McKinsey Global Institute

Climate risk and response: Physical hazards and socioeconomic impacts

Will India get too hot to work?

Case study

November 2020

McKinsey Global Institute

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Introduction to case studies

In January 2020, the McKinsey Global Institute published *Climate risk and response: Physical hazards and socioeconomic impacts*. In that report, we measured the impact of climate change by the extent to which it could affect human beings, human-made physical assets, and the natural world. We explored risks today and over the next three decades and examined specific cases to understand the mechanisms through which climate change leads to increased socioeconomic risk. This is one of our case studies, focused on India. The analysis was completed prior to the COVID-19 pandemic.

In order to link physical climate risk to socioeconomic impact, we investigated cases that illustrated exposure to climate change extremes and proximity to physical thresholds. These cover a range of sectors and geographies and provide the basis of a "micro-tomacro" approach that is a characteristic of McKinsey Global Institute research. To inform our selection of cases, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We found these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

We ultimately chose nine cases to reflect these systems and based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds (Exhibit 1). As such, these cases represent leading-edge examples of climate change risk. Each case is specific to a geography and an exposed system, and thus is not representative of an "average" environment or level of risk across the world. Our cases show that the direct risk from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" of capital (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). We typically define the climate state today as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Through our case studies, we also assess the knock-on effects that could occur, for example to downstream sectors or consumers. We primarily rely on past examples and empirical estimates for this assessment of knock-on effects, which is likely not exhaustive given the complexities associated with socioeconomic systems. Through this "micro" approach, we offer decision makers a methodology by which to assess direct physical climate risk, its characteristics, and its potential knock-on impacts.

Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. Such an "inherent risk" assessment allows us to understand the magnitude of the challenge and highlight the case for action. (We also choose a sea level rise scenario for one of our cases that is consistent with the RCP 8.5 trajectory). Our case studies cover each of the five systems we assess to be directly affected by physical climate risk, across geographies and sectors. While climate change will have an economic impact across many sectors, our cases highlight the impact on construction, agriculture, finance, fishing, tourism, manufacturing, real estate, and a range of infrastructure-based sectors. The cases include the following:

— For livability and workability, we look at the risk of exposure to extreme heat and humidity in India and what that could mean for that country's urban population and outdoor-based sectors, as well as at the changing Mediterranean climate and how that could affect sectors such as wine and tourism.

— For food systems, we focus on the likelihood of a multiple-breadbasket failure affecting wheat, corn, rice, and soy, as well as, specifically in Africa, the impact on wheat and coffee production in Ethiopia and cotton and corn production in Mozambique.

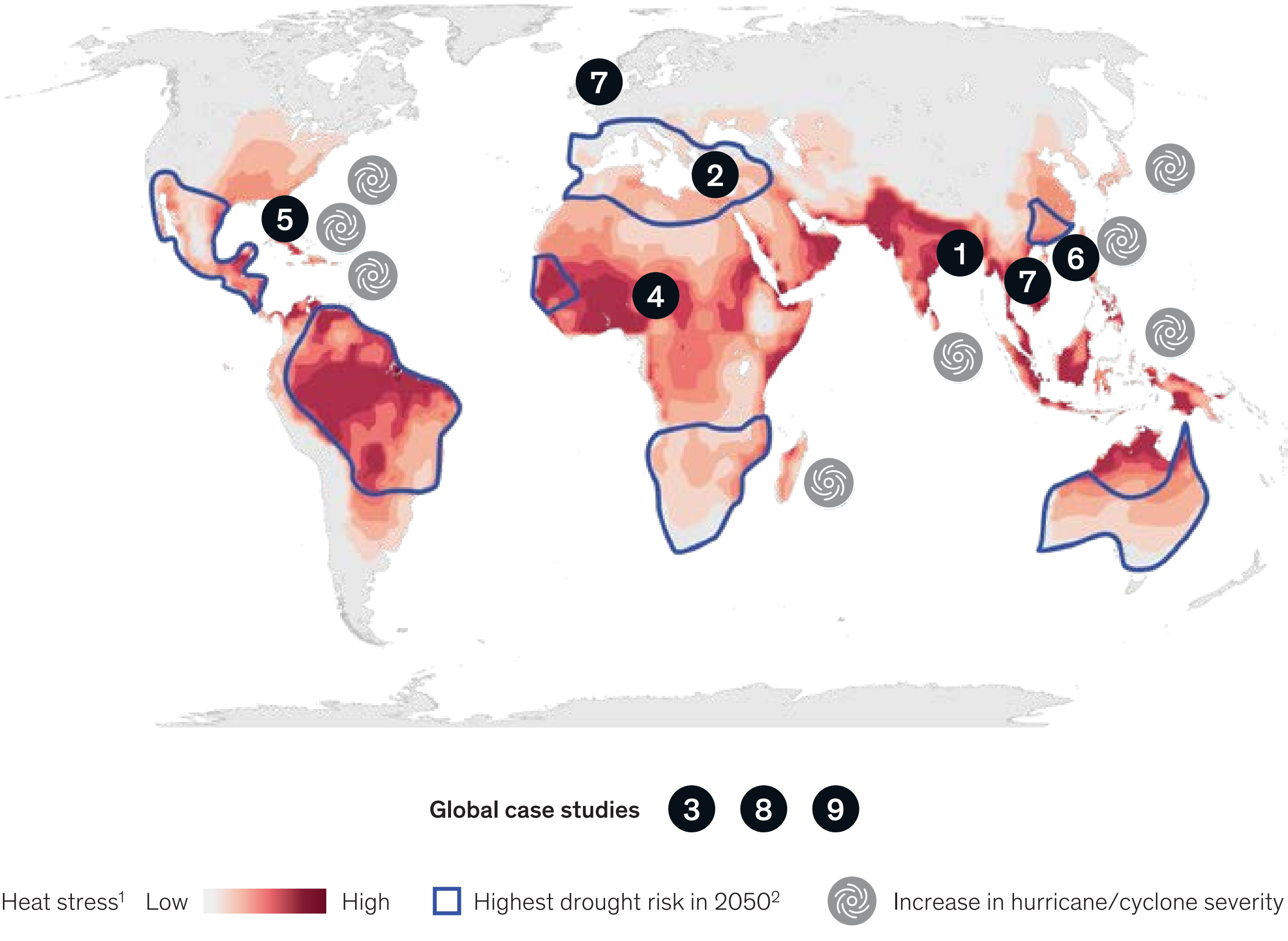
— For physical assets, we look at the potential impact of storm surge and tidal flooding on Florida real estate and the extent to which global supply chains, including for semiconductors and rare earths, could be vulnerable to the changing climate.

— For infrastructure services, we examine 17 types of infrastructure assets, including the potential impact on coastal cities such as Bristol in England and Ho Chi Minh City in Vietnam.

— Finally, for natural capital, we examine the potential impacts of glacial melt and runoff in the Hindu Kush region of the Himalayas; what ocean warming and acidification could mean for global fishing and the people whose livelihoods depend on it; as well as potential disturbance to forests, which cover nearly one-third of the world's land and are key to the way of life for 2.4 billion people.

Exhibit 1

We have selected nine case studies of leading-edge climate change impacts across all major geographies, sectors, and affected systems.



Livability and workability	1	Will India get too hot to work?
	2	A Mediterranean basin without a Mediterranean climate?
Food systems	3	Will the world's breadbaskets become less reliable?
	4	How will African farmers adjust to changing patterns of precipitation?
Physical assets	5	Will mortgages and markets stay afloat in Florida?
	6	Could climate become the weak link in your supply chain?
Infrastructure services	7	Can coastal cities turn the tide on rising flood risk?
	8	Will infrastructure bend or break under climate stress?
Natural capital	9	Reduced dividends on natural capital?

1. Heat stress measured in wet-bulb temperatures.
2. Drought risk defined based on time in drought according to Palmer Drought Severity index (PDSI).

Source: Woodwell Climate Research Center; McKinsey Global Institute analysis

Pause while setting up a road sign. Agra, India.

India

Will India get too hot to work?

India has been on a remarkable development journey over the past two decades. The world's most populous democracy has averaged 7 percent year-over-year growth since its economic liberalization in the late 1990s and has been among the fastest-growing nations in the G-20 since 2014. Its rapid economic growth has allowed India to dramatically increase the quality of life of its citizens. In the decade between 2005 and 2015, more than 270 million people, or a quarter of India's population, were lifted out of multifactor poverty.[1]

While India is grappling with the COVID-19 pandemic, it cannot lose sight of climate risk, which is rising. The coronavirus crisis holds profound lessons that can help us address climate risk—if we make greater economic and environmental resiliency core to our planning for the recovery ahead.[2] Indeed economic stimulus in the wake of the pandemic can help restore growth, while also addressing climate risk.[3] India's strong economic performance is expected to resume over the coming decades, creating the world's third largest consumer market, and slowly but surely delivering housing, sanitation, electricity, and other necessities to the remaining 300 million citizens who still live in multifactor poverty.[4] This does not mean, however, that future growth will be without challenges. For example, uncertainty still remains around the duration and impact of the pandemic. Then there are other non-pandemic related challenges. According to the World Economic Forum, more than half of Indian workers need reskilling by 2022 in order to meet the talent demands of a rapidly modernizing economy.[5] The participation rate of women in the labor force lags well behind its peers, at only 25 percent, and over the next 30 years the national electric power system will have to quadruple in size to keep pace with rapid growth in electricity demand.[6] In addition to these significant developmental priorities, India faces another, increasingly visible threat that it must cope with: a rapidly changing and degrading physical environment. The challenges of water scarcity and air pollution are well known. Less well appreciated is the impact extreme heat and humidity will likely have on the economy and the toll it could take on human life.

In this case study, we analyze the direct impact of climate-change-driven heat and humidity extremes on India. We first analyze the "inherent risk" that is expected to manifest over the next decade, absent adaptation and mitigation, and then examine the evolution of that risk through to 2050 under an RCP 8.5 scenario.[7] We find that India could become one of the first places in the world to experience heat waves that cross the survivability limit for a healthy human being sitting in the shade. Without targeted adaptation action, around 160-200 million

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1 Oxford Poverty and Human Development Index, Global Multidimensional Poverty Index (MPI), 2018. Multifactor poverty is an index that includes access not only to income, but also to electricity, proper nutrition, sanitation facilities, educational opportunity, and housing.

2 *Addressing climate change in a post-pandemic world*, McKinsey & Company, April, 2020.

3 *How a post pandemic stimulus can both create jobs and help the climate*, McKinsey & Company, May 2020.

4 Long-term forecasts include, but not restricted to, World Economic Forum, 2019, Standard Chartered, 2019, Government of India, 2019, Bloomberg, 2019, Japan Center for Economic Research, 2017. Forecasts are generally built on the explicit assumption that many of the historical drivers of growth will persist into the future. These include: favorable demographics (about seven million new workers have joined the labor force each year for the past decade); a strong and rapidly growing services sector, producing 43 percent of GDP and growing at about 8 percent a year; continuing digitization of both the private and public sectors; a strong domestic consumption rate (roughly 60 percent of GDP) relative to peer countries; and a high savings rate (30.5 percent in 2018).

5 *The future of jobs report 2018*, World Economic Forum, 2018.

6 "Labor force participation rate, female, India," The World Bank; Gautam Raina and Sunanda Sinha, "Outlook on the Indian scenario of solar energy strategies: Policies and challenges," *Energy Strategy Reviews*, April 2019, Volume 24.

7 The scientific community has developed a set of standardized scenarios that act as a common language across climate modeling research. These scenarios project changes in atmospheric greenhouse gas levels over time and are known as Representative Concentration Pathways (RCPs). We have relied on RCP 8.5 for the analysis in this report to represent the changes in atmospheric greenhouse gas concentrations that could occur absent a mitigation response over the next three decades. While RCP 8.5 has been criticized for projecting unrealistic levels of GHG emissions in the second half of the century, it has been adopted as a reasonable choice when investigating changes over the next two to three decades in isolation. Please see technical appendix of the full report for further details. The climate state today is defined as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060.

people in India could annually bear a 5 percent chance of being exposed to a lethal heat wave as early as 2030, a ~40 percent cumulative likelihood over the decade centered on 2030.[8] We further estimate that the effective number of outdoor working hours lost will increase approximately 15 percent by 2030, resulting in approximately 2.5-4.5 percent, or $150-250 billion, risk to GDP.[9] By 2050, both the intensity of and exposure to lethal heat waves, as well as the impact on outdoor work, could increase in a nonlinear way.

Given the inherent risk projection, adaptation is likely to happen, for example, by shifting working hours for outdoor workers, undertaking albedo heat management efforts in cities, establishing early-warning systems and cooling shelters to protect people, and, at the extreme, movement of people and capital from high-risk areas. Investing in heat management will be critical, and stakeholders will also need to consider approaches to accelerate the transition out of outdoor work already underway. Adaptation in general will be challenging because heat is a pervasive risk and involves fundamental changes in how people conduct their daily lives (for example, shifting work hours may entail potential cultural and economic difficulties). Adaptation will be particularly challenging for the urban poor, who will likely require public support, for example in the form of emergency shelters. We calculate that addressing some of the risk of lethal heat waves by 2030, using air-conditioning, could come with capital costs of up to $110 billion.[10] Both public- and private-sector stakeholders have an important role to play in developing and delivering the necessary technological and regulatory solutions.

The threat of extreme heat and humidity is less widely appreciated than that of water scarcity and air pollution

Some 600 million people in India already face high to extreme water stress, and 70 percent of available water resources are contaminated, according to the National Institution for Transforming India (NITI Aayog).[11] By the end of 2020, 21 cities, including New Delhi and Hyderabad, are projected to run out of groundwater, affecting 100 million people, and by 2030 the national water supply is forecast to outstrip demand by 100 percent, leaving 40 percent of the population, or half a billion people, without access to drinking water.[12]

In addition, a 2018 *Lancet* report found that mean exposure to airborne particles in India was more than twice the level recommended by the Indian National Ambient Air Quality Standard, and nine times higher than the World Health Organization's recommended safe exposure level.[13] Currently, one in eight deaths in India every year is due to air-pollution-related disease.[14]

There have been several steps taken to address these issues. In May 2019, the Ministry of Water Resources, River Development & Ganga Rejuvenation merged with the Ministry of Drinking Water and Sanitation to form the Ministry of Jal Shakti, which has a sweeping mandate to address water scarcity across India. In January 2019, the government launched the National Clean Air Programme, with the goal of cutting pollution in the 100 most affected cities by 20 to 30 percent by 2024. A third environmental threat remains, however: the effect of climate-change-driven heat and humidity extremes on India's people.

The most fundamental impact of climate change is an increase in temperatures across the globe. As temperatures increase, the most vulnerable nations will be those in areas

8 Cumulative likelihood calculated by using annual probabilities for the climate state in the 2030 period. Annual probabilities are independent and can therefore be aggregated to arrive at a cumulative decadal probability. This calculation is a rough approximation as follows: It assumes that the annual probability of X percent applies to every year in the decade centered on 2030. We first calculate the cumulative probability of the event not occurring in that decade, which is 1 minus X raised to the power of 10. The cumulative probability of a the event occurring at some point in the decade is then 1 minus that number.
9 Dollar amounts calculated in real terms, using 2011–12 rupees and spot exchange rates.
10 This estimate takes into account BAU grow rates of air-conditioning penetration.
11 NITI Aayog, Composite Water Management Index, 2018.
12 Ibid.
13 India State-Level Disease Burden Initiative Air Pollution Collaborators, "The impact of air pollution in deaths, disease burden, and life expectancy across the states of India: The Global Burden of Disease Study 2017," *Lancet Planetary Health*, January 2019, Volume 3, Number 1.
14 Ibid.

that are already hot and humid. This is because there are limits to the levels of heat stress under which human bodies (as well as physical and natural systems) can effectively operate, and the nations closest to those thresholds today will be the first to experience the consequences of crossing them.

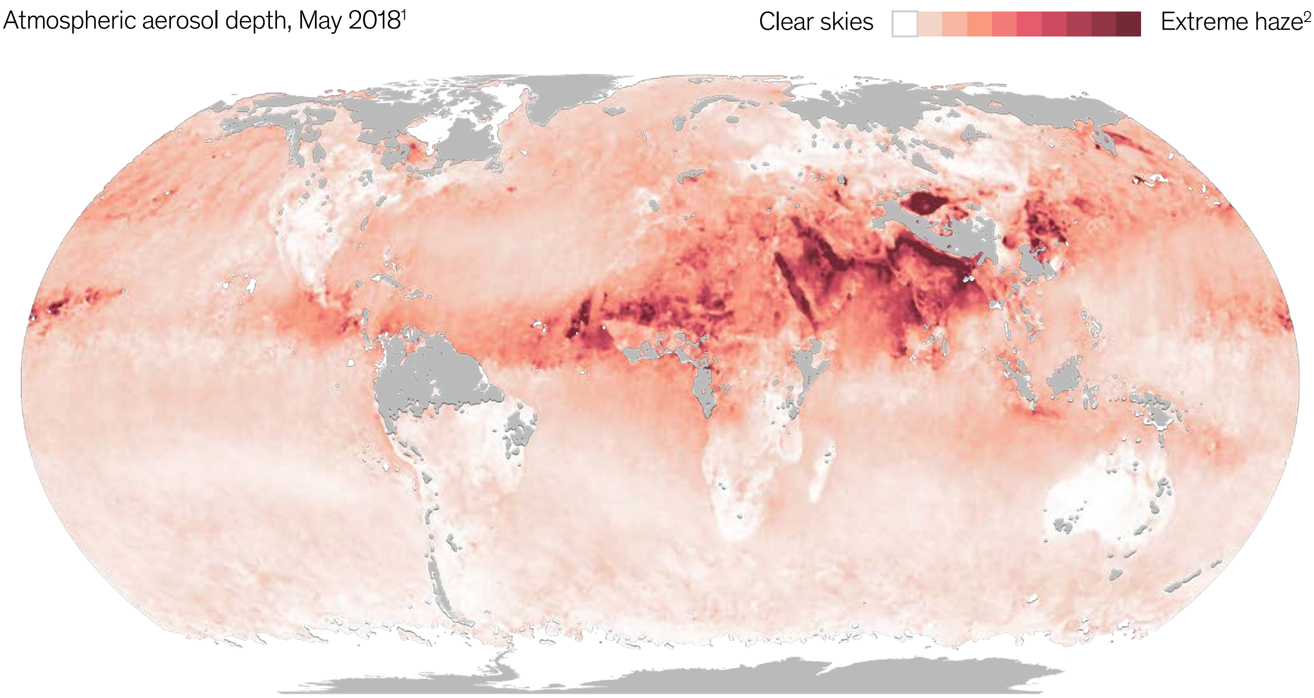
While the hottest air temperatures ever recorded have been in places like Saudi Arabia, the Sahara Desert, and Death Valley, California, in the United States, the north of India has historically exhibited some of the world's hottest wet-bulb temperatures.[15] Wet-bulb temperature is an indicator that combines air temperature and relative humidity. It provides a more accurate measure of heat stress on the human body than air temperature alone (see Box 1, "What extreme heat and humidity mean for the human body").

Over the past 30 years, maximum wet-bulb temperatures across India have steadily climbed, driven by an increase in humidity, but maximum air temperatures have not increased.[16] The explanation for these two different trends is the concurrent rise in atmospheric aerosols, or air pollution, which reflect a proportion of incoming sunlight and therefore artificially cool the region, reducing air temperatures (India-1).[17] Additionally, widespread irrigation reduces air temperature through evaporation, but increases humidity.[18] In other words, the air pollution crisis is reducing the amount of heat stress currently facing India's economy and its people, and, in many areas, heat stress is influenced by irrigation practices. However, as stakeholders act to reduce air pollution levels, and as the Earth warms over the coming decades, the true magnitude of the threat from extreme heat and humidity will manifest itself.[19]

Case study India-1

Temperatures during India's hottest months are mitigated by a high concentration of atmospheric particles.

Atmospheric aerosol depth, May 2018[1]



1. Atmospheric aerosol depth is a measure of the extinction of the solar beam by dust and haze. It is a dimensionless number that is related to the amount of aerosol in the vertical column of atmosphere over the observation location.
2. We define extreme haze as atmospheric aerosol depth of 1.0.

Source: NASA Earth Observatory

[15] Steven C. Sherwood and Matthew Huber, "An adaptability limit to climate change due to heat stress," *Proceedings of the National Academy of Sciences*, May 25, 2010, Volume 107, Number 21; Eun-Soon Im, Jeremy S. Pal, and Elfatih A. B. Eltahir, "Deadly heat waves projected in the densely populated agricultural regions of South Asia," *Science Advances*, August 2, 2017, Volume 3, Number 8.

[16] Geert Jan van Oldenborgh et al., "Extreme heat in India and anthropogenic climate change," *Natural Hazards and Earth System Sciences*, 2018, Volume 18, Number 1.

[17] Ibid.

[18] Ibid.

[19] US NASA Earth Observatory.

Box 1.

What extreme heat and humidity mean for the human body

The human body must maintain a relatively stable core temperature of approximately 37 degrees Celsius to function properly. Pushing the core temperature out of equilibrium only a few degrees in either direction results in rapid negative consequences.[1] Physiological literature shows that performance under heat stress declines very rapidly.[2] The core temperature needs to rise only 0.06 degree to compromise task performance requiring vigilance, 0.2 degree to compromise multitasking ability, 0.9 degree to compromise neuromuscular coordination, 1.3 degrees to affect simple mental performance, 3 degrees to induce dangerous heat stroke, and 5 degrees to cause death.[3]

In environments where air temperatures are higher than skin or core temperatures, the body loses its ability to effectively dissipate heat through radiation and convection, and core temperature is determined primarily by a combination of activity level and wet-bulb temperature—a measure of air temperature and relative humidity—that determines how much heat the body can exhaust through the evaporation of sweat.[4]

Human beings are able to acclimatize to extreme temperatures by increasing the volume of sweat that their bodies process. The Bedouin, for example, have lived in the deserts of North Africa and the Arabian Peninsula for hundreds of years. They survive extreme air temperatures without the use of air-conditioning because they can dissipate enormous quantities of heat into the dry desert air through perspiration. With the introduction of humidity, however, the ability of air to hold additional water decreases, and the evaporation of sweat becomes more difficult, making heat stress harder to bear.[5]

For this reason, high wet-bulb temperatures—a function of both air temperature and relative humidity—are more dangerous to human beings than extreme air temperatures. Wet-bulb temperature is technically defined as the minimum temperature to which a parcel of air can be cooled by evaporation at a constant pressure. As wet-bulb temperatures increase, the ability of human beings to exert effort or perform work decreases due to two factors: firstly, the need to take breaks to avoid the physiological consequences of core temperature rise, and secondly, the body "self-limiting" or instinctively fatiguing, to prevent overheating.[6] At a wet-bulb temperature of 35 degrees, healthy, well-hydrated human beings resting in the shade would see core temperatures rise to lethal levels after roughly four to five hours of exposure.[7] Any introduction of direct sunlight, activity, or dehydration would shorten this period. According to the scientific literature, 35 degrees wet-bulb temperature is commonly regarded as the heat-stress limit for human survival.[8] In order to better conceptualize this threshold, 35-degree wet-bulb temperature can be roughly defined as a convex line on a temperature/humidity axis, running between 35-degree air temperature with 100 percent relative humidity, and 50-degree air temperature with 40 percent relative humidity.

1 Gaither D. Bynum et al., "Induced hyperthermia in sedated humans and the concept of a critical thermal maximum," *American Journal of Physiology*, November 1978, Volume 235, Number 5.

2 P. A. Hancock and Ioannis Vasmatzidis, "Human occupational performance limits under stress: The thermal environment as a prototypical example," *Ergonomics*, 1998, Volume 41, Number 8.

3 Ibid.

4 Ken Parsons, *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance*, second edition, New York, NY: Taylor & Francis Group, 2014.

5 Ibid.

6 Tord Kjellstrom et al., "Estimating population heat exposure and impacts on working people in conjunction with climate change," *International Journal of Biometeorology*, March 2018, Volume 62, Number 3.

7 Steven C. Sherwood and Matthew Huber, "An adaptability limit to climate change due to heat stress," *Proceedings of the National Academy of Sciences*, May 25, 2010, Volume 107, Number 21; threshold confirmed, assuming light clothing cover, using the physiological Predicted Heat Strain (PHS) model; Jacques Malchaire et al., "Development and validation of the predicted heat strain model," *Annals of Occupational Hygiene*, March 2001, Volume 45, Number 2.

8 Steven C. Sherwood and Matthew Huber, "An adaptability limit to climate change due to heat stress," *Proceedings of the National Academy of Sciences*, May 2010, Volume 107, Number 21; Eun-Soon Im, Jeremy S. Pal, and Elfatih A. B. Eltahir, "Deadly heat waves projected in the densely populated agricultural regions of South Asia," *Science Advances*, August 2017, Volume 3, Number 8.

Rising wet-bulb temperatures could put millions of lives and billions of dollars at-risk

Climate models project that some areas of India may become the first places on Earth to be exposed to heat and humidity so extreme that, without adaptation measures such as air-conditioning, healthy adults risk succumbing to heat waves in large numbers (India-2).[20] While wet-bulb temperatures during the worst heat waves in India today rarely, if ever, exceed 32 degrees, the climatological analysis conducted for this case study indicates that temperatures during the most severe heat waves in the hottest parts of India could begin to breach 34 degrees by 2030. Such high temperatures have been recorded only a couple of times on Earth, including a 34.6-degree wet-bulb measurement on the coast of the Persian Gulf in July of 2015, and a later 35.4-degree wet-bulb measurement in the same region. This indicates that temperature extremes of this magnitude have already become possible in our current climate, though they remain very rare and small in spatial extent.[21] Exposure to 34-degree wet-bulb temperatures will increase mortality risk for the sick and elderly, but more importantly, due to the amplifying urban heat-island effect, urban or peri-urban centers exposed to these temperatures may cross the 35-degree survivability threshold for healthy adults.[22]

Based on a district-by-district geospatial analysis of population urbanicity, we estimate that, under our "inherent risk" scenario, 160-200 million people could be living in urban areas in India with a non-zero annual probability of experiencing a lethal heatwave as soon as 2030. Under business-as-usual air conditioning growth, only about half will have protection from air conditioning. The average annual probability of a lethal heatwave in those regions is projected to be ~5 percent, meaning the probability of at least one heatwave occurring during the decade centered around 2030 will be ~40 percent. (India-2). By 2050, the number of people living in at-risk regions will increase to 310-480, and the average annual probability to 14 percent, meaning the probability of at least one heatwave occurring during the decade centered around 2050 will be ~80 percent. It is likely that most people will own an air conditioning unit by 2050.

Another consequence of chronic exposure to extreme heat is a rapid decrease in the capacity for outdoor work. This phenomenon occurs not only due to the need to take breaks to avoid dangerous core temperature rise, but also because the body will fatigue to reduce the amount of work (and therefore heat) that it is able to produce, in a process known as "self-limiting," which is a function of the wet-bulb temperature.[23] This is significant because India's economy is highly dependent on heat-exposed labor. As of 2017, heat-exposed work produces about 50 percent of GDP, drives about 30 percent of GDP growth, and employs about 75 percent of the labor force, some 380 million people.[24]

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20 Eun-Soon Im, Jeremy S. Pal, and Elfatih A. B. Eltahir, "Deadly heat waves projected in the densely populated agricultural regions of South Asia," *Science Advances*, August 2017, Volume 3, Number 8.

21 Christoph Schär, "The worst heat waves to come," *Nature Climate Change,* October 2015, Volume 6; Tom Matthews, "Humid heat and climate change," *Progress in Physical Geography,* 2018, Volume 42, Number 3.

22 These numbers are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. A global analysis of 419 major cities showed that the average daytime temperature difference between urban areas and their immediate surroundings is +1.5 ± 1.2°C, with some outliers up to 7°C warmer. Shushi Peng et al., "Surface urban heat island across 419 global big cities," *Environmental Science & Technology*, January 2012, Volume 46, Number 2. Research has demonstrated that many cities in India exhibit a negative urban heat island intensity in summer—that is, during the hot pre-monsoon season, they are cooler than their surroundings. This cooling effect is due to both to atmospheric aerosols and the relatively high vegetation cover in cities compared with their surroundings, which contain largely barren lands that are converted to croplands only post-monsoon. While these findings apply to much of the Indian subcontinent, the authors found that many cities in the north of the country exhibit statistically significant positive urban heat island intensities. Because this area of the country is also projected to be the first to exhibit heat waves close to the 35-degree threshold and because a reduction in atmospheric aerosols could further reduce the artificial cooling effect currently underway, these cities are at risk of having 34-degree heat waves amplified to 35-degree heat waves. Hiteshri Shastri et al., "Flip flop of day-night and summer-winter surface urban heat island intensity in India," *Nature Scientific Reports*, January 9, 2017, Volume 7.

23 Peter Brode et global: et al., "Estimated work ability in warm outdoor environments depends on the chosen heat stress assessment metric," *International Journal of Biometeorology*, April 2017, Number 62.

24 Reserve Bank of India, Database on Indian Economy. Exposed sectors include exclusively outdoor sectors such as agriculture, mining, and quarrying, as well as indoor sectors with poor air-conditioning penetration including manufacturing, hospitality, and transport.

Case study India-2

The annual probability of lethal heat waves in India and surrounding areas is expected to increase between 2018 and 2050.

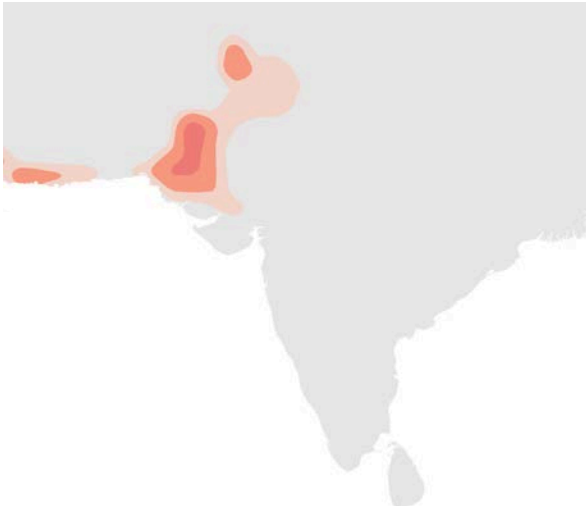
Based on RCP 8.5

Annual probability of a lethal heat wave[1]

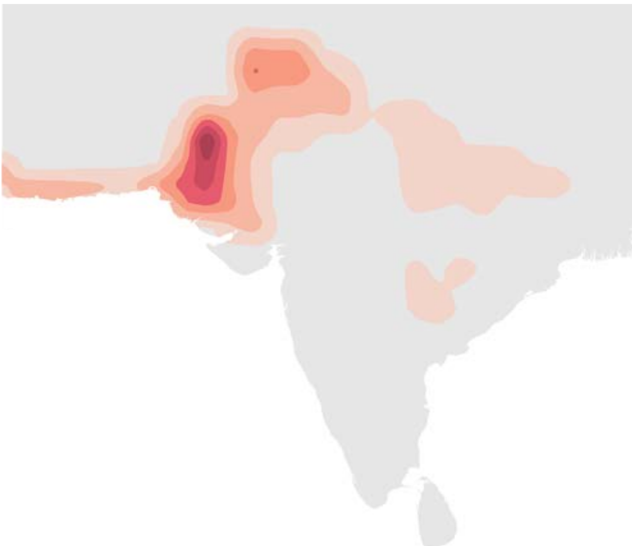
%

≤2 | 3–10 | 11–20 | 21–30 | 31–40 | 41–50 | 51–60 | 61–70 | >70

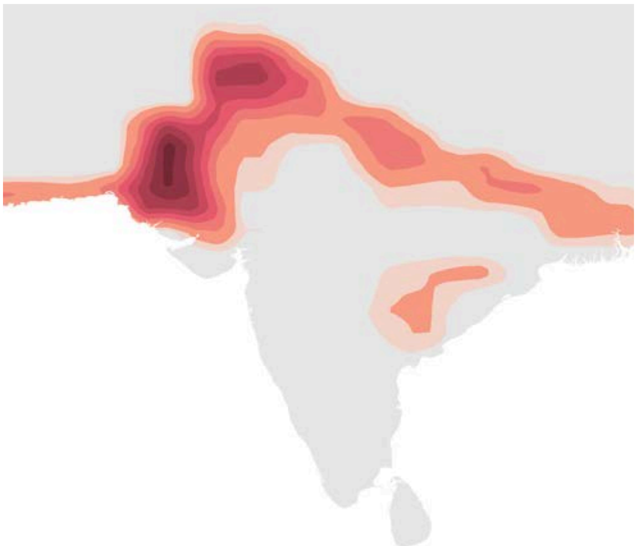
Today



2030



2050



1. A lethal heat wave is defined as a three-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb, where wet-bulb temperature is defined as the lowest temperature to which a parcel of air can be cooled by evaporation at constant pressure. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. Under these conditions, a healthy, well-hydrated human being resting in the shade would see core body temperatures rise to lethal levels after roughly 4–5 hours of exposure. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects, and do not factor in air conditioner penetration.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woodwell Climate Research Center

Historically, India's extreme summer wet-bulb temperatures have limited, or in some cases even prevented, outdoor work from occurring during the hottest hours of the hottest and most humid days of the year. Between 1951 and 1980, across India, an average of approximately 10 percent of daylight hours were effectively lost for outdoor work due to extreme heat and humidity in a given year.[25] Today, climate models indicate that this has increased to roughly 15 percent on average across India.[26] In 2019, air temperatures exceeded 44 degrees Celsius in Odisha, with relative humidity of about 37 percent, equating to a wet-bulb temperature of 31 degrees, stopping outdoor work between 11 a.m. and 4 p.m. across cities.[27] In Churu, air temperatures hit 49 degrees, with relative humidity of about 28 percent, equating to a wet-bulb temperature of 32 degrees and stopping all outdoor activity during the same period.[28]

By 2030, in the climate scenario considered here, the average number of effectively lost daylight hours for outdoor work could further increase by about 15 percent, equivalent to an additional three and a half weeks a year of 11:00 a.m. to 4:00 p.m. lost working hours. It is important to note that this is an average number, and the increase in extreme heat will not be distributed evenly across the country. The areas in the northwest and on the east coast (where hot continental air mixes with humid ocean currents) will experience larger increases than the less-humid interior (India-3).

Past MGI analysis has found that in 2030 a significant proportion of workers in India will still be expected to work outside, and we estimate about 40 percent of GDP will still depend on heat-exposed work. Based on a geospatial, district-by-district analysis of exposed GDP and projected lost working hours, as well as considering effects on other sectors that exchange inputs and outputs with sectors exposed to outdoor heat, we calculate that an increase in lost labor hours due to rising heat and humidity could put approximately 2.5-4.5 percent of GDP at risk by 2030, equivalent to roughly $150-250 billion.[29] This is considering an average year, and a "business-as-usual" pace of sectoral transitions.

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25 Based on equivalent lost working hour projections derived from climate models. Hours unworkable due to heat is defined as the percentage of a given 12-hour workday lost due to extreme heat. This number of lost working hours should not be interpreted as an absolute 10 percent of hours during which no work occurs, rather, it is inclusive of losses in worker productivity while working, as well as breaks.

26 Note these estimations are also subject to uncertainty based on atmospheric aerosol behavior. The 2019 International Labour Organization (ILO) report *Working on a warmer planet* estimated the total lost working hours in India because of extreme heat at 4.3 percent of hours lost in 1995, increasing to 5.8 percent by 2030. The difference between results can be accounted for as follows: (1) the total ILO numbers are presented as a percentage of total labor force hours (weighted for population and sector), and ours are presented as a percentage of total possible working hours, and weighted for area, (2) our values are calculated assuming a spectrum of work intensity occurring in all sectors, using a continuous function derived from ISO heat-exposure safety standards adjusted according to Josh Foster et al., "A New Paradigm To Quantify The Reduction Of Physical Work Capacity In The Heat,"Medicine and Science in Sports and Exercise, June 2019, Volume 51, Issue 6, whereas the ILO figures are calculated assuming that each sector has a only a single work intensity value using three ISO curves adjusted according to Tord Kjellstrom et al., "Estimating population heat exposure and impacts on working people in conjunction with climate change," International Journal of Biometeorology, March 2018, Volume 62, Issue 3; (3) the ILO figures are based on RCP 2.6, whereas ours are based on RCP 8.5; (4) our projections are corrected for bias using ERA-Interim reanalysis data set, whereas ILO numbers are not.

27 Debjoy Sengupta, "Extreme heat takes toll on coal output; state governments ask Coal India to alter production schedule," *Economic Times*, May 27, 2015.

28 Joanna Slater, "'It is horrid': India roasts under heat wave with temperatures above 120 degrees," *Washington Post*, June 5, 2019.

29 Our GDP-at-risk analysis was performed as follows: scientists at the Woodwell Climate Research Center created a grid-cell by grid-cell projection of the profile of daily wet-bulb globe temperatures using a bias-corrected ensemble of global climate models. This daily temperature profile was then translated into lost working hours following the approach of John P. Dunne et al., "Reductions in labour capacity from heat stress under climate warming," Nature Climate Change, February 2013, Volume 3, using ISO heat exposure standards. These standards were then corrected using empirical evidence from Josh Foster et al., "A New Paradigm To Quantify The Reduction Of Physical Work Capacity In The Heat," Medicine and Science in Sports and Exercise, June 2019, Volume 51, Issue 6, to account for the fact that ISO standards are overly conservative. Finally, the number of lost working hours for each grid cell were summed to an annual number. Given annual number of lost working hours per grid cell, we then multiplied the lost hours share by GDP generated by sectors exposed to heat. The sectors considered here included agriculture, construction, mining and quarrying, manufacturing (where we considered half of the GDP in the sector to be exposed to heat), and a selection of services that are more "outdoor-based," including hotels, restaurants, and transport services. Business, financial, and other knowledge services were considered completely non-exposed, although this may be a conservative assumption.

Case study India-3

The affected area and intensity of extreme heat and humidity is projected to increase, leading to a higher expected share of lost working hours in India and surrounding areas.

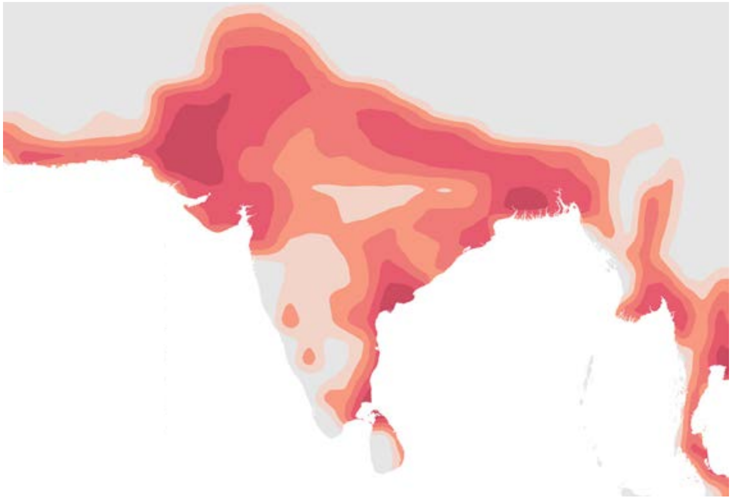
Based on RCP 8.5

Share of lost working hours[1]

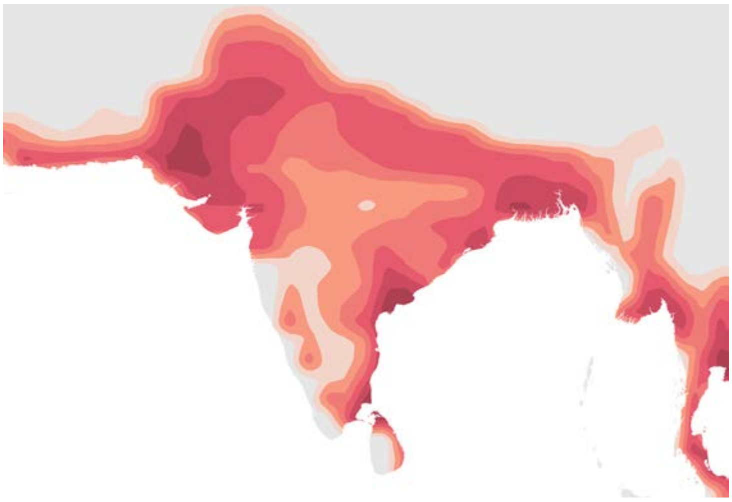
%

- ≤5
- 6–10
- 11–15
- 16–20
- 21–25
- 26–30
- 31–35
- 36–40
- >40

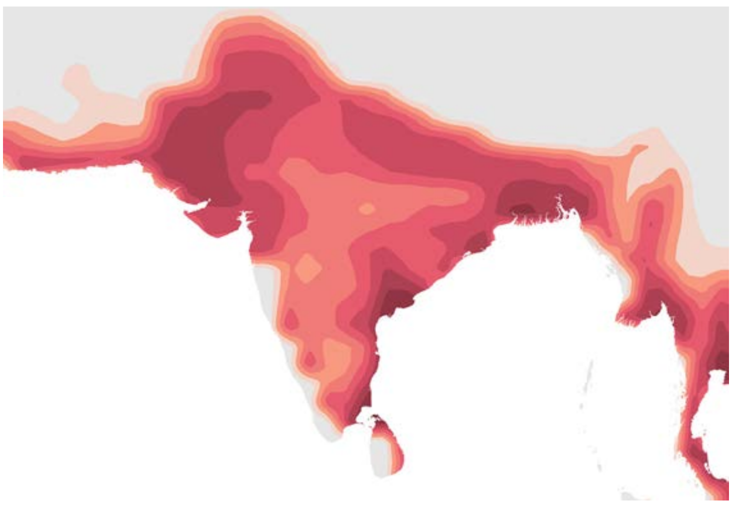
Today



2030



2050



1. Lost working hours include loss in worker productivity as well as breaks, based on an average year that is an ensemble average of climate models.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woodwell Climate Research Center

Absent mitigation, the risks from extreme heat will continue to evolve. Climate models demonstrate that by 2050, some small parts of India will be under such intense heat and humidity duress that the equivalent of 30 percent or more of annual daylight hours will effectively be lost each year for outdoor work. More importantly, by 2050, portions of northern India could begin to experience heat waves that could cross the 35-degree wet-bulb survivability with a cumulative probability of occurrence approaching 100 percent in a given decade.

Aggressive adaptation and sector transition could reduce the economic risk from extreme heat in India

Given the inherent risk of rising wet-bulb temperatures, India must adapt through capacity and knowledge building, material investment in adaptive technology and infrastructure, and supporting the economy's transition away from outdoor work.

Cooling plans

The government is already taking steps toward this. In response to the challenges laid out above, the Indian Ministry of Environment, Forests, and Climate Change released the India Cooling Action Plan in March 2019, making India the first major country in the world to release a national policy document on cooling.[30] There is also action underway at the local level. The Ahmedabad Municipal Corporation developed the first heat-action plan in India in response to the record-breaking 2010 heat wave that killed 300 people in a single day.[31] As of 2018, 17 other cities and 11 states have released or are in the process of developing heat-action plans.[32]

Capacity building

Capacity and knowledge building is a crucial first step for all stakeholders because it allows decision makers to quantify the level of heat-related risk they face and establish a perspective on how that risk could evolve based on both climatic and economic factors. At the local level, Ahmedabad has implemented programs to build residents' awareness of the dangers of extreme heat by, for example, establishing a seven-day probabilistic heat-wave early warning system. To date, heat waves are largely defined across India according to the behavior of dry-bulb air temperature.[33] Future investment in capacity and knowledge building should focus on incorporating the impact of humidity into heat-wave projections and policy, to aid in identification of high-risk regions and communities.

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30 Radhika Lalit and Ankit Kalanki, *How India is solving its cooling challenge*, Rocky Mountain Institute, 2019; *India Cooling Action Plan*, Government of India, Department of Environment, Forests, and Climate Change, 2018.

31 Kim Knowlton et al., "Development and implementation of South Asia's first heat-health action plan in Ahmedabad (Gujarat, India)," *International Journal of Environmental Research and Public Health*, 2014, Volume 11, Number 4.

32 *Chilling prospects: Providing sustainable cooling for all*, Sustainable Energy for All, 2018.

33 Geert Jan van Oldenborgh et al., "Extreme heat in India and anthropogenic climate change," *Natural Hazards and Earth System Sciences*, 2018, Volume 18, Number 1.

Transition work indoors

The pace of India's transition away from outdoor work in the economy and the rate at which it invests in adaptation could significantly impact the economic risk of lost hours, and also the toll on life from heat waves. As outlined above, our inherent risk estimate of the impact of decreasing labor productivity due to extreme heat is 2.5-4.5 percent of GDP by 2030, with the range based on whether a hotter and more humid year manifests, or a colder and less humid one. However, there are uncertainties associated with this analysis one associated with climatic conditions, and the other associated with exposure of the economy to those climatic conditions (see Box 2, "Understanding climatological uncertainties associated with the impact of heat and humidity on India"). For the climate uncertainty, we assess the impact of hotter and more humid years, and colder and less humid years, which could occur due to natural variability. This is measured to be +0.6 percent / –1.4 percent of GDP, relative to our base case estimate (India-4). If India's economic transition to a service-based economy is slowed, our mean estimate of 4 percent of GDP could increase by as much as 0.6 percentage point. Assuming a very rapid transition and adaptation scenario in which only unavoidable outdoor work is exposed and 100 percent of indoor GDP is protected by air-conditioning by 2030, the total GDP impact could decrease by 2.2 percentage points.

Case study India-4

We consider the impact of two forms of uncertainty on GDP at risk from heat and humidity in India; reducing exposure could more than halve GDP at risk.

Based on RCP 8.5

Distribution of GDP at risk by 2030 due to an increase in heat and humidity, based on various climate and economic exposure scenarios
% of total 2030 GDP

		Climate uncertainty		
		Better than average year 25th percentile climate model projection	**Average year** Multi model mean projection	**Worse than average year** 75th percentile climate model projection
Exposure uncertainty	**Multisector exposure with no sector shift** • Multiple heat-exposed sectors • Assumes sectoral composition of economy stays constant	3.0	4.6	5.3
	Multisector exposure, assuming expected economic evolution • Multiple heat-exposed sectors • Assumes transition toward service economy continues	2.5	4.0	4.5
	Agriculture, mining, and construction only, assuming expected economic evolution • Only unavoidably outdoor work exposed • Assumes transition toward service economy continues	1.2	1.8	2.1

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected. Assumes multiplier of 2 for direct + indirect effects.
Source: Woodwell Climate Research Center; McKinsey Global Institute analysis

Box 2.

Understanding climatological uncertainties associated with the impact of heat and humidity on India

While we have taken care to design our analysis in a robust manner, there are factors we did not consider in our analysis that could increase or decrease the results presented here. Our results could be increased or decreased by two types of factors: climatological and socioeconomic. The climatological factors that could change our results include the risk of an unusually hot or cold year or period due to natural variability, different evolutions of atmospheric aerosol concentrations over India, changes in irrigation volume and extent, and changes in the behavior of urban heat-island effects in at-risk regions. The socioeconomic factors include the pace of transition to a service economy, and any adaptation actions taken by the Indian government or people.

Because lethal heat waves are acute (or "tail") events, estimating the probability of occurrence required examining projections of wet-bulb-temperature extremes in warmer- and colder- than average years, as opposed to just interrogating an average year. The reason that this is necessary is that an extreme heat wave may not be possible during an average year, but may become possible during a hotter-than-average year, due to natural variability of the climate, for example during an El Nino cycle. To capture natural variability, we used the spread of outcomes across the entire ensemble of climate models. In other words, uncertainty resulting from natural variability, as captured by ensemble model spread, is already included in our estimate of probability. While it was not possible to do a full treatment of the other listed sources of climatological uncertainty listed here, the heat wave analysis was re-run using subsets of the 20 selected GCMs according to their ability to replicate various aerosol species over India. This analysis demonstrated that while aerosols play a role in determining heat wave probability, the future projections regarding an increase in the probability and spatial extent of lethal heat waves are likely robust.

When estimating the GDP lost due to decreasing labor productivity, similar restrictions limited our ability to quantify the impact of aerosols, irrigation, and possible changes in urban heat-island effects. Our base case here was based on the average of the 20 climate models. We were therefore able to estimate the uncertainty introduced by natural variability by examining the multimodel ensemble spread. We estimate that, based on the 75th and 25th percentile ensemble results, in a hotter and more humid year, the GDP impact could be 4.5 percent. In a relatively cooler and less humid year, it could be 2.5 percent.

Investment in cooling measures

Investment in adaptive technology and infrastructure allows decision makers to reduce the direct impacts from heat-related risk. Available options can broadly be divided into active cooling measures, such as air-conditioning technology, and passive cooling measures including traditional building design, alternative coolers, and urban albedo management. The challenge of providing enough cooling is complicated by the fact that India faces increases in both air temperature and relative humidity, so stakeholders are somewhat constrained in their ability to address heat risk through passive cooling technology. Many traditional cooling methods (for example, evaporative coolers and stepwells) leverage the cooling ability of evaporation, the efficacy of which decreases rapidly in high-humidity conditions.

Government policies

Adaptation can also be accelerated through direct government actions, such as prescribing changes in labor hours or the establishment of heat-resilient urban design standards, and indirect or facilitative actions, such as mandating the development of heat-action plans or multiple-stakeholder coordination. India's national plan highlights a portfolio of recommended priority actions, including using market and policy drivers to promote low-energy cooling technology, fast-tracking building energy codes and thermal comfort standards, and allocating government funding for targeted programs to enable cooling for economically weaker segments of the population through affordable housing design and construction, cool-roof programs, and development of localized heat-action plans.[34] For some work, shifting hours is easily possible, for example in construction, where floodlights can be used at night. In other sectors, such as agriculture, night work is more difficult. In addition, working early hours may cause cultural and economic difficulties. If people start working two or three hours after midnight, it has consequences for society in general. Commuting times have to be adapted, changes in lifestyle are necessary, and schools and shops have to open at different hours, leading to additional adaptation costs.[35]

Air conditioning

We calculate the cost of providing the entire population exposed to lethal heat wave risk with air-conditioning in 2030 to be roughly $110 billion.[36] For the poorest urban segments, air-conditioned emergency shelters or similar solutions will likely have to be provided in addition, possibly complemented by targeted affordable (air-conditioned) housing programs. Additionally, the greenhouse-gas intensity of current air-conditioning technology will need to be addressed to avoid further exacerbating climate change. The private sector can play an important role in driving innovation here (see Box 3, "The need for innovation in air-conditioning").

[34] *India Cooling Action Plan*, Government of India, Ministry of Environment, Forest, and Climate Change, 2018.
[35] Marguerite Holloway, "As Phoenix heats up, the night comes alive," *New York Times*, August 13, 2019.
[36] These numbers are derived as follows: under expected air-conditioner penetration rates according to the Indian National Cooling Plan, we calculate there will still be 100 million urban people exposed to heat wave risk by 2030. Because the average Indian household size is 5 people, and the plurality of households fall into the one-room category, we calculate it would take roughly 25 million additional air-conditioner units to protect the entire exposed population. The cost of producing these 25 million units would be approximately $10 billion, and they would require ~125 GW of new solar generation capacity to run which, at ~$800 per kilowatt to build, would cost an additional $100 billion. Johnny Wood, *India is now producing the world's cheapest solar power*, World Economic Forum, June 28, 2019.

Box 3.

The need for innovation in air-conditioning

The most effective tool for combating heat is the air conditioner, but widespread expansion of installed air-conditioning runs the risk of dramatically increasing global greenhouse gas emissions and exacerbating climate change. Investment in reducing electricity grid carbon intensity, increasing air conditioner efficiency, and transitioning away from coolants with high global warming potential is therefore necessary to maximize the efficacy of the air conditioner as a risk mitigation tool.

Air conditioners cause both direct and indirect emissions of greenhouse gases. Direct emissions are leaks of coolants from the units themselves. Prior to 1989, most air-conditioning units used a class of coolants called hydrochlorofluorocarbons.[1] After the discovery that they deplete the ozone layer, the nations of the world came together to sign the 1987 Montreal Protocol, which required manufacturers to switch to alternative, non-ozone-degenerative coolants. Among the most popular classes of alternative coolants are hydrofluorocarbons, or HFCs. Although they do not deplete the ozone layer, they are extremely powerful greenhouse gases. For example, releasing one tonne of HFC-410a into the atmosphere is the equivalent of releasing 2,088 tonnes of CO_2.[2]

Indirect emissions refer to the carbon emissions generated during the production of the electricity consumed by an individual air-conditioning unit. Efficiency factors vary, but as a rule, air conditioners are energy-intensive devices. In 2016, global air conditioner stock consumed 2,000 terawatt hours (TWh) of energy, more than double the entire electricity consumption of the African continent.[3] In Mumbai and New Delhi, room air conditioners account for 40 to 60 percent of peak power demand in summer.[4]

To meet electricity demand under a business-as-usual growth scenario for room and commercial air conditioners and chillers (assuming no additional adaptation), India will have to add enough generation capacity to the national grid to provide an additional 200 TWh by 2030.[5] If this capacity is provided using the current generation mix, meeting air conditioner demand will release an additional 1.4 billion tonnes of CO_2 equivalent (that is, including coolant leakage) into the atmosphere between now and 2030.[6] Renewables technology can help manage some of this risk, as can investments in a new generation of air-conditioning technology. The private sector will need to be a crucial part of enabling an effective cooling solution for India, and other parts of the world facing increased temperatures.

1 Iain Campbell, Ankit Kalanki, and Sneha Sachar, *Solving the global cooling challenge: How to counter the climate threat from room air conditioners*, Rocky Mountain Institute, 2018.
2 Mohit Sharma, Vaibhav Chaturvedi, and Pallav Purohit, "Long-term carbon dioxide and hydrofluorocarbon emissions from commercial space cooling and refrigeration in India: A detailed analysis within an integrated assessment modelling framework," *Climatic Change*, August 2017, Volume 143, Number 3–4.
3 *The future of cooling: Opportunities for energy-efficient air conditioning*, International Energy Agency, 2018.
4 Radhika Lalit and Ankit Kalanki, *How India is solving its cooling challenge*, Rocky Mountain Institute, 2019.
5 *India Cooling Action Plan*, Government of India, Ministry of Environment, Forest, and Climate Change, 2018.
6 Assuming a 2016–17 carbon intensity value of 0.8 TCO_2/MWh, according to the Ministry of Power Central Electricity Authority, Government of India, 2018.

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