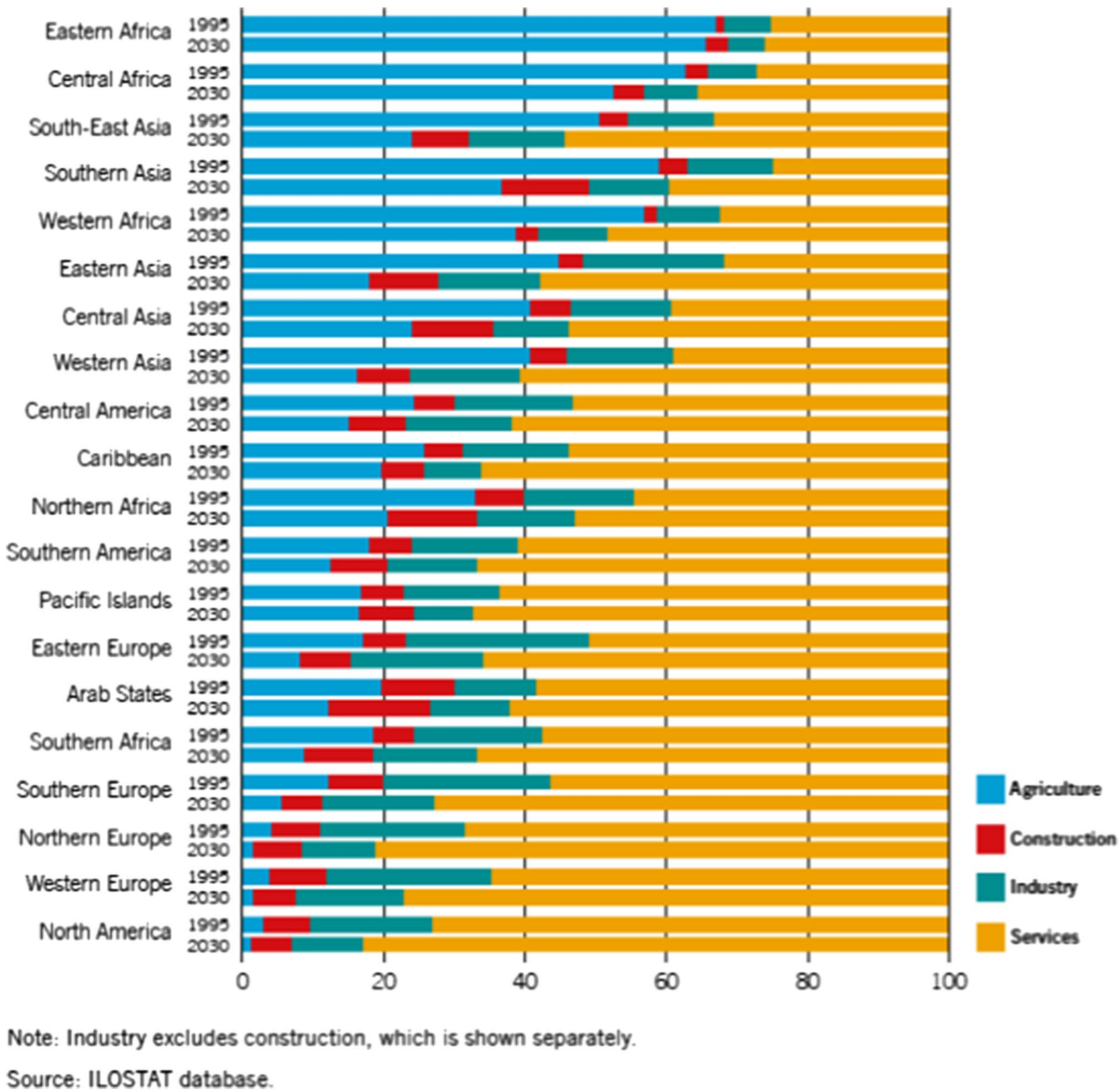

Fig. 8 Sectoral analysis of total employment by sub-region, in 1995 and projections of 2030 (in %) (source: ILO 2019). This figure has been reproduced after kind permission from the Rights & Licensing, ILO Publishing, Department of Communication

leveraging breakthrough technologies. In addition, adaptation approaches through the development of cool roofs and green barriers/green buildings would reduce energy consumption and help regulate the exposure to maximum temperatures during daytime but most importantly to the minimum temperatures at night—providing an alternative approach to attain cooling effect, and thus, avoid to some or more extent the influence of heat stress on mental health and physiological systems.

Climate change and public health in India: a regional perspective

According to India Meteorological Department (IMD) data, average temperatures in India have increased by 0.6 °C between 1901−1910 and 2009−2018 (IMD 2020). It is projected that under an unhindered changing climate scenario, the future average temperatures in India could increase from 25.1 °C to reach as high as 29.1 °C by 2100. This changing climate will negatively impact the living standards in

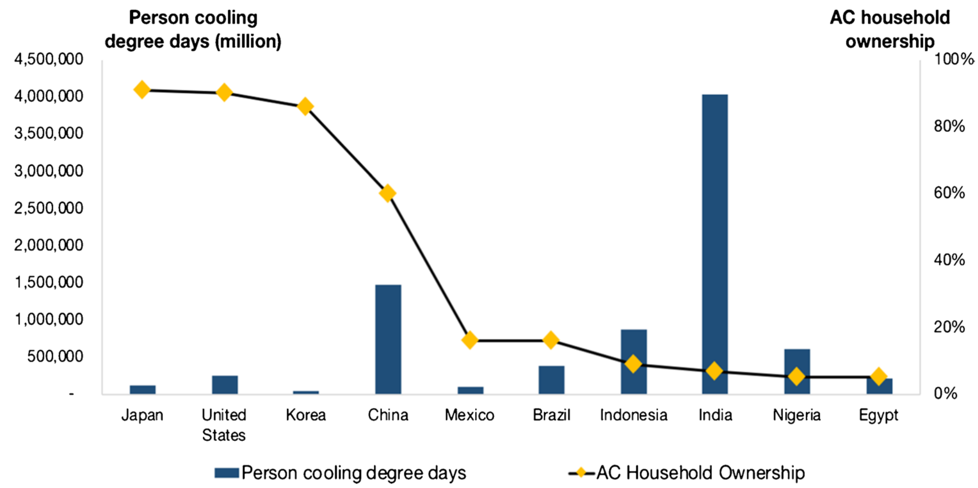

Fig. 9 Cooling demand vis-à-vis current air-conditioner ownership in different parts of the world (source: RMI 2019)

India, with already water-stressed areas being more vulnerable compared with the national average (Krishnan et al. 2020). Climate change in India is linked with multiple health impacts through numerous pathways, e.g., heat stress, wider spread of non-communicable (infectious) diseases, deteriorating ambient air quality and malnutrition, among others (FAO 2015; Romanello et al. 2021).

Heatwaves

By definition, heatwaves should not be considered until the maximum temperature at a station reaches at least 40 °C in plains, 37 °C in coastal areas and at least 30 °C in hilly areas, according to the India Meteorological Department (IMD) (IMD 2021). A deviation in max. temperature by + 4.5 °C to + 6.4 °C from normal should be considered as heatwaves, whereas a deviation from normal by > + 6.4 °C should be declared as severe heatwaves (IMD 2021). On the second day, a heat wave is proclaimed if the requirements hold true for two stations in a meteorological subdivision for two consecutive day. There have been two instances of "mega heat waves" because to stalled jet stream loops in the atmosphere: one in Europe killed 70,000 people in 2003, and another in Russia killed 56,000 people just 7 years later (Fig. 10) (The Conversation 2020). Even in the USA, heatwaves are the prominent risk factor of weather-related deaths.

Heatwaves cause dehydration, heat cramps, heat exhaustion and strokes are also found to exacerbate cardiovascular and kidney diseases (Kenney et al. 2014; Guleria and Gupta 2018; Johnson et al. 2019; NDMA 2021). Pregnant women, children and the elderly are particularly vulnerable to the impacts of the heatwave. During the extreme heatwave of April through June in 2010, a total of 24 neonatal ICU patients were admitted in the city of Ahmedabad (the States of Gujarat, western India), in comparison to 8 and 4 in 2009 and 2011 (Kakkad et al. 2014). The 2010 heatwave in the city of Ahmedabad (western India) has been identified to be associated with 1344 excess deaths in the month of May (Azhar et al. 2014). The intensity, duration, frequency and early occurrence of heat waves are all expected to increase due to the global climate change (USEPA 2021). As global heat wave characteristics are changing, the frequency, intensity and duration of heat waves are also increasing in India. Southern India which was previously untouched by heatwaves is likely to be impacted severely by extreme heat wave by the end of the twenty-first century (Das and Umamahesh 2021). A recent study has identified Northwestern, Central and South-Central regions as new hotspots of heat waves in India over the past 65 years (Singh et al. 2021c). Their study also highlighted that the heat waves led mortality risk

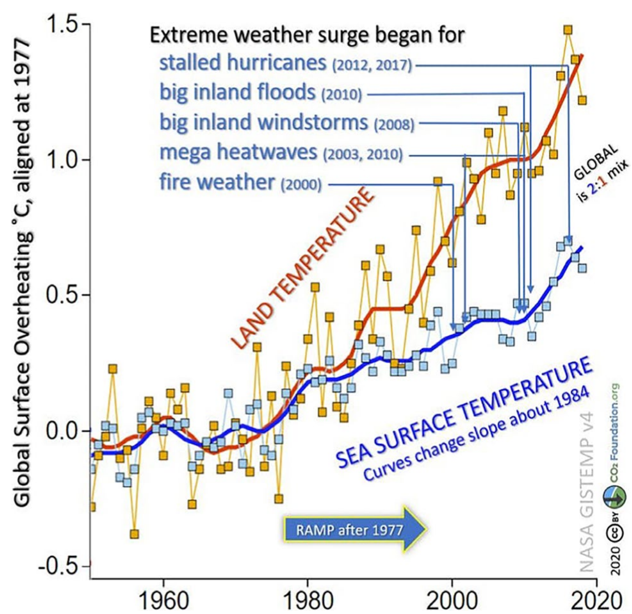

Fig. 10 Time-series record of the global surface overheating and mega heatwaves and other extreme weather surges (source: The Conversation 2020)

reporting a significant positive correlation between severe heat wave events and observed all-cause mortality in Andhra Pradesh (0.73) as well as in Odisha (0.62); these two states have witnessed most deaths due to the heat wave events in 1998, 2003, 2007, and 2015 (Singh et al. 2021c). Their study revisited previous findings from the IMD that most of the states exhibit a positive correlation between severe heat wave events and all-cause mortality (Fig. 11). Furthermore, another study found that the frequency of heatwaves will increase by 0.5 events per decade and their duration will increase by 4–7 days per decade in central and northwest India (Rohini et al. 2019). A recent study estimates that in India, 1.5 million excess annual deaths shall occur due to extreme temperatures by 2100 (Greenstone and Jina 2019). Thus, India could witness a 10% increase in death rates of the current death rate due to climate change.

Cold waves, daily mean temperature, diurnal temperature range and moderately cold temperature, in addition to heat waves, have a negative impact on human health (Fu et al. 2018; Singh et al. 2019; Mall et al. 2021). The moderately cold temperatures, when compared with extremely cold/moderately hot/extremely hot temperatures, have higher attributable risks: 6.3% [95% UI: 1.1−11.1] for all medical deaths, 27.2% [11.4−40.2] for stroke, 9.7% [3.7−15.3] for IHD (ischaemic heart disease) and 6.5% [3.5−9.2] for respiratory diseases (Fu et al. 2018). Thus, their study suggested that moderately cold temperature should also be taken into account as one of the prominent public health risk factors (Fu et al. 2018).

Non-communicable diseases (NCDs)

Changing climate is altering the patterns of precipitation and increasing the average temperature of the globe. This is altering the ecology of vectors and hence facilitating the spread of vector-borne diseases into new areas. For instance, due to warming up in the hilly states of the Himalayas, states in the north and northeast, including Himachal Pradesh (HP), Manipur, Mizoram, Nagaland and Arunachal Pradesh, are more likely to become malaria-prone regions. Malaria spread is also shifting from central India to the southwest coastal states of Maharashtra, Karnataka and Kerala. Similarly, dengue is now also spreading to hilly areas. Among the Himalayan states, HP and Uttarakhand as well as the north-eastern states of Manipur, Mizoram, Nagaland, Sikkim and Tripura have become dengue prone over the recent years (CBHI 2018).

Based on all five climate change projection models, Fig. 12a depicts the likely distribution of dengue fever transmission in 2050. It takes into account the combined effects of climate change and per capita gross domestic product (GDP) (Messina et al. 2015). Dengue transmission is presently occurring in red areas, according to the models, and is likely to continue until 2050. Dengue is not currently transmitted in dark green areas, and it is not expected to do so in the future. Dengue fever is anticipated to expand or reduce in light yellow and green areas, respectively, from its existing distribution. The distribution of dengue fever transmission in 2085 can be seen in Fig. 12b, which is based on climate projections from CCGCMA2 of vapor pressure (humidity) (Messina et al. 2015). Dengue transmission is not anticipated in the green areas on the map, while it is highly likely to occur in the red areas.

Climate change is also extending the malaria transmission window (for both *Plasmodium vivax* and *Plasmodium falciparum*) in the northeast Himalayas, with the window increasing from 7−9 to 10−12 months (Sarkar et al. 2019). Climate change can also affect infectious diseases

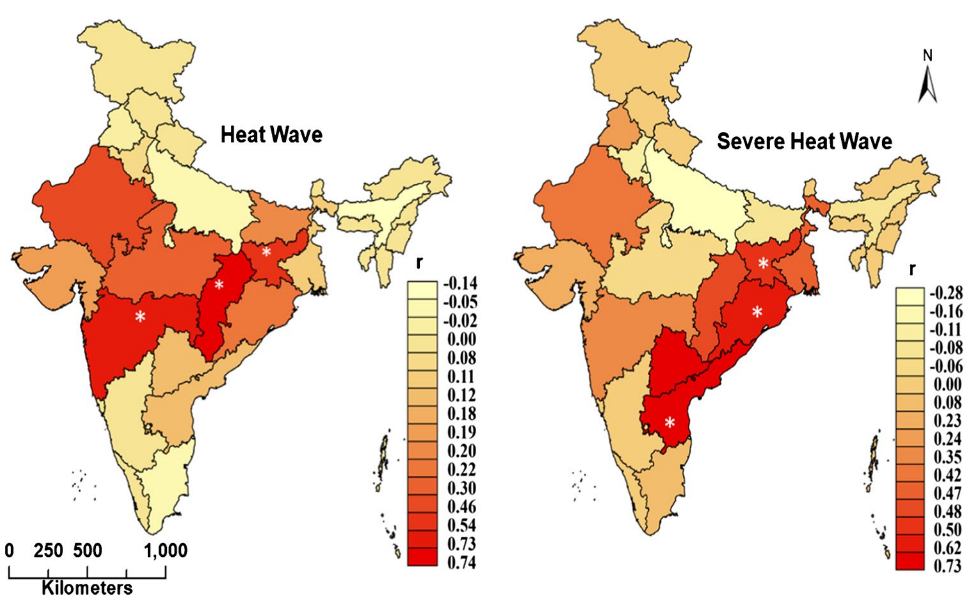

Fig. 11 Analysis of the correlation coefficients between heat waves and severe heat waves and all-cause mortality by state. An asterisk in the map indicates a significant correlation coefficient ($p < 0.05$) (source: Singh et al. 2021c)

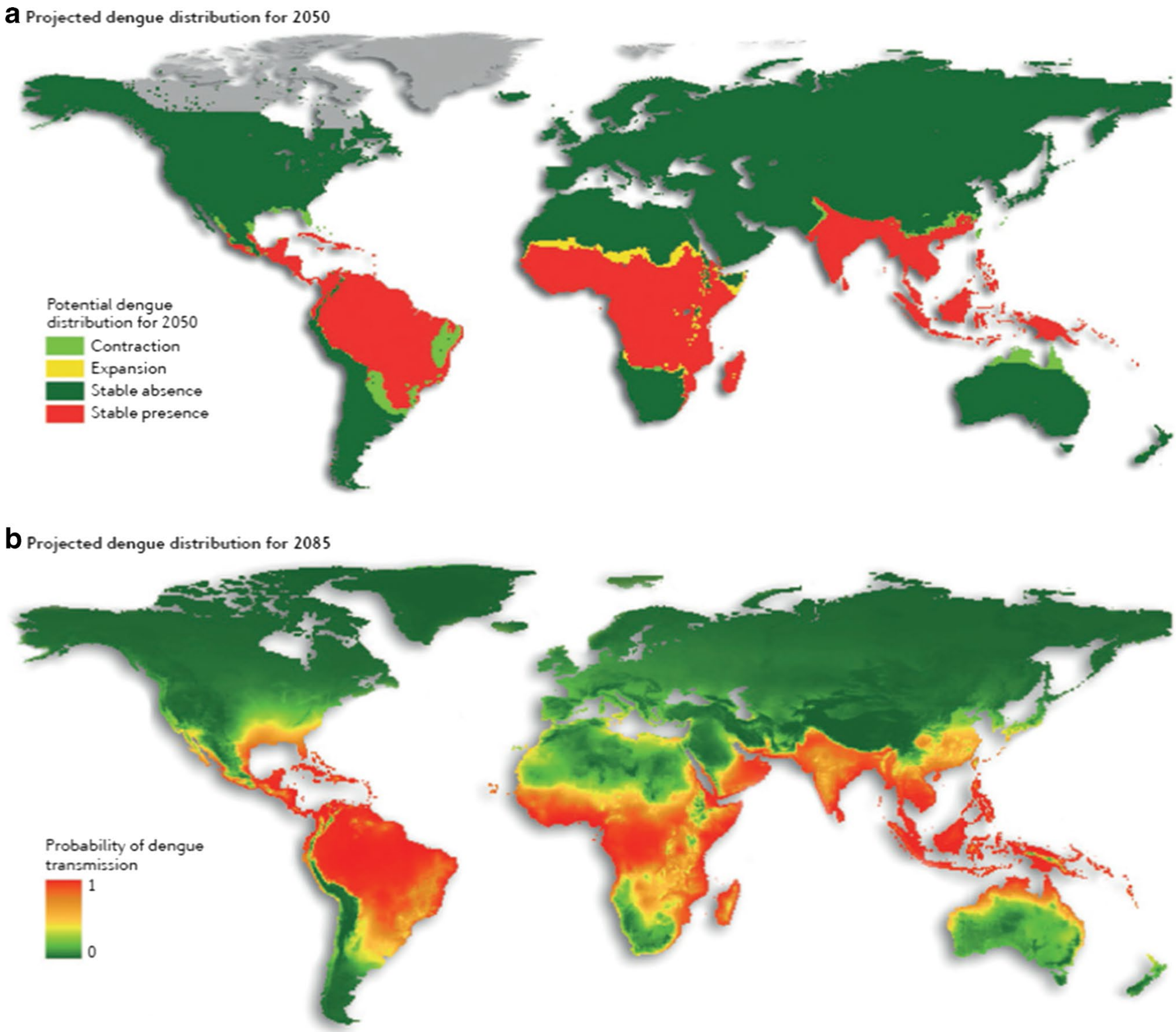

Fig. 12 Statistical future projection of the global distribution of dengue (source: Messina et al. 2015). Part a and b reproduced after kind permission from the corresponding author Dr. Jane P. Messina

by shortening their extrinsic incubation period (EIP: the amount of time taken for the organism to develop in the host) (WHO 2021b). Kerala, for example, has a much shorter dengue EIP of 8−15 days, and the state is experiencing a higher number of dengue cases over the years (Mutheneni et al. 2017). Chikungunya is another infectious disease that has been rising over the years. The number of clinically suspected cases of chikungunya in India has more than tripled over the last 7 years, with Bihar being one of the worst-hit states by the disease. The state had no cases of Chikungunya in 2013 and 2014, while in 2017, there were 1249 cases recorded of the disease. North-eastern states of Meghalaya and Tripura have also recorded a rise in chikungunya cases from 0 to 200 and 0 to 468, respectively, from 2013 to 2017 (CBHI 2018).

In addition to gradually changing temperature and precipitation patterns, climate change-associated extreme events such as floods can increase substantially the transmission of water-borne diseases, viz., typhoid fever, cholera, leptospirosis and hepatitis A (Mall et al. 2017; Chaubey et al. 2021, 2022). Flooding can result in stormwater overflow, leading to contamination of water supplies and resulting in a spike in water-borne diseases. An earlier study found a strong relationship between extreme precipitation and gastrointestinal illness (GI) among all ages: hospitalizations for GI-related illnesses increased by 1.6 times during Chennai's floods in India between 2004 and 2007 (Bush et al. 2014). Likewise, after the 2018 floods in Kerala, in 1 month, the state witnessed 2598 suspected cases of leptospirosis with 95 suspected deaths, while confirmed cases were 1318 with a death rate of 53 (4.0%) (IDSP 2018). Children and pregnant women are the most vulnerable populations in such cases. Workers who handle corpses on a regular basis in a flood situation are at risk of contracting tuberculosis, blood-borne viruses (such as Hepatitis B/C and HIV) and digestive tract infections (such as rotavirus diarrhoea, salmonellosis, *Escherichia coli*, typhoid/paratyphoid fever, hepatitis A, shigellosis and cholera) (WHO 2019).

Crop yield and nutrition content

Agriculture is one of the sectors most heavily impacted by climate change and is strongly linked with nutrition through multiple pathways. Climate change is resulting in reduced crop productivity at global as well as regional scales (Mall et al. 2018; Sonkar et al. 2019; Patel et al. 2022). For example, a previous study has projected for India a reduction of 9.1 ± 5.4% per °C in wheat and 6.6 ± 3.8% per °C in rice yields with increasing temperature (Zhao et al. 2017). Additionally, under a warming climate, wheat and rice production would suffer a pest-induced global loss of 10−25% per °C of warming (Deutsch et al. 2018). Sub-Saharan Africa and South Asia are particularly vulnerable to climate change-related productivity losses because their staple foods are often produced above their optimum temperatures.

In addition to affecting the overall yield, climate change also causes a decrease in the nutritional value of crops due to the rapid maturation of crops. Additionally, nutrient-rich crops are more susceptible to droughts, pests, diseases and temperature variability. Many key crops will have 3−17% reduced protein, iron and zinc concentrations when cultivated at elevated CO_2 levels of 550 ppm, according to a prior study (Smith and Myers 2018). By 2050, this would cause India to witness a 2.9% increase in zinc-deficient and 2.2% increase in protein-deficient population, with 49.6 million new zinc-deficient and 38.2 million new protein-deficient population. The study also projects that 106.1 million children (under 5 years) and 396 million women (15−59 years) would become iron-deficient. In a setting where anemia and micronutrient deficiency disorders are already widespread, there will be an exacerbation of undernutrition in India. The alternate pathway of transition to processed foods in the face of diminishing food and nutrition security can promote the growing epidemic of childhood overweight and obesity at the other end of the malnutrition spectrum, thus playing out the global syndemic of undernutrition, overnutrition and climate change (WHO 2017, 2021c). A recent estimate suggests that India's GDP (gross domestic product) in 2100 may decline by 10% at 3 °C of global warming due to declining agricultural productivity, sea-level rise and increases in health expenditure; 2.6% at 2 °C of global warming and 13.4% at over 4 °C due to declining labor productivity caused by changes in temperature and precipitation; and 90% at 3 °C, based on the historical relationship between temperature and GDP (Picciariello et al. 2021). The unirrigated agricultural areas are particularly more vulnerable to this reduction, where the drop in incomes could be as high as 20−25% (Sarkar 2018).

Earth science missions—augmenting our understanding of global climate change/air pollution/health, among others

The Airborne Science Program uses aircraft-based platforms to make high-resolution measurements to improve understanding of global systems (NASA 2022). Though we discuss below mainly NASA and its collaborative missions with other space agencies in the domain of global climate change, air pollution and health, it is worthwhile mentioning that the contributions of other space agencies, e.g., Indian Space Research Organization (ISRO), Japan Aerospace Exploration Agency (JAXA), China National Space Administration and Russian Space Research Institute (IKI) are also very important and well acknowledged globally.

Aqua (instruments: AIRS; AMSU; CERES; MODIS; AMSR-E)

Aqua's main goal is to increase an understanding of the Earth's water cycle by collecting data on ocean evaporation, atmospheric water vapor, clouds, precipitation, soil moisture, sea and land ice and snow cover.

Terra (instruments: ASTER; CERES; MISR; MODIS; MOPITT)

The five instruments on the spacecraft simultaneously examine the atmosphere, ocean, land, snow and ice of the planet. Additionally, the onboard MODIS and ASTER equipment offer crucial data collection for evaluating and managing natural catastrophes and other situations.

Aura (instruments: HIRDLS; MLS; OMI; TES)

Ozone, trace gases and aerosols are measured by its instruments, which are then used to interpret the atmospheric chemistry, air quality and their connections to climate change.

CALIPSO

The French space agency, CNES, collaborates with NASA on CALIPSO and manages the satellite. CloudSat data is combined with that from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission to provide 3D views of how clouds and aerosols originate, change and impact weather, climate and air quality.

CloudSat

CloudSat's radar penetrates clouds to expose their vertical structure since it is 1000 times more sensitive than weather radars. For 3D perspectives of how clouds and aerosols originate, change and influence weather, climate and air quality, its data is combined with that of CALIPSO. It was created through a collaboration between the Canadian Space Agency and NASA.

CYGNSS

Eight microsatellites are used in the CYGNSS mission to record wind speeds over the oceans, which helps scientists better understand and forecast hurricanes.

DSCOVR

DSCOVR, a collaboration between NOAA, NASA and the US Air Force, gathers information about the Earth's atmosphere and keeps its ability to continuously monitor the solar wind. With the help of this data, NOAA produces space weather forecasts and alerts for occurrences like geomagnetic storms brought on by the variations in the solar wind.

ECOSTRESS

The ECOsystem Spaceborne Thermal Radiometer Experiment on the Space Station mission, which is currently in orbit around the International Space Station, will record plant temperatures to determine their water requirements. This can help improve the effectiveness of crop irrigation and provide predictions for how various plant species will adapt to climate change.

EMIT

The Earth Surface Mineral Dust Source Investigation (EMIT), mounted on the International Space Station, will examine the makeup of the planet's arid regions to investigate how dust loading and transit in the atmosphere impact climate.

GEDI

The Global Ecosystem Dynamics Investigation (GEDI), scheduled to launch in 2024 on the exterior of the International Space Station, will be the first space-borne laser to measure the structure of the planet's tropical and temperate forests in high resolution in three dimensions. This will make it easier to comprehend climate change.

GeoCarb

The Geostationary Carbon Observatory (GeoCarb) aims to collect 10 million daily observations of the concentrations of carbon dioxide, methane, carbon monoxide and solar-induced fluorescence (SIF) by mounting instrument(s) on a commercial communication satellite flying in geostationary orbit.

GPM

The Global Precipitation Measurement mission, which includes a network of satellites from different countries and continents, boosts knowledge of the water and energy cycles and enhances storm forecasting.

GRACE-FO

The Gravity Recovery and Climate Experiment Follow On mission continues the original GRACE mission of measuring changes in gravity distribution over Earth's surface to reveal the movement of large masses of water and ice.

GRIFEX

A technological validation mission created by JPL, the GEO-CAPE ROIC In-Flight Performance Experiment (GRIFEX), increases spaceborne measurements of atmospheric composition important to climate change.

HyspIRI

The HyspIRI (or Hyperspectral Infrared Imager) mission analyses ecosystems around the world and provides vital data on natural disasters including volcanoes, wildfires and drought. The sort of plant that is there and its health will be able to be determined by HyspIRI.

ICESat-2

The Ice, Cloud and Land Elevation Satellite-2 mission continues ICESat's laser-altimeter measurements of ice-sheet elevation, sea-ice thickness and tree-canopy height to track changes in the ice sheets of Greenland and Antarctica and determine the mass of all the vegetation on the planet.

ISS-RapidScat

Microwaves are fired off the ocean's surface by ISS-RapidScat, which then measures the pulses that return. Stronger signals indicate rougher waves brought on by more powerful winds. It is worthwhile mentioning here that for making accurate short- and long-term weather forecasts, tracking storms, examining climatic patterns and comprehending how the wind, ocean and marine life interact, ocean-wind statistics are essential.

Jason-3

The US-European satellite programme called Jason-3 measures changes in ocean surface height. Understanding ocean circulation patterns, regional and global sea-level variations and climate change would all benefit from measurements made over such a long period.

Landsat 7/8/9

Landsat satellites repeatedly image the surface of the Earth with a spatial resolution that reveals how people interact with their surroundings. It is a cooperative project of NASA and the US Geological Survey that informs decisions globally on urban development, natural disasters, forest loss and regrowth, glacier melting, agriculture and a variety of other topics.

LIS

The Lightning Imaging Sensor (LIS) is still used to gauge the frequency, intensity and size of lightning strikes. Enhancing our knowledge of lightning and its relationships to the weather can help us better predict the weather; comprehend climate change, the chemistry and physics of the atmosphere; and ensure the safety of aircraft and spacecraft.

MAIA

MAIA's main purpose is to augment our understanding of the effects of different types of particulate air pollution on our health, scheduled to launch in 2022.

NOAA-N

Developed by NASA for the National Oceanic and Atmospheric Administration, NOAA-N is a polar-orbiting satellite (NOAA). To better weather forecasting and global climate research, NOAA-N gathers data on Earth's environment and atmosphere.

OCO-2/OCO-3

The Orbiting Carbon Observatory mission's objective is to deepen knowledge of the carbon cycle and the mechanisms that control atmospheric CO_2 levels so that scientists can forecast CO_2 increases and their effects on Earth's climate more accurately.

Sentinel-6 Michael Freilich (formerly Sentinel-6A)

Sentinel-6 Michael Freilich continues the work started by the Jason-1, Jason-2/OSTM and Jason-3 missions by measuring the sea surface height with extreme precision. To aid in the production of numerical weather forecasts, a secondary goal is the collection of high-resolution vertical profiles of temperature and water vapor.

SMAP

The Soil Moisture Active Passive mission measures soil moisture and identifies areas of frozen or thawed soil using both active (radar) and passive (receiving natural microwave emissions from the ground) techniques. The mission is still being carried out despite the radar not functioning. SMAP improves the ability to track and forecast floods, droughts and agricultural yields by deepening our understanding of the connections between the water, energy and carbon cycles.

SORCE

The total and temporal amount of sunlight that reaches Earth is continuously measured by Solar Radiation and Climate Experiment. Scientists can better comprehend the sun's effects on Earth's weather and climate systems with the use of SORCE data.

Suomi NPP

The NPP satellite has five very diverse instruments on board to track Earth's ecology and climate. Land cover will be mapped using NPP values, and vegetation productivity will be tracked over time. The NPP measures marine and land surface temperatures as well as air ozone and aerosols. The NPP keeps track of glaciers, land ice and sea ice all across the world. Natural catastrophes like volcanic eruptions, wildfires, droughts, floods, dust storms and hurricanes/typhoons can also be monitored by NPP.

SWOT

Water body changes on Earth will be meticulously measured by the Surface Water and Ocean Topography (SWOT) satellite. At least twice every 21 days, the satellite will analyse Earth's water bodies and help with global freshwater management, improve ocean circulation models and make weather and climate predictions.

TEMPO

The TEMPO (Tropospheric Emissions: Monitoring Pollution) mission will be the first space-based instrument to perform high spatial resolution monitoring of main air pollutants continuously across the North American continent, scheduled to launch in 2022.

Policies and actions

Based on the IPCC's AR4 report, showing increased intensity and frequency of extreme weather events, especially in tropical and sub-tropical regions, the PMCC was formed in 2007 and reconstituted in 2014 to raise awareness and preparedness for climate actions. The National Action Plan for Climate Change (NAPCC) was introduced in 2008 to achieve mitigation and adaptation to climate change. Taking messages and decisions forward, from COP21 (2015, in Paris, France) through COP26 (2021, in Glasgow, UK), India is reframing actions to address climate change and environmental and public health. In order to place a proper attention on climate change and its influence on human health, the Ministry of Health and Family Welfare formed a National Expert Group on Climate Change and Health in 2015−2016. The group was constituted to develop a National Action Plan on Climate Change and Human Health (NAPCCHH) (NAPCCHH 2018). The major objectives of NAPCCHH include elements for building climate-resilient health systems (Kumar et al. 2020). Additionally, health adaptation in India is one of the priority actions listed in its NDCs (nationally determined contributions) (NAPCCHH 2018). The National Disaster Management Authority of India (NDMA) has developed a national heat-health action plan that is to be adopted by all states. This is primarily focused on adaptation and partly to build resilience towards the health impacts of climate change (MoHFW 2019; WHO 2021a).

Recommendations to stakeholders for implementing policies in the country are as given below:

1. Community-based mapping of the vulnerable population on both regional and national level.
2. City-level climate action plans accounting for specific microclimates and health impacts.
3. Climate change mitigation and adaptation policies must be assessed and combined with the air pollution abatement policies.
4. Promote research and facilitate capacity building on climate change and health to understand the changing disease burden and health impact assessment.

Conclusions

Mobilization of funds for researching climate change-air pollution-public health domain should be considered a top-rank priority. Healthcare professionals and researchers working on air pollution and climate change must keep collaborating and share their data for a joint study on different health outcomes. Gridded mapping of the vulnerable population across the country based on gender, age groups, socioeconomic status (SES), etc. is needed to better understand the extent of direct as well as indirect negative impacts of climate change on public health in India. Climate-resilient and climate-smart healthcare system approaches are needed to guide actions required to transform and reorient healthcare systems to effectively align health development and delivery with global climate goals. Stringent policies and actions in India on a gridded basis are also needed for coping with the impact of climatic change on public health in near-term, mid-term and long-term future scenarios.

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Declarations

Ethics approval and consent to participate Not applicable.

Conflict of interest The authors declare that they have no competing interests to mention.

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