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Climate risk and response in Asia

Future of Asia

November 2020

McKinsey Global Institute

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Authors
Jonathan Woetzel, Shanghai
Oliver Tonby, Singapore
Mekala Krishnan, Boston
Yuito Yamada, Tokyo
Suvojoy Sengupta, Gurgaon
Dickon Pinner, San Francisco
Ruslan Fakhrutdinov, Moscow
Tetsu Watanabe, Tokyo

Preface

While the world manages the COVID-19 pandemic, it is important to recognize and plan for other significant global risks. Climate change, if not managed, could deliver large social and economic impacts around the world, and in some ways, Asia may be more vulnerable than other regions. In this report, we examine the physical effects of a changing climate for Asia. We explore risks today and over the next three decades and examine cases to understand the mechanisms through which physical climate change leads to increased socioeconomic risk, with modeling and estimation of probabilities and magnitude of impacts. Based on macro and micro analysis, we highlight potential adaptation and mitigation strategies for the region. Our aim is not to be prescriptive but to help inform decision makers so that they can better assess, adapt to, and mitigate the physical risks of climate change.

This research builds on recent McKinsey Future of Asia and climate risk work in order to provide a deeper understanding of climate risk that already exists in the region and is growing. McKinsey has long focused on issues of environmental sustainability, dating to client studies in the early 1970s and extending to the present; for example, the April 2020 McKinsey article *Addressing climate change in a post-pandemic world*. This regional view follows publication in January 2020 of the McKinsey Global Institute's global report, *Climate risk and response: Physical hazards and socioeconomic impacts*. The research for this report was led by Jonathan Woetzel, an MGI director based in Shanghai, and Mekala Krishnan, an MGI partner in Boston, together with McKinsey senior partners Oliver Tonby, chairman of McKinsey Asia based in Singapore, and Dickon Pinner, leader of McKinsey's global Sustainability Practice based in San Francisco, and partners Yuito Yamada in Tokyo, leader of McKinsey's Sustainability practice in Asia, and Suvojoy Sungupta in Gurgaon. The project team was led by Ruslan Fakhrutdinov, Tetsu Watanabe, Erica Zhuang, and Youting Lee. Brian Cooperman, David Carmona, Godart van Gendt, and Peter De Ford provided guidance, modeling, analytics, and data support. The analysis was completed in the first half of 2020 and does not reflect any potential COVID-19 economic impacts.

While McKinsey employs many scientists, including climate scientists, we are not a climate research institution. Woodwell Climate Research Center (Woodwell) produced the scientific analyses of physical climate hazards in this report. Woodwell has been focused on climate science research since 1985; its scientists are widely published in major scientific journals, testify to lawmakers around the world, and are regularly cited in major media outlets. Methodological design and results were independently reviewed by Dr. Luke Harrington, an expert in the modeling of climate extremes and a research fellow at the University of Oxford's Environmental Change Institute. The review reflects his independent perspectives. Final design choices and interpretation of climate hazard results were made by Woodwell. In addition, Woodwell scientists produced maps and data visualization for the report. Our research also benefited from the Water Risk Atlas developed by the World Resources Institute.

A number of individuals generously contributed their time, insight, and expertise. In particular, we would like to thank Toru Matsui, chief operating officer of the Energy Solutions Business Unit, Mitsui & Co.; Hiro Mizuno, member of the board, Tesla; and Charlotte Roule, chief executive officer of Engie China.

We would also like to thank current and former McKinsey and MGI colleagues who provided valuable input, including: Sameer Ahmed, Aaron Bielenberg, Poonam Bhandarkar, Brodie Boland, Antonio Castellano, Megan Conor, Peter Cooper, Kaushik Das, Angus Dawson, Will Glazener, Stephan Görner, Andrew Grant, Apollo Guan, Alastair Hamilton, Sonam Handa, Claudia Kampel, Joshua Katz, Grace Lam, Timo Leenman, Johanna von der Leyen, Yunzhi Li, Cady Liang, Junjie Ma, Peter Mannion, Ketav Mehta, Raphaële Moeremans, Michele Perlman, Carter Powis, Jianfei Ren, Greg Santoni, Jeongmin Seong, Suyin Soon, Sophie Underwood, Yoshitaka Uriuda, Maarten van der Velden, Steven Vercammen, Antonio Volpin, Dean Walter, Magdalena Wlodarczak, Wei Xin, Hao Xu, and Jane Zhou.

This report was produced by MGI senior editor Anna Bernasek, editorial director Peter Gumbel, external editor David Wigan, production manager Julie Philpot, and designers Marisa Carder, Laura Brown, and Patrick White. We also thank our colleagues Dennis Alexander, Tim Beacom, Nienke Beuwer, Nura Funda, Cathy Gui, Kate Hegarty, Deadra Henderson, Kristen Jennings, Karen P. Jones, Lauren Meling, and Rebeca Robboy for their contributions and support.

As with all MGI research, this work is independent, reflects our own views, and has not been commissioned by any business, government, or other institution. We welcome your comments on the research at MGI@mckinsey.com.

James Manyika
Director and Co-chair, McKinsey Global Institute
Senior Partner, McKinsey & Company
San Francisco

Sven Smit
Director and Co-chair, McKinsey Global Institute
Senior Partner, McKinsey & Company
Amsterdam

Jonathan Woetzel
Director, McKinsey Global Institute
Senior Partner, McKinsey & Company
Shanghai

November 2020

Ravaged thatch house after typhoon.
© Michael Hall/The Image Bank/Getty Images

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In brief

Climate risk and response in Asia

Asia is, in many ways, on the front line of a changing climate. With many low-lying coastal cities exposed to flood and typhoon risk, extreme increases in heat and humidity expected across the region, and extreme precipitation expected in some areas but drought expected in others, Asian societies and economies will be increasingly vulnerable to climate risk without adaptation and mitigation. In our January 2020 global report, *Climate risk and response: Physical hazards and socioeconomic impacts*, we found that risk from climate change is already present and growing around the world. In this report, we look closer at Asia to determine how climate risk could develop in the next three decades and lay out an effective response for adaptation and mitigation. While climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations, we focus on RCP 8.5 because it enables us to assess the full inherent physical risk of climate change in the absence of further decarbonization. We link climate models with economic projections to examine micro cases that illustrate exposure to climate change extremes and proximity to physical thresholds. A separate geospatial assessment examines six indicators to assess potential socioeconomic impact in 16 countries. Key findings include:

In many ways, Asia is expected to experience more severe socioeconomic impacts of climate change than global averages in the absence of adaptation and mitigation. Under RCP 8.5, by 2050, up to 1.2 billion people globally could be living in areas with nonzero annual probability of lethal heat waves, with the vast majority in Asia. We find that the probability of being exposed to a lethal heat wave at least once in the decade centered on 2050 in Asia could increase to 80 percent. Asia accounts for more than two-thirds of the global GDP at risk from effective outdoor working hours lost due to increased heat and humidity by 2050. By 2050, Asia could account for more than 75 percent of the global capital stock that could be damaged from riverine flooding in a given year.

Different regions within Asia will have different exposure to climate risk, requiring different responses. Using MGI's Four Asias framework—Frontier Asia, Emerging Asia, Advanced Asia, and China—countries with lower levels of GDP per capita, namely Frontier Asia and Emerging Asia, are most at risk from the impacts of climate change. By 2050, under RCP 8.5, there could be an increase in 7 to 12 percentage points of share of working hours effectively lost in climate-exposed regions due to rising heat and humidity in Frontier Asia and Emerging Asia, compared to 2 to 5 percentage points for Advanced Asia and China.

The socioeconomic impacts of climate change will increase as system thresholds are breached and knock-on effects materialize. For example, almost one-third of Australia could see the number of high fire risk days per year grow by more than 20, increasing the share of capital stock exposed to at least five high fire risk days from 44 percent today to 60 percent in 2050. The cost of real estate and infrastructure damage from a 100-year flood in Tokyo could more than double to $14.2 billion by 2050 without additional adaptation.

As the pace and scale of adaptation in Asia increase, the region can take advantage of opportunities such as infrastructure investment. Massive investment in infrastructure throughout the region, amounting to $1.7 trillion annually through 2030, provides a unique opportunity to embed climate risk into infrastructure design. An effective adaptation plan for the region includes diagnosing risk and enabling a response, protecting people and assets, building resilience, reducing exposure, and financing and insuring. While doing so, stakeholders must address the regressive nature of climate risk.

Mitigation is essential to prevent a buildup of risk, and Asia is well placed to lead global mitigation efforts. It accounts for 45 percent of global emissions and half of potential global investment in electric power in the next decade. We find that key mitigation actions in Asia include: a shift from coal to renewables, as coal accounts for 90 percent of power emissions in the region; decarbonizing industrial operations, for example, steel and cement emissions in Asia account for 80 percent of global CO_2 emissions; transforming agriculture and forestry, which, combined, account for 10 percent of CO_2 emissions in Asia and over 40 percent of CH_4 emissions; and decarbonizing road transportation and buildings.

A critical part of enabling this transition will be managing the risks that may arise, such as rising costs, labor displacement, and impacts on specific communities. In the coal industry in India, for example, there is significant risk of electricity price growth caused by the capital expenditures needed to install renewables and of potential job losses. In China, finding ways to scale decarbonization technologies in the production of steel will be key to ensuring that the industry's massive output is not disrupted. In Indonesia, supporting livelihoods dependent on the agricultural sector as it decarbonizes will be essential. And in Japan, providing incentives and policies to help overcome the higher up-front cost of battery electric vehicles would facilitate the transition to EVs.

While the adaptation and mitigation challenges facing Asia are significant, they can be overcome. And indeed, stakeholders throughout the region are already working together in this endeavor. Building on and accelerating these efforts could pay off not only in protecting lives and livelihoods but in promoting sustainable growth and prosperity over the long term.

This assessment of the hazards and impacts of physical climate risk is based on an "inherent risk" scenario absent any adaptation and mitigation response. We have used **RCP 8.5** scenario of greenhouse gas concentrations because the higher emissions scenario it represents allows us to assess inherent risk.

How a changing climate may affect Asia

In many ways, Asia may experience more severe impacts from climate change than global averages by 2050, absent adaptation and mitigation.

Socioeconomic systems directly affected by physical climate change absent adaptation, 2050[3]

Livability and workability

GDP at risk annually from rising heat and humidity[1]

Population living in areas experiencing lethal heat waves[2]

Physical assets and infrastructure

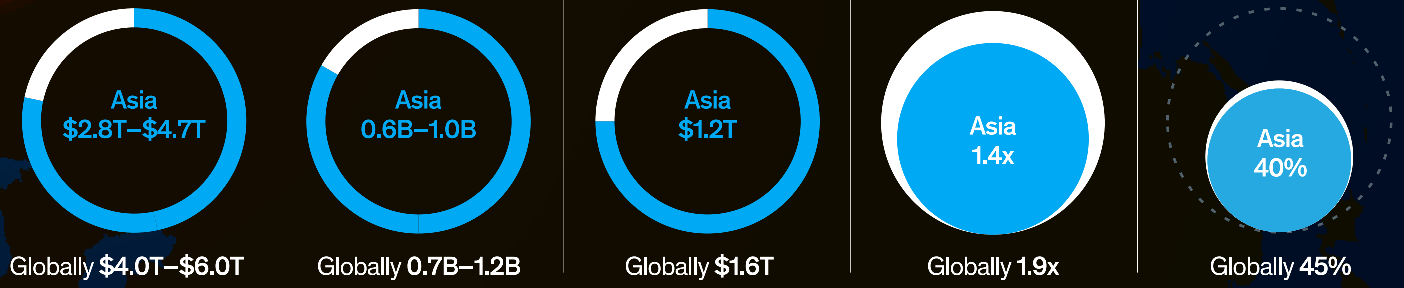
Expected damage to capital stock from riverine flooding

Food systems

Likelihood of >5% grain-yield decline relative to today

Natural capital

Land area experiencing biome shifts



Examples of physical climate risk without adaptation, **today,**[3] **2030, and 2050**

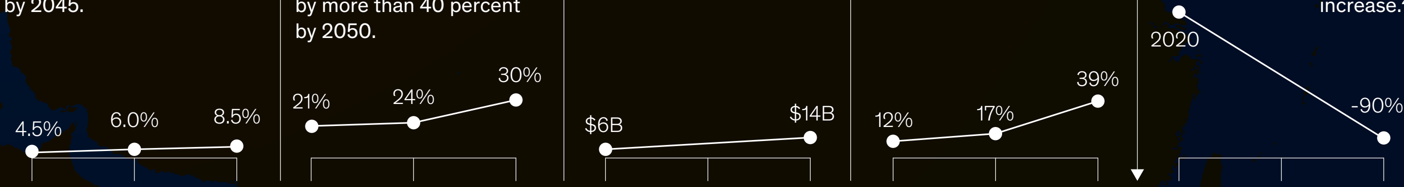
In China, the average share of effective outdoor working hours lost each year in climate-exposed regions to extreme heat and humidity could more than double by 2045.

In India the average share of effective outdoor working hours lost each year in climate-exposed regions to extreme heat and humidity could increase by more than 40 percent by 2050.

The cost of real estate and infrastructure damage from a 100-year flood in Tokyo could more than double to $14.2 billion.

In India, rice, corn, soy, and wheat could face a 27 p.p. increase in the likelihood of more than 10% yield declines.

Up to 90% of coral could suffer severe degradation in the Coral Triangle and Great Barrier Reef under climate change scenarios with 2°C global mean temperature increase.[4]



The pace and scale of adaptation in Asia need to increase to manage increased risk.

Strategies for Asia to consider include:

Diagnose risk and enable response

Protect people and assets

Build resilience

Reduce exposure

Finance and Insure

Mitigation is essential to prevent the further buildup of risk.

Strategies for Asia to consider include:

Shift from coal to renewable energy

90%

of Asia's power emissions come from coal

Decarbonize industrial operations

~80%

of global CO_2 emissions in the steel and cement industries are from Asia

Transform agriculture and forestry

20%

of global methane gases come from Asia's agriculture

Electrify daily life to decarbonize road transportation and buildings

33%

of global transportation and buildings' GHG emissions come from Asia[5]

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1 Calculated based on share of working hours effectively lost due to rising heat and humidity.

2 We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. 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. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.

3 Climate state today is defined as the average conditions between 1998 and 2017, 2030 as the average of 2021–40, and 2050 as the average of 2041–60.

4 Scott F. Heron et al., *Impacts of Climate Change on World Heritage Coral Reefs: A First Global Scientific Assessment*, Paris, UNESCO World Heritage Centre, 2017.

5 Based on AR5 GWP20.

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Executive summary

Earth's climate is changing after more than 10,000 years of relative stability, and Asia is, in many ways, on the front line. Climate science tells us that, absent adaptation and mitigation, the climate hazards the region faces in the future, from heat waves to flooding to wildfires, are likely to be more severe, more intense, or both (see Box E1, "Understanding climate risk"). Indeed, the socioeconomic impacts in Asia in some cases could be more severe than in many other parts of the world. As Asia seeks to grow its economy—and remain a key source of growth for the world—climate is a critical challenge that the region will need to manage.

Yet Asia is also well positioned to address these challenges and capture the opportunities that come from managing climate risk effectively. Infrastructure and urban areas are still being built out in many parts of Asia, which gives the region a chance to ensure that what goes up is more resilient and better able to withstand heightened risk. At the same time, key economies in the region, such as China and Japan, are leading the world in technologies, from electric vehicles to renewable energy, that are necessary to adapt to and mitigate climate change. Of course, there are plenty of challenges. First, the funds required to invest in adaptation and mitigation are significant. Second, navigating any transition, especially one that shifts whole industries toward decarbonization, will be no easy feat. But if Asia can marshal its spirit of innovation and determination, it could lead the world in one of its principal challenges.

This report quantifies the physical risk from climate change for Asia. We characterize risks within and across different countries and categorize impacts across four different types of countries in Asia: Frontier Asia, Emerging Asia, Advanced Asia, and China. While establishing the overall risks of climate change in Asia through our six case studies and geospatial analysis, this report seeks to also emphasize the path forward through adaptation and mitigation. We also highlight adaptation and mitigation strategies for policy makers and business leaders in the region to consider.

54%

the share of the global population living in the 16 Asian countries we focus on in this report

Box E1

Understanding climate risk

A changing climate is introducing new risks that are significant today and will grow. These risks can be grouped into three types: physical (arising from the physical effects of climate change); transition (arising from the transition to a low-carbon economy); and liability (arising from those affected by climate change seeking compensation for losses).[1] We focus on physical risk in this report.

This report builds on the analysis and methodology of a January 2020 global report, *Climate risk and response: Physical hazards and socioeconomic impacts.* For a detailed explanation of that methodology, please see the report.

Physical climate risks are probabilistic because of the probabilistic nature of the underlying climate hazards that create risk; for example, a certain likelihood is associated with having floods of a given severity, or days above a certain temperature, in a year. By hazards, we mean climate-enhanced physical phenomena (acute or chronic) that have the potential to affect natural and socioeconomic systems. A changing climate means these likelihoods are shifting. Following standard practice, our findings are therefore typically framed as statistically expected values—the statistically expected average impact across a range of probabilities of different hazard manifestations. We also report the value of tail risks—that is, low-probability, high-impact events like a one-in-100-year storm—on an annual basis.

We estimate inherent physical risk, absent adaptation and mitigation, to assess the magnitude of the challenge and highlight the case for action for two periods: between today and 2030, and from 2030 to 2050. We draw on climate model forecasts to showcase how the climate has changed and could continue to change, how a changing climate creates new risks and uncertainties, and what steps can be taken to best manage them. Climate impact research makes extensive use of scenarios with lower (Representative Concentration Pathway 2.6) and higher (RCP 8.5) CO_2 concentrations. Our research is most concerned with understanding inherent physical risks, to assess the magnitude of the challenge and highlight the case for action. We have therefore chosen to focus on the higher-emission, lower-mitigation scenario, RCP 8.5, to assess physical risk in the absence of further decarbonization.[2]

Key uncertainties in our analysis include the emissions pathway and pace of warming, climate model accuracy and natural variability, the magnitude of direct and indirect socioeconomic impacts, and the socioeconomic response. Assessing these uncertainties, we find our approach likely results in conservative estimates of inherent risk because of the skew in uncertainties of many hazard projections toward "worse" outcomes as well as challenges with modeling the many potential knock-on effects associated with direct physical risk.[3]

In this report, we focus on Asia, and in order to link physical climate risk to socioeconomic impact, we investigate six specific cases that illustrate exposure to climate change extremes and proximity to physical thresholds. These cover a range of sectors and geographies in Asia and provide the basis of a "micro-to-macro" approach that is a characteristic of MGI research. We use a five-systems framework for measuring potential direct and indirect impacts of the changing climate in Asia: livability and workability, food systems, physical assets, infrastructure services, and natural capital. Our case studies cut across these five systems. They build on our research in the global report, which found seven characteristics of climate risk: it is increasing, spatial, nonstationary, nonlinear, systemic, regressive, and underprepared.

In a separate analysis, we use geospatial data to provide a perspective on climate change over the next 30 years in 16 countries: Australia, Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, New Zealand, Pakistan, the Philippines, Thailand, Vietnam, and South Korea.

We examined six indicators for our analytical framework, across the five socioeconomic systems: (1) Livability and workability—the share of the population living in areas experiencing a nonzero annual probability of lethal heat waves, annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, and water stress, measured as the annual demand for water as a share of the annual supply of water; (2) Food systems—annual probability of a change in agricultural yields for major crops;[4] (3) Physical assets and (4) Infrastructure services—annual share of capital stock at risk of riverine flooding; (5) Natural capital—share of land surface changing climate classification, known as biome shift.[5] (For details of our methodology, see the technical appendix.)

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[1] For more details, see *Climate change: What are the risks to financial stability?*, Bank of England.

[2] For a full discussion of our choice of RCP 8.5 and details of our methodology, see the technical appendix of our global report, *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020. See also Christopher R. Schwalm, Spencer Glendon, and Philip B. Duffy, "RCP8.5 tracks cumulative CO_2 emissions," *Proceedings of the National Academy of Sciences*, August 2020.

[3] See Naomi Oreskes and Nicholas Stern, "Climate change will cost us even more than we think," *New York Times*, October 23, 2019; and *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.

[4] Major crops are rice, corn, soy, and wheat.

[5] The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. We have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.

As Earth's climate warms and hazards intensify, Asia may face more severe impacts than other regions

Wildfires in Australia, typhoons in China, Japan, and South Korea, and extreme heat in Bangladesh, India, and Pakistan are just some of the intensifying climate hazards science predicts for Asia. While we analyze climate hazards and the potential socioeconomic impact of them for the overall region, we also identify four types of Asia. Each has a different climate profile, and different exposure and response to physical climate risk. We also find that countries with lower per capita GDP are more at risk from climate change.

By 2050, parts of Asia may see increasing average temperatures, lethal heat waves, extreme precipitation events, severe hurricanes, drought, and changes in water supply
Based on the RCP 8.5 scenario, we identify some of Asia's key climate hazards below. We illustrate these hazards with maps that show local areas most likely to see more severe and/or frequent hazards over the coming decades (Exhibit E1). Highlights include:

— Asia is expected to see an increase in average temperature of more than two degrees Celsius by 2050 compared with preindustrial levels, with significant temperature increases predicted for parts of Australia, China, and the Indian subcontinent.[1]

— Large cities in parts of Bangladesh, India, and Pakistan could be among the first places in the world to experience lethal heat waves that exceed the survivability threshold.[2]

— The likelihood of extreme precipitation events could increase three- or fourfold by 2050 in areas including, for example, eastern Japan, central and eastern China, parts of South Korea, and Indonesia.[3]

— The likelihood of severe typhoon precipitation is expected to triple by 2040 in some parts of Asia, including coastal areas of China, Japan, and South Korea.[4]

— The share of time spent in drought in southwestern Australia could grow to more than 80 percent by 2050, and the share in some parts of China could be 40 to 60 percent.[5]

— In several parts of Australia, mean annual surface water supply could significantly decrease by 2050.[6] Conversely, in parts of China, water supply could increase by more than 20 percent. Parts of the Indian subcontinent could also see an increase in water supply.

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[1] We define the preindustrial period as 1880 to 1910.

[2] Modeled by Woodwell using the mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 global climate models. Models were independently bias corrected using the ERA-Interim data set. Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature exceeds the survivability threshold for a healthy human resting in the shade, 34°C wet-bulb. Wet-bulb temperature is the lowest temperature to which air can be cooled by the evaporation of water at a constant pressure. We took the average wet-bulb temperature of the hottest six-hour period across each rolling three-day period as the relevant threshold. 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 four to five 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.

[3] Extreme precipitation events are defined as once-in-50-year occurrences (that is, with a 2 percent annual likelihood) in the 1950–81 period. Modeled by Woodwell using the median projection from 20 CMIP5 global climate models.

[4] An event that had a 1 percent annual likelihood in the 1981–2000 period. Modeled by Woodwell using the Coupled Hurricane Intensity Prediction System (CHIPS) model. Kerry Emanuel, *The Coupled Hurricane Intensity Prediction System (CHIPS)*, MIT, 2019. Time periods available for the hurricane modeling were 1981–2000 (baseline) and 2031–50 (future). These are the results for one of the main hurricane regions of the world. Others, for example those affecting the Indian subcontinent, have not been modeled here.

[5] Modeled by Woodwell using the median projection of 20 CMIP5 global climate models, using the self-correcting Palmer Drought Severity Index. Projections were corrected to account for increasing atmospheric CO_2 concentrations.

[6] Taken from the World Resources Institute Water Risk Atlas, 2018, which relies on six underlying CMIP5 models. Time periods in this raw data set are the 20-year spans centered on 2020, 2030, and 2040. Data for 1998–2017 and 2041–60 were linearly extrapolated from the 60-year trend provided in the base data set. Note that this is a measure of surface water supply and does not account for changes in demand for water.

Exhibit E1

Climate hazards are projected to intensify in Asia.

Based on RCP 8.5

Illustrative examples

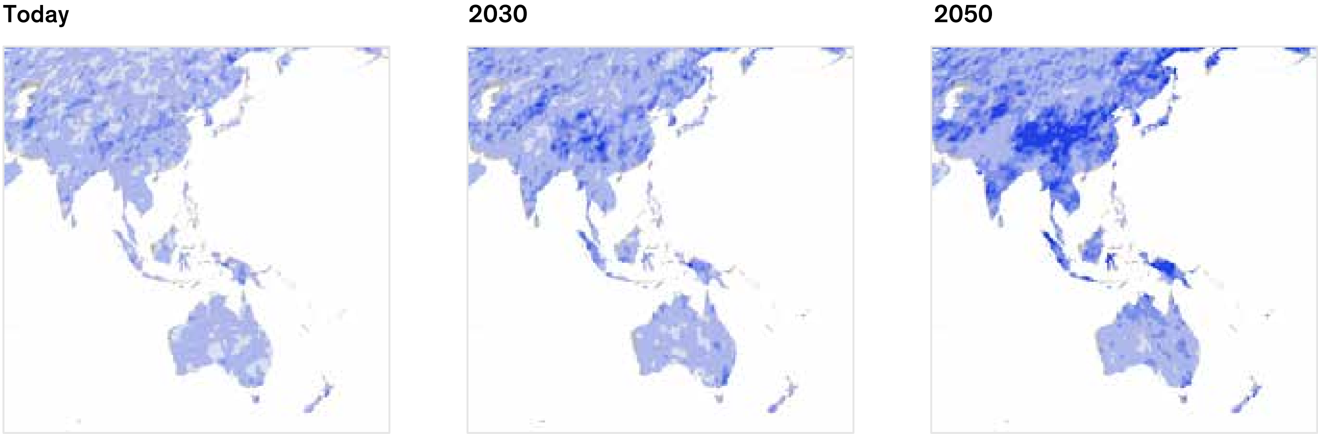
Increase in average annual temperature,
shift compared to preindustrial climate, °C[1]

Today

2030

2050

Extreme precipitation,
change of likelihood compared to a 1950–81 50-year precipitation event[2]



Today

2030

2050

Typhoons (precipitation),
change of likelihood in 2040 compared with a 1981–2000 100-year typhoon[3]

- ≤1.00x
- 1.01–1.25x
- 1.26–1.75x
- 1.76–2.25x
- 2.26–3.00x
- >3.00x

Exhibit E1 (continued)

Climate hazards are projected to intensify in Asia (continued).

Based on RCP 8.5

Illustrative examples

Today **2030** **2050**

Drought frequency,
% of decade in drought[4]

Lethal heat wave probability,
% p.a.[5]

Exhibit E1 (continued)

Climate hazards are projected to intensify in Asia (continued).

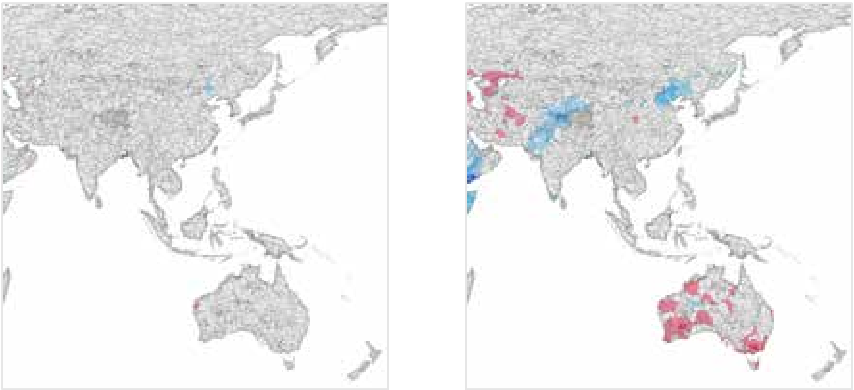
Based on RCP 8.5

Illustrative examples

Today **2030** **2050**

Water supply,
change in surface water compared with 2018 (map boundaries represent water basins), %[6]

- 🟥 -70 to -40
- 🟥 -40 to -20
- ⬜ -20 to 20
- 🟦 20 to 40
- 🟦 40 to 70
- 🟦 >70



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1. Taken from KNMI Climate Explorer, 2019, using mean of the full CMIP5 ensemble of models. Preindustrial period defined as 1880–1910.
2. Modeled by Woodwell Climate Research Center using median projection from 20 CMIP5 global climate models.
3. Time periods available for hurricane modeling were 1981–2000 baseline and 2031–50 future. Results for one of world's main hurricane regions. Others, for example those affecting Indian subcontinent, not modeled here.
4. Measured using 3-month rolling average. Drought is defined as rolling 3-month period with average Palmer Drought Severity Index (PDSI) <-2. PDSI is temperature- and precipitation-based metric calculated based on deviation from historical mean. Values generally range from +4 (extremely wet) to -4 (extremely dry). Modeled by Woodwell Climate Research Center using median projection of 20 CMIP5 global climate models, using the self-correcting PDSI. Projections corrected to account for increasing atmospheric CO$_2$ concentrations.
5. Lethal heat wave defined as 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb, where wet-bulb temperature is defined as lowest temperature to which parcel of air can be cooled by evaporation at constant pressure. Threshold chosen because 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 35°C threshold. Under these conditions, a healthy, well-hydrated human being resting in shade would see core body temperatures rise to lethal levels after roughly 4–5 hours of exposure. Projections subject to uncertainty related to future behavior of atmospheric aerosols and urban heat island or cooling island effects. Modeled by Woodwell Climate Research Center using mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 global climate models.
6. Taken from World Resources Institute Water Risk Atlas, 2018, which relies on 6 underlying CMIP5 models.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: KNMI Climate Explorer, 2019; Woodwell Climate Research Center using Coupled Hurricane Intensity Prediction System (CHIPS) model from Kerry Emanuel, MIT, 2019; World Resources Institute Water Risk Atlas, 2018; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

In many ways, Asia is expected to experience more severe socioeconomic impacts of climate change than global averages, in the absence of adaptation and mitigation
Asia stands out as being more exposed to physical climate risk than other parts of the world in the absence of adaptation and mitigation (Exhibit E2).[7] Under RCP 8.5, by 2050, between 600 million and one billion people in Asia will be living in areas with a nonzero annual probability of lethal heat waves. That compares with a global total of 700 million to 1.2 billion; in other words, a substantial majority of these people are in Asia. For Asia, the probability of being exposed to a lethal heat wave at least once in the decade centered on 2050 could increase to 80 percent.[8] By 2050, on average, between $2.8 trillion and $4.7 trillion of GDP in Asia annually will be at risk from an effective loss of outdoor working hours because of increased heat and humidity; this is because as such conditions rise, the human body tires more easily and needs to take more frequent breaks. The Asian GDP at risk accounts for more than two-thirds of the total annual global GDP impact.[9] Finally, about $1.2 trillion in capital stock in Asia is expected to be damaged by riverine flooding in a given year by 2050, equivalent to about 75 percent of the global impact.[10]

600M–1B

number of people in Asia living in areas with a nonzero probability of lethal heat waves by 2050

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[7] In this report, we look at 16 countries that account collectively for about 95 percent of Asia's population and GDP. They make up 54 percent of global population and one-third of global GDP.

[8] The ranges in the number of people exposed to extreme heat and lethal heat waves in 2030 and 2050 are based on the ranges of population projections from the UN World Population Prospects and the UN World Urbanization Prospects, to bound population growth based on high and low variants, and based on urban and total population growth rate. The calculated probabilities of exposure to lethal heat waves are approximations. They assume that the annual probability of X percent applies to every year in the decade centered on 2030 or 2050. We first calculate the cumulative probability of a heat wave not occurring in that decade, which is 1-X10 .The cumulative probability of a heat wave occurring at least once in the decade is then 1 minus that number.

[9] The lower end of the range assumes that today's sectoral composition persists, while the higher end is based on projections from IHS Markit Economics and Country Risk on sectoral transitions and GDP increases. The dollar impact is calculated by multiplying the share of hours lost in outdoor sectors with GDP in these sectors (this assumes that consensus projections do not factor in losses to GDP from climate change). We used backward multipliers from input-output tables to include knock-on effects.

[10] For estimation of capital stock at risk of riverine flooding we used a country level Urban Damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under a business-as-usual scenario (RCP 8.5, SSP 2) and existing levels of flood protection.

For other systems, Asia might be less exposed to climate risks than the world, although risks in these areas are still expected to increase by 2050. For food systems, we find the risk of a grain yield decline of greater than 5 percent in a given year could be 1.4 times higher by 2050 for Asia relative to today, compared with 1.9 times globally. For natural capital, the share of today's land area projected to experience biome shifts by 2050 is 40 percent for Asia, slightly less than the 45 percent global average.[11]

Exhibit E2

People, physical assets, and GDP may be more at risk from climate change in Asia than globally, but food systems and natural capital slightly less so.

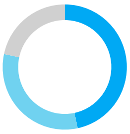
Based on RCP 8.5

First-order impact only, by 2050

Livability and workability

GDP at risk annually due to labor productivity affected by extreme heat and humidity[1]

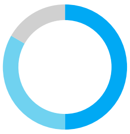
Globally **$4T–$6T**



Asia **$2.8T–$4.7T**

People living in areas with >0% annual probability of lethal heat waves[2]

Globally **0.7B–1.2B**

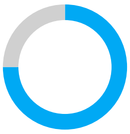


Asia **0.6B–1.0B**

Physical assets/infrastructure

Capital stock that could be damaged from riverine flooding in given year by 2050[3]

Globally **$1.6T**



Asia **$1.2T**

Food systems

Increased risk of >5% grain yield decline in given year, vs today[4]	Globally	Asia
	1.9x	**1.4x**

Natural capital

Land area projected to experience biome shift, affecting ecosystems and livelihoods[5]	Globally	Asia
	~45%	**~40%**

1. Defined as risk from outdoor working hours affected by extreme heat and humidity in climate-exposed regions annually. Heat and humidity reduce labor capacity because workers must take breaks to avoid heatstroke and because the body naturally limits its efforts to prevent overexertion. Range here is based on pace of sectoral transition across countries.
2. Lethal heat wave defined as 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. Threshold chosen because 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 35°C threshold. Projections subject to uncertainty related to future behavior of atmospheric aerosols and urban heat island or cooling island effects. Range based on range of population projections from UN World Population Prospects and UN World Urbanization Prospects, to bound population growth based on high and low variants, and based on urban and total population growth rates.
3. For estimation of capital stock at risk of riverine flooding, we used country-level urban damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under business-as-usual scenario (RCP 8.5, Shared Socioeconomic Pathways 2) and existing levels of flood protection. Risk values calculated based on expected values, ie, probability-weighted value at risk.
4. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits.
5. Biome refers to naturally occurring community of flora and fauna inhabiting a particular region. Changes in the Köppen Climate Classification System used as indicative proxy for shifts in biome.

Source: Rubel and Kottek, 2010; Woodwell Climate Research Center; World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

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[11] The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. We have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.

$1T–$1.5T

GDP at risk from heat and humidity in an average year in China by 2050

We identify four types of Asia, each with a different climate profile and exposure and response to physical climate risk: Frontier Asia, Emerging Asia, Advanced Asia, and China

We categorize each of the 16 countries in the Four Asias framework that we have identified in our previous Future of Asia work.[12] While impacts vary across as well as within countries, we broadly find that these factors will play out differently across the Four Asias. We use the Four Asias framework to contextualize climate hazards, their socioeconomic impacts, and potential responses. Each category is exposed to different combinations of hazards at varying levels of intensity, suggesting that they will require distinct response frameworks.

Frontier Asia consists of Bangladesh, India, and Pakistan. These countries could see extreme increases in heat and humidity, which may significantly affect workability and livability. By 2050, their average temperatures are projected to rise by two to four degrees Celsius, and they could face much higher probabilities of lethal heat waves. By 2050, these countries could see extreme precipitation events more frequently than in the second half of the 20th century and may experience less drought. Climate change would also have the biggest negative impact on Asian crop yield in this group of countries. For example, the annual probability of a yield decline of 10 percent or more for four major crops (rice, corn, soy, and wheat) is expected to increase from 12 percent today to 39 percent by 2050 for India, and from 40 percent to 53 percent for Pakistan.[13] Annual probability of a yield improvement of 10 percent or more for the four major crops is expected to decrease from 17 percent today to 5 percent by 2050 for India, and from 38 percent to 27 percent for Pakistan.

Emerging Asia consists of major Southeast Asian countries: Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Thailand, and Vietnam. Like Frontier Asia, these countries are projected to see extreme increases in heat and humidity by 2050 (although potentially less extreme than Frontier Asia), and growing exposure to extreme precipitation events. The impact on workability will be significant for these countries due to their high percentage of outdoor working hours work taking place in outdoor and labor-intensive sectors.

Advanced Asia consists of Australia, Japan, New Zealand, and South Korea. Overall, these countries are expected to see slightly lower impacts of climate change along many dimensions than Frontier Asia and Emerging Asia. Rather, Advanced Asia is expected to be an agricultural net beneficiary of climate change over the near term. However, for some countries in the region, the effects on water supply and drought are the main challenges. Typhoon and extreme precipitation risk could also increase in some parts of Japan and South Korea. In addition, the region is likely to see biome shift, or share of land surface changing climate classification.

China is climatically heterogeneous due to its location on a wide range of latitudes. Still, the country in aggregate is predicted to become hotter. In the country overall, the average share of effective outdoor working hours lost each year in exposed areas due to extreme heat and humidity could increase from 4.5 percent in 2020 to as much as 6.0 percent in 2030 and 8.5 percent in 2050. As a result, the share of China's GDP that could be lost to heat and humidity, currently 1.5 percent, could rise to 2 to 3 percent by 2050—equivalent to $1 trillion to $1.5 trillion in GDP at risk in an average year. Like Advanced Asia, China is expected to be an agricultural net beneficiary of climate change in the near term, with increasing statistically expected yields and volatility skewed toward positive outcomes. However, risks to infrastructure and supply chains will increase due to more frequent extreme precipitation events and typhoons in many areas; this is particularly important given China's role in regional and global supply chains.

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[12] Our Four Asias framework is based on a methodology developed in McKinsey's Future of Asia research and reflects measures of scale (including GDP and population), economic development, regional integration and trade, and global connectedness. In this report, we look at 16 countries that account collectively for about 95 percent of the region's population and GDP: Australia, Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, New Zealand, Pakistan, the Philippines, South Korea, Thailand, and Vietnam. Note that our broader body of research includes a wider range of countries, but we have limited the analysis here to 16 countries based on data availability. For a detailed discussion of the Four Asias, see *The future of Asia: Asian flows and networks are defining the next phase of globalization*, McKinsey Global Institute, September 2019.

[13] Yield changes are measured relative to the mean yield for the 1998–2017 period.

We find that countries with lower levels of per capita GDP, namely Frontier Asia and Emerging Asia, are most at risk from the impacts of climate change. Relying more on outdoor work and natural capital, they are subject to climates closer to physical thresholds that affect human beings' ability to work outdoors. By 2050, under RCP 8.5, there could be an increase in 7 to 12 percentage points of share of working hours effectively lost in exposed areas due to rising heat and humidity in Frontier Asia and Emerging Asia, compared to 2 to 5 percentage points for Advanced Asia and China. They also have more limited financial means to adapt.

$8.4B

the upper range of knock-on costs from a 100-year flood in Ho Chi Minh City by 2050

Our cases show socioeconomic impacts are increasing and system thresholds may be breached

We examined six case studies showing the impacts of climate change under RCP 8.5 on five socioeconomic systems across Asia. For the livability and workability system, we considered two case studies: what extreme heat and humidity mean for urban populations and outdoor-based sectors in China and India. For food systems, we focused on the likelihood of a multiple-breadbasket failure affecting six major breadbaskets in Asia by crop (rice, corn, soy, and wheat). For physical assets and infrastructure services, we examined 17 types of infrastructure assets for their vulnerability to different types of climate hazards, with a focus on two case studies: the potential impacts of flooding in Tokyo and wildfires in Australia. For natural capital, we examined the potential impacts of climate change on glaciers, oceans, and forests.

We find that climate risk is increasing in these six cases, and the characteristics of climate risk we identified from our global analysis—increasing, spatial, nonstationary, nonlinear, systemic, regressive, and underprepared—are evident. In agriculture, for example, we find that the impact varies across locations, with crop yields increasing in some areas but decreasing in others. In that same case study, we find that risk is nonstationary. For example, in 1998–2017, a 15 percent shock to corn and wheat production was a once-in-a-century event. The likelihood becomes one-in-20 for corn and one-in-33 for wheat by 2050. In our analysis of flooding in Tokyo, we determine that climate risk can have nonlinear impacts. The average flooded depth from a 100-year flood event would be 1.7 times higher by 2050, but the real estate and infrastructure damage from the same event would be 2.2 to 2.4 times higher, 30 percent more than the increase in flood depth.

While the direct impact of physical climate risk is local, it can have knock-on or systemic effects across regions, sectors, and economies through interconnected socioeconomic systems. We find that knock-on impacts could be especially large when people and assets that are affected are central to local economies and those local economies are tied into other economic and financial systems. For example, our past research on Ho Chi Minh City found that direct infrastructure damage from a 100-year flood could be between $500 million and $1 billion by 2050, but knock-on costs could be between $1.6 billion and $8.4 billion.[14]

In the case of India and China, where we analyze the impact of extreme heat, we find evidence that risk is regressive, because the biggest impact will be on the most economically vulnerable.

Finally, our case studies indicate that the pace and scale of adaptation will need to significantly increase. For now, Asian countries have insufficient adaptation measures in place for hazards such as extreme heat and typhoons. Adaptation is likely to entail rising costs and tough choices. Moreover, adaptation costs could rise over time; for example, in cities including Jakarta, Mumbai, Tokyo, and the cost of building new sea walls and other protection from flooding hazards is likely to increase as sea levels rise.

We find some similarities between climate risk and the COVID-19 pandemic (see Box E2, "What Asia can learn from the COVID-19 pandemic to prepare for climate risk"). Both have an array of socioeconomic impacts and share similar characteristics. For example, both are systemic, nonstationary, and nonlinear, and disproportionally affect the most vulnerable.

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[14] Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Peter Cooper, *Can coastal cities turn the tide on rising flood risk?*, McKinsey & Company, April 2020.

Box E2

What Asia can learn from the COVID-19 pandemic to prepare for climate risk

Pandemics and climate risk are both physical shocks that have an array of socioeconomic impacts.[1] Both are also systemic, nonstationary, nonlinear, and regressive.

The current pandemic may provide a foretaste of the impact of a full-fledged climate crisis, with simultaneous exogenous shocks to supply and demand, disruption of supply chains, and global transmission and amplification mechanisms.

Pandemics and climate risks require the same fundamental shifts, from optimizing the short-term performance of systems to ensuring longer-term resilience. Healthcare systems, physical assets, infrastructure services, supply chains, and cities have all been designed to function largely within a very narrow band of conditions. However, physical assumptions may be obsolete as climate variables change, suggesting new thinking about the design of factories, infrastructure, and urban areas is required. Asia needs to invest $1.7 trillion annually by 2030 to maintain the growth momentum, so the need is pressing and real.[2]

Both COVID-19 and climate are global threats. Addressing climate change will require cooperation in the years ahead. Large-scale projects can mobilize cross-border resources, minimize decarbonization costs, and enable innovation. New ideas currently on the table include regional carbon trading and pricing systems, a carbon bank for Asia, and a technology investment fund.

And finally, the pandemic has prompted a rethink of priorities and led to discussions about investment that can foster long-term sustainability. Indeed, many people believe investment in economic recovery should be tied to sustainability requirements.[3] UN Secretary-General António Guterres has urged countries to support companies creating green jobs. China has outlined a recovery pathway that will accelerate the building of infrastructure, with some 25 provinces announcing $7 trillion in investment plans, including in renewable energy, electric vehicles, and smart city infrastructure.[4]

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[1] Dickon Pinner, Matt Rogers, and Hamid Samandari, *Addressing climate change in a post-pandemic world*, McKinsey & Company, April 2020.

[2] Infrastructure investment is defined as fixed asset investment in four sectors: transportation (road, rail, air, and ports), energy, telecommunications, and water and sanitation (including dams, irrigation, and flood control waterworks). Asian Development Bank (ADB) estimate. ADB, *Meeting Asia's infrastructure needs*, 2017.

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

[4] Helen Ding and Wee Kean Fong, *4 investment areas to stimulate China's economy after COVID-19*, World Resources Institute, April 2020.

Rising temperatures could affect livability and effective working hours in major Asian economies and cause regressive impacts within countries

Our analysis indicates that countries with lower levels of per capita GDP are most at risk of impacts from extreme heat and humidity. In our case study analysis, we looked more closely at China and India to identify how people's lives and livelihoods could be affected.

China is highly exposed to hot weather. By 2030, extreme heat and lethal heat waves could affect between ten million and 45 million people.[15] The average person in that group could face a roughly 25 percent chance of experiencing a lethal heat wave at least once in the decade around 2030 (without factoring in air-conditioning), compared with zero chance at present. By 2050, the number of people exposed to extreme heat and lethal heat waves could climb to between 110 million and 250 million. For this group, the probability of being exposed to a lethal heat wave at least once in the decade around 2050 could rise to 35 percent. In China, we find that the average share of effective outdoor working hours lost each year to extreme heat and humidity in exposed areas could increase from 4.5 percent in 2020 to as much as 6.0 percent in 2030 and 8.5 percent in 2050. Moreover, by 2050, in five of the top

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[15] Jonathan Woetzel, Kimberly Henderson, Mekala Krishnan, Haimeng Zhang, and Grace Lam, *Leading the battle against climate change: Actions for China*, McKinsey & Company, 2020. Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature exceeds the survivability threshold for a healthy human resting in the shade, 34°C wet-bulb. Wet-bulb temperature is the lowest temperature to which air can be cooled by evaporation of water into the air at a 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-degree wet-bulb heat waves over the 35-degree 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 four to five 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.

ten populated cities, the average share of effective outdoor working hours lost could increase by more than 5 percent from today.

In India, we find that effectively 30 percent of annual daylight hours may be lost by 2050 in exposed areas, more than a 40 percent increase from today. By 2050, in four of the five most populous cities in India, the average share of effective outdoor working hours lost each year would increase by more than 5 percentage points compared with today.[16]

30%

annual daylight hours that may be effectively lost in India by 2050 due to extreme heat and humidity

Both China and India will experience sizable socioeconomic impacts of extreme heat and humidity by 2050. Lower income groups in both countries are more susceptible than higher income groups, for multiple reasons. First, these populations typically work in outdoor-based industries such as agriculture, mining, and construction. (These industries account for a sizable share of each country's economy today: about 16 percent of China's GDP and 26 percent of India's.) Second, adaptation is expensive and may be out of reach for the economically most vulnerable. By 2030, some 160 million to 200 million people in India are expected to live in urban areas with a nonzero probability of lethal heat waves.[17] Out of that number, about 80 million to 120 million people do not have air-conditioned homes, and many may not be able to afford air-conditioning. Third, livelihoods could be affected by multiple climate hazards. For example, Indian agriculture may be hit not only by lost hours from extreme heat and humidity but by potential yield declines as well.

Adaptation efforts include early warning systems and cooling shelters to protect those without air-conditioning. Working hours for outdoor workers could be shifted, and cities could implement albedo heat-management efforts. Beyond the costs involved, adaptation could be challenging if it changes how people conduct their daily lives or requires them to move to less at-risk areas.

A changing climate could increase the volatility of crop yields across Asia, potentially causing price spikes

In our case study analysis, we examined six Asian breadbaskets—China, India, Southeast Asia, the Indian subcontinent, Australia and New Zealand, and Japan and South Korea—to reveal different impacts among individual crops.[18] We find that by 2030, corn would be at increasing risk of yield declines, rice and wheat would become increasingly volatile, and soy would benefit from higher temperatures.

We examined the probability of a yield decline or improvement of greater than 10 percent for today, 2030, and 2050.[19] We find that certain countries are more exposed than others because of their climatic conditions and composition of crops. Although climate risks will not necessarily reduce agricultural yields for some breadbaskets or crops, they will likely increase production volatility, destabilizing farmers' incomes. Furthermore, both oversupply and undersupply could have a negative impact. Oversupply could affect farmers who may face lower prices for their crops, while undersupply could lead to food shortages and price spikes. Even limited reductions in stock-to-use ratios have in the past triggered food price

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[16] *Will India get too hot to work?*, McKinsey Global Institute, November 2020.

[17] Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature exceeds the survivability threshold for a healthy human resting in the shade, 34°C wet-bulb. Wet-bulb temperature is the lowest temperature to which air can be cooled by evaporation of water into the air at a 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-degree wet-bulb heat waves over the 35-degree 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 four to five 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.

[18] To estimate the likelihood of harvest failure, we employ crop models from the Agricultural Model Intercomparison and Improvement Project (AgMIP) library that translate outputs from climate models into crop yields for each modeled grid cell. Using all available climate models for the period from 1998 to 2060, we construct a probability distribution of yields for each crop in each grid cell. For the purpose of this analysis, we focus on grid cells in the six highest-producing breadbasket regions in Asia for each crop. In the analysis, Asia was split into six regions (China, India, Southeast Asia, the Indian subcontinent, Australia and New Zealand, and Japan and South Korea), then top-producing subregions of those regions were analyzed. By the nature of the choice of agricultural models, these results do not account for specific extreme events such as flash flooding or individual heat waves. All crop modeling has been done under the assumption that historic increases in CO_2 fertilization continue to increase with atmospheric CO_2 content. Uncertainty related to this assumption would lead to overestimating yields and underestimating the likelihood of breadbasket failures.

[19] Yield changes are measured relative to the mean yield for the 1998–2017 period.

spikes. In 2008, cereal prices rose by 100 percent, although global production of grains barely changed.[20]

In China, we expect growing volatility in crop production due to changes in patterns of precipitation and temperature. We find that rice, wheat, and corn could experience a shift in yield distribution and an increase in volatility skewed toward undersupply outcomes by 2030 because of more severe climate hazards. But that shift could reverse by 2050, with yield distribution and increased volatility shifting toward oversupply outcomes.[21] Soy could see lower risk in both the 2030 and the 2050 time frames. A yield shock from increased production volatility in China could have significant knock-on effects, given China's share of global grain production (30 percent of global rice production, 23 percent of corn, 5 percent of soybeans, and 17 percent of wheat).[22]

In Frontier Asia, India will be most affected among the six Asian breadbaskets. By 2030 and by 2050, all four crops could face increasing risks of yield declines exceeding 10 percent, whereas no crops would have increased probability of a yield improvement greater than 10 percent. Because India is the second-largest crop producer in Asia, concurrent food shocks in other breadbaskets (for example, China) could trigger higher prices or, potentially, food supply shock. Similarly, we find that both Bangladesh and Pakistan could face increasing probability of crop yield decline greater than 10 percent. The two countries may also experience a decreasing probability of a rice and corn yield improvement greater than 10 percent by 2050.

In Emerging Asia, we find increased probability of yield change (increase or decrease) of more than 10 percent in the production of rice, corn, and soy by 2050. Since Emerging Asia produces about 26 percent of Asia's rice and 10 percent of its corn, this could have a significant impact on price volatility.

In Advanced Asia, climate change could improve the yields of some crops, in particular soy and rice. This region might benefit from climate change. For example, in Japan, as a result of increasing irrigation water temperature, the rice cultivation period could be prolonged. This will allow greater flexibility in the crop season than is possible now, resulting in a reduction in the frequency of cool-summer damage in northern districts.

26%

the share of Asia's rice produced in Emerging Asia

To combat declining yields and increasing volatility, Asia may consider adaptation measures including gene editing, investment in irrigation infrastructure, shifting sowing dates, erosion protection, and planting trees. To make the food system more resilient, private and public research could be expanded. For instance, research on technologies could aim to make crops more resistant to abiotic and biotic stresses. To offset the risk of a harvest failure of greater than 15 percent, the current global stock-to-use ratio could be increased to 35 to 40 percent, making use of periods of surplus and low prices.

Assets and infrastructure services could increasingly come under threat from climate hazards such as floods in Tokyo and wildfires in Australia

We find a growing risk from climate change across all types of infrastructure we examined in the areas of energy, water, transportation, and telecommunications. Each infrastructure asset type has unique vulnerabilities to climate hazards. In transportation, for example, only a few millimeters of airport runway flooding can cause disruption. Rail and roads are more affected by flooding than by heat, because of the vulnerability of signaling systems to water exposure and the impacts of even small amounts of water; traffic can slow by 30 percent with just a few centimeters of water on the road. We look more closely at flood risk in Tokyo and wildfire risk in Australia as extreme climate hazards in Asia.

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[20] FAOSTAT, Food and Agriculture Organization of the United Nations (FAO).

[21] Multidirectional impacts of climate change by 2030 and by 2050 are observed in China. This is mainly driven by the multidirectional nature of specific climate factors that could affect crop yields both positively and negatively. For example, intensifying climate hazards in China may reduce yields of rice and wheat by 2030, whereas accumulated CO_2 in the atmosphere would serve as fertilizer and could improve yields by 2050. For corn, China may face an increase in precipitation that has a bigger impact than the increase in temperature, and corn yields from 2030 to 2050 would be greater than yields in the period from today to 2030.

[22] US Department of Agriculture (USDA), Foreign Agricultural Service.

In the case of Tokyo, we estimate the impact of a compound flood event of simultaneous one-in-100-year rainfall, streamflow, and storm surge events both today and in 2050 (Exhibit E3).[23] We find evidence of the nonlinearity of climate risk. While the average flood depth in Tokyo could increase 1.7 times by 2050, the real estate and infrastructure damage from the same event would be 2.2 to 2.4 times higher, 30 percent more than the increase in flood depth. Each of these 100-year events respectively is equivalent to a 28-year rainfall, 32-year storm surge, and 71-year streamflow event in 2050.[24] The actions for reducing inundation risks are classified broadly into measures for improving river channels, such as expansion of the channels, excavation of riverbeds, and embankment and measures for controlling flooding such as dam or flood control facilities. For both measures, the impacts on communities and the natural environment should be considered.

In Australia, we find wildfires could cause substantial damage to different types of infrastructure assets ranging from transportation to energy. By 2050, we expect 30 percent of the country by area to experience an increase in the number of high fire risk days of more than 20 days per year (Exhibit E4).[25] It is important to note that, although most areas with high fire risk days today are in central regions of Australia with relatively sparser population densities, those areas would expand to the areas with high vegetation and population density by 2030 and expand farther by 2050. This implies that the risk of a wildfire would become much higher by 2030 because of the increased probability of ignition events (wildfires are also often caused by human activities). We also find that some of the most populated and capital-dense areas (for example, New South Wales) could see the steepest increase in the number of high fire risk days. The share of population living in an area with more than ten high fire risk days per year would increase to 46 percent by 2050, from 26 percent today. Furthermore, the share of capital stock exposed for a given number of high fire risk days reveals that the distribution curve would shift right from today to 2030 and 2050 because of growing exposure of capital stock to wildfires. Increased frequency of Australian wildfires could drive up the share of capital stock exposed to at least five high fire risk days from 44 percent today to 60 percent in 2050. Energy infrastructure assets (for example, transmission and distribution lines) are particularly vulnerable to wildfires because it is challenging to avoid locating those assets in areas with low wildfire exposure. Other vulnerable infrastructure assets include transportation (airport, rail, and roads) and telecommunications (base substations, radio towers, and cable, for example). To adapt to the increasing risks of wildfires, action must be taken along the risk management life cycle: 1) prevention, 2) detection, 3) fire management, 4) restoration, and 5) remediation.

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[23] Tokyo is vulnerable to all three sources of flooding: fluvial, pluvial, and coastal. To simulate the worst-case scenario, all three flood sources were used as inputs to model the 24-hour compound flood event. In this context, the compound flood event is defined as the flood extent caused by the 1-in-100-year rainfall, streamflow, and storm surge events occurring simultaneously. The 1-in-100-year rainfall, streamflow, and storm surge values were calculated independently from each other using various data sources. However, this does not mean that the rainfall, streamflow, and storm surge events are probabilistically independent of each other. The probability of an extreme storm surge event can be higher when conditioned on the occurrence of extreme precipitation compared to the probability of extreme storm surge estimated when assuming the two events are independent, for example. Therefore, in order to avoid underestimating flood risk, all three flood sources were modeled together to provide a realistic estimate of the 1-in-100-year flood event. See technical appendix for further details.

[24] We do not expect significant intensification of streamflow by 2050 due to a potential decrease in snowpack.

[25] A high fire risk day is defined as a day when the fire weather index is high enough to account for the majority (79 percent) of observed historical fires. We project risk of wildfires based on climatic conditions (precipitation, air temperature, wind speed, relative humidity, snow cover, latitude, and time of year) but do not consider ignition events or the prevalence of combustible materials. This is why we see a discrepancy between the map with historical fire events and the map with high fire risk days. See the technical appendix for detailed methodologies.

Exhibit E3

Flooding in Tokyo is expected to become more frequent and intense by 2050 due to climate change in the absence of adaptation and mitigation.

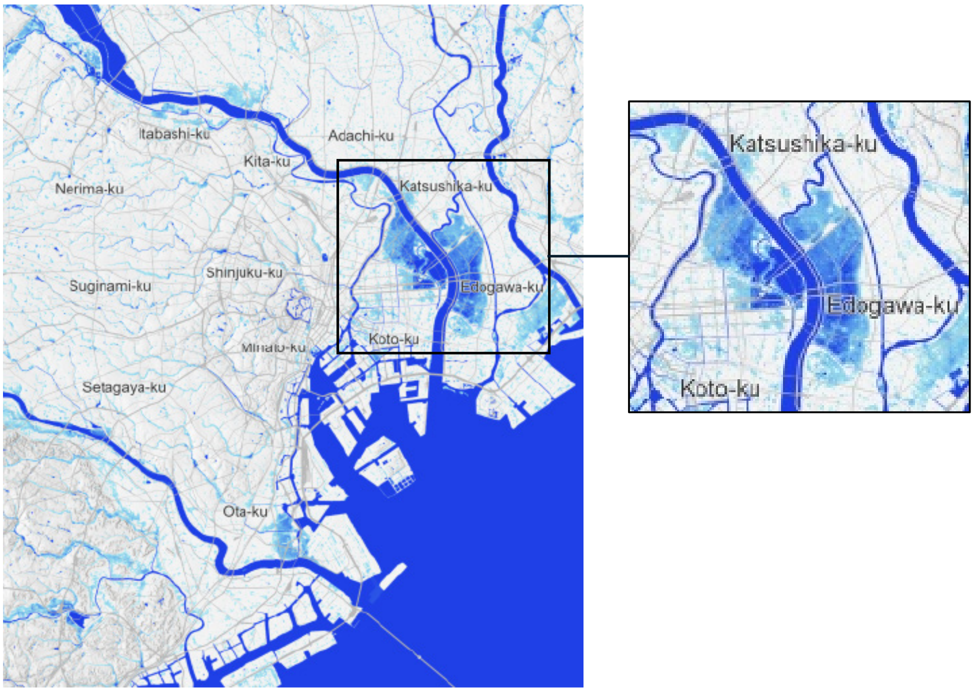
Based on RCP 8.5

Combined flood effects from 100-year rainfall, storm surge, and streamflow in Tokyo

Water level
15 cm ▨ 2+ meters

Today, 100-year event

100-year event in each category today is equivalent to
28-year rainfall, 32-year storm surge, and 71-year streamflow event in 2050



2050, 100-year event

100-year event in each category in 2050 is equivalent to
484-year rainfall, 307-year storm surge, and 152-year streamflow event today

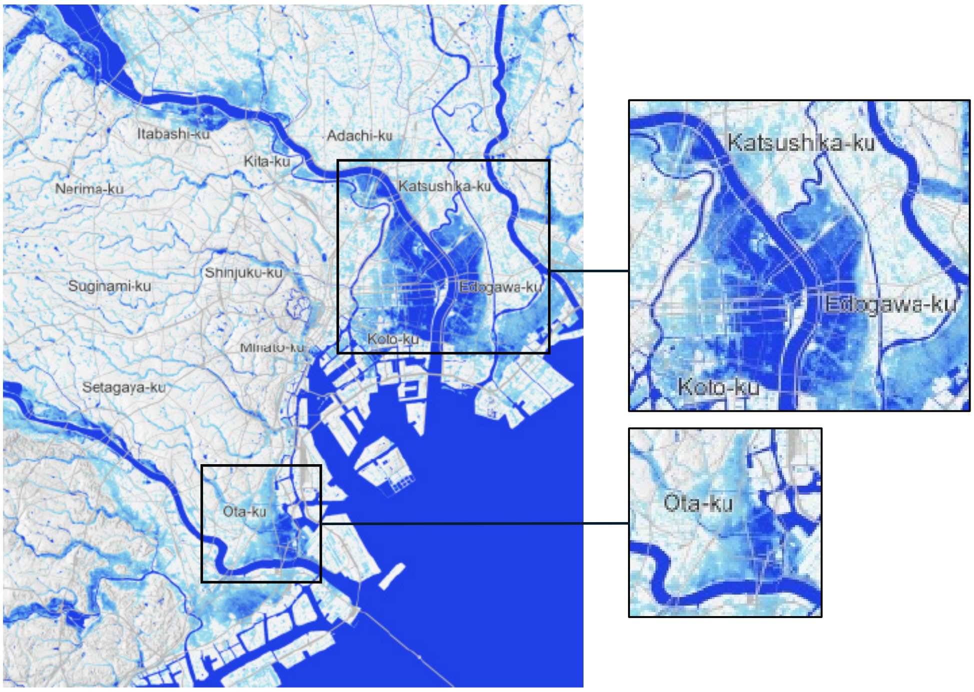
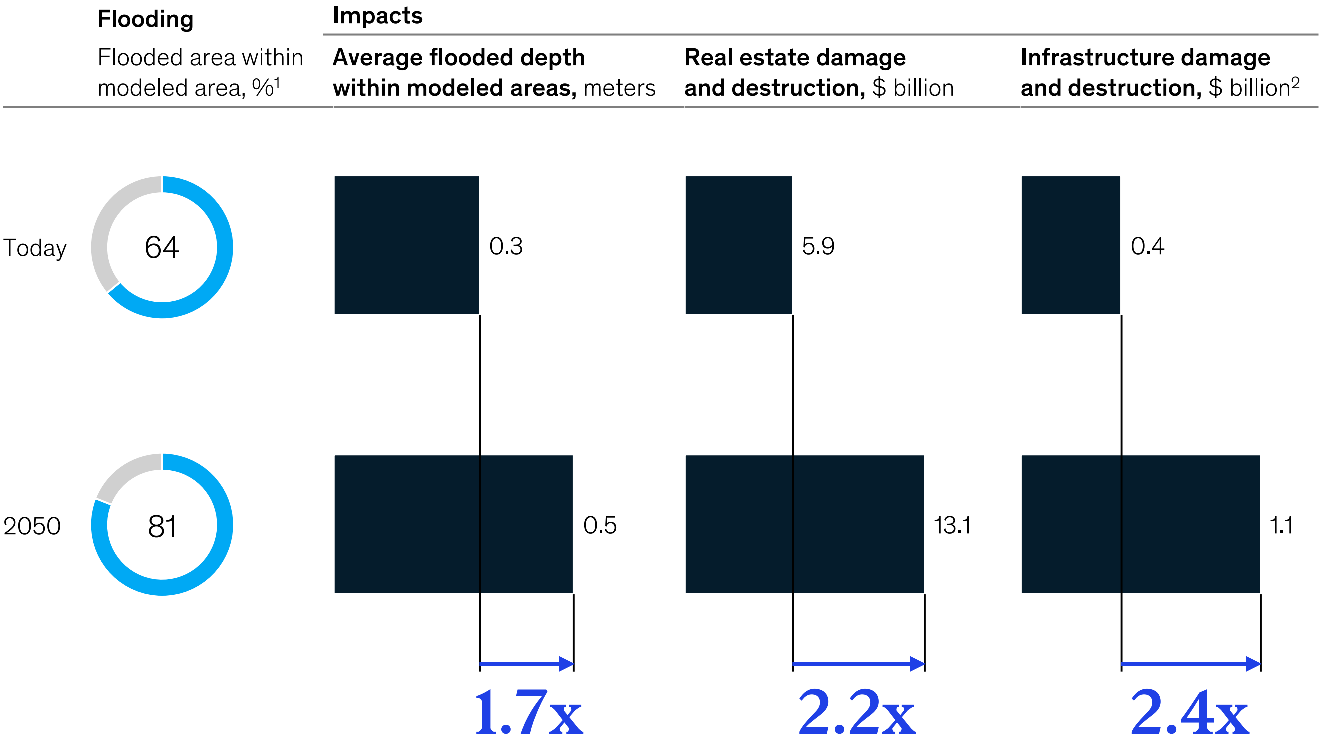


Exhibit E3 (continued)

Flooding in Tokyo is expected to become more frequent and intense by 2050 due to climate change in the absence of adaptation and mitigation (continued).

Based on RCP 8.5

Combined flood effects from 100-year rainfall, storm surge, and streamflow in Tokyo



1. Flooded area considered for grids with depth greater than 0.01.
2. Damage identified for several assets (eg, substations, stations, data centers, hospitals).

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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. To simulate the worst-case scenario, all three flood sources were used as inputs to model the 24-hour compound flood event. In this context, the compound flood event is defined as the flood extent caused by the 1-in-100 year rainfall, streamflow, and storm surge events occurring simultaneously. The 1-in-100 year rainfall, streamflow, and storm surge values were calculated independently from each other using various data sources. These events are not independent, and this was done therefore in order to avoid underestimating flood risk and to provide a realistic estimate of the 1-in-100 year flood event. See technical appendix for further details.

Source: European Commission; Woodwell Climate Research Center; McKinsey Global Institute analysis

60%

the share of capital stock in Australia that may be exposed to at least five high-risk fire days a year by 2050

Exhibit E4

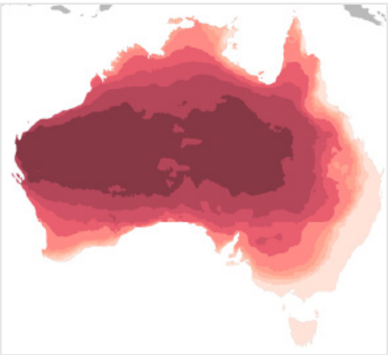
Wildfires are expected to become more frequent in Australia by 2030 and 2050 without adaptation or mitigation.

Based on RCP 8.5

Number of high fire risk days per year[1]

Today

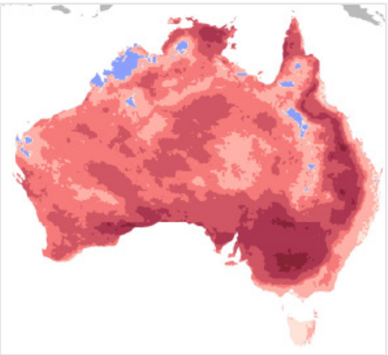
- 🟥 0–25
- 🟥 26–50
- 🟥 51–75
- 🟥 76–100
- 🟥 101–150
- 🟥 151–200
- 🟥 201–250
- 🟥 251–300
- 🟥 >300



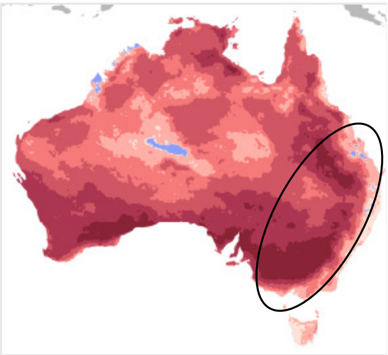
Change from today …

🟦 <0 🟥 1–5 🟥 6–10 🟥 11–20 🟥 21–30 🟥 >30

… to 2030



… to 2050



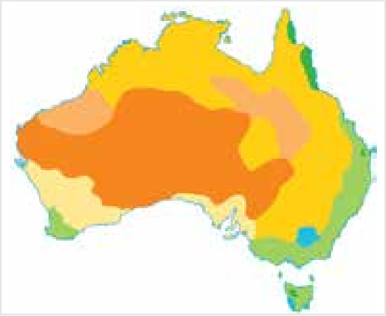
Most populated and capital-dense areas of Australia

30% of country area will see an increase of 20+ days in number of high fire risk days per year

Australia today

Vegetation regions

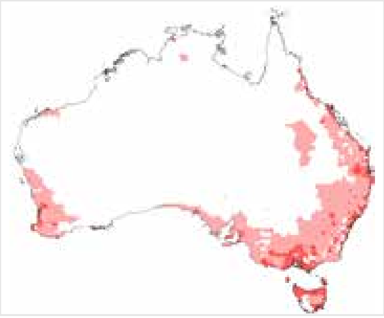
- 🟧 Desert
- 🟧 Grassland
- 🟨 Woodland
- 🟨 Scrubland
- 🟩 Rainforest
- 🟩 Forest
- 🟦 Alpine vegetation



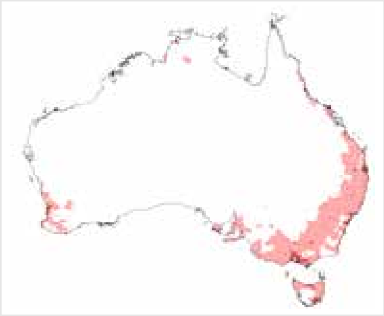
Density today

Low ☐ 🟥 🟥 🟥 High

Capital stock[2]



Population



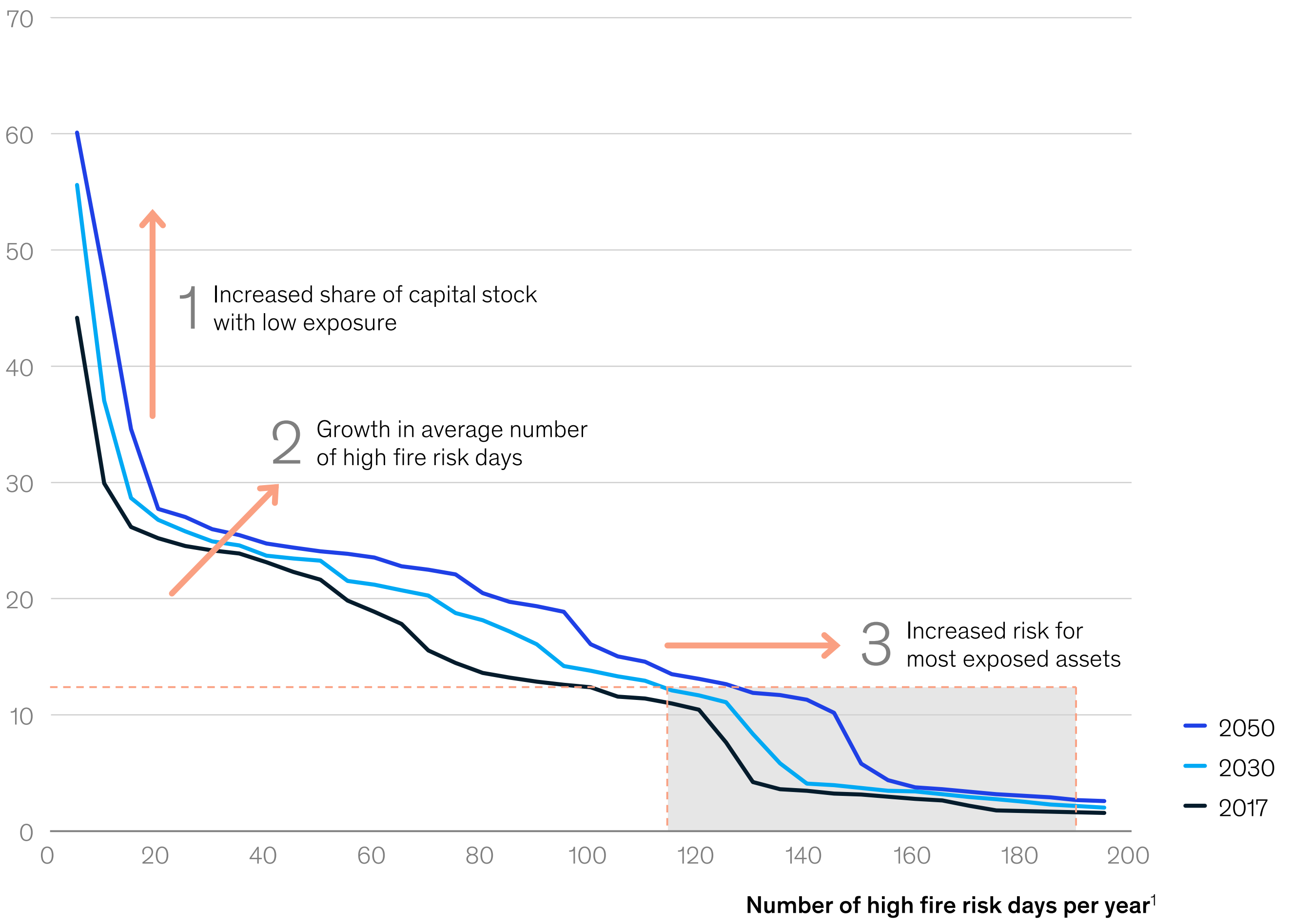
Some of the most populated and capital-dense areas (eg, New South Wales) will see the steepest increase in number of high fire risk days

Exhibit E4 (continued)

Wildfires are expected to become more frequent in Australia by 2030 and 2050 without adaptation or mitigation (continued).

Based on RCP 8.5

Share of capital stock at risk of wildfires (cumulative), %[3]



	1 Share of capital stock exposed to at least 5 high fire risk days, %	**Average number of high fire risk days per year,** weighted average based on capital stock value 2 Weighted based on all capital stock	3 Weighted based on 10% most exposed capital stock
Today	44	28	154
2030	56	32	164
2050	60	37	178

1. Defined as day when fire weather index is high enough to account for majority (79%) of observed historical fires. Fire weather index is general metric of fire danger used globally and is a function of precipitation, air temperature, wind speed, relative humidity, snow cover, latitude, and time of year.
2. Capital stock value is defined as sum of replacement value of industrial, residential, and commercial buildings. Capital stock density is defined as total capital stock value by statistical area 2 (SA2) divided by SA2 area.
3. Based on capital stock value.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: Australian Geography Teachers Association; Geoscience Australia; UN Office for the Coordination of Humanitarian Affairs; Woodwell Climate Research Center; McKinsey Global Institute analysis

47%

the share of national wealth in low income countries dependent on natural capital

Climate change is already having an impact on natural capital such as glaciers and ocean systems, and this could increasingly affect the services they provide
The Asia–Pacific region is rich with natural capital, defined as the world's stock of natural resources, and has some of the largest and most diverse ecosystems on Earth. According to the World Bank, 47 percent of national wealth in low income countries comes from natural capital, compared to 3 percent in Organisation for Economic Co-operation and Development (OECD) countries.[26] Asia–Pacific is the second-largest region of developing countries in the world, and natural capital provides valuable social and economic services to billions of people in the region.

However, climate change is intensifying the degradation of Asia's natural capital that is already endangered. For example, in the Hindu Kush Himalayan region, glacial mass is expected to drop by 10 to 25 percent by 2030, and by 20 to 40 percent by 2050 in some subregions.[27] By 2050, up to 90 percent of coral reefs in the Coral Triangle and Great Barrier Reef could suffer severe degradation under scenarios with two degrees Celsius global mean temperature increase.[28] Rising ocean temperatures are already affecting fishing yields. From 1930 to 2010, seafood yields in the Sea of Japan fell by 35 percent.[29] Finally, by 2050, some 35 percent of mangroves in Southeast Asia may disappear, a significant loss since the region accounts for about half of the world's mangroves, which are natural storm barriers and store and sequester carbon.[30]

Overarching and intensifying natural capital challenges in Asia require enhanced financing. For example, countries may consider the allocation of public funds for natural capital programs, incentives and market mechanisms to engage the private sector, and the introduction of environmental taxes on natural capital consumption and pollution.

The pace and scale of adaptation need to increase to manage climate change in the absence of mitigation

Climate science tells us that warming over the next decade is already locked in, suggesting that socioeconomic impacts are a virtual certainty across Asia.[31] In response, policy makers and business leaders will need to formulate adaptation strategies. But there are opportunities. For example, massive investment in infrastructure across the region presents a key opportunity to embed climate risk into future infrastructure design. To maintain its current growth trajectory, Asia must invest $1.7 trillion annually through 2030, according to the Asian Development Bank.[32]

We investigated about 50 adaptation case studies across Asia, through which we identified and detailed five adaptation measures: diagnose risk and enable response, protect people and assets, build resilience, reduce exposure, and finance and insure (Exhibit E5).

In most decision-making scenarios, there will be difficult trade-offs between what to adapt now versus later or where to invest versus perform managed retreat. Similarly, trade-offs will need to be made in weighing investing today versus delaying adaptation until needs are more acute, and how resilient to make any adaptation investment (for example, resilient to the climate projected in 2030 versus 2050).

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[26] World Bank, *The Changing Wealth of Nations 2018: Building a Sustainable Future*, Washington, DC: World Bank, 2018.

[27] J. M. Maurer et al., "Acceleration of ice loss across the Himalayas over the past 40 years," *Science Advances*, June 2019, Volume 5, Number 6; Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, 2019.

[28] Scott F. Heron et al., *Impacts of Climate Change on World Heritage Coral Reefs : A First Global Scientific Assessment*, Paris, UNESCO World Heritage Centre, 2017.

[29] Christopher M. Free et al., "Impacts of historical warming on marine fisheries production," *Science*, March 2019, Volume 363, Number 6430.

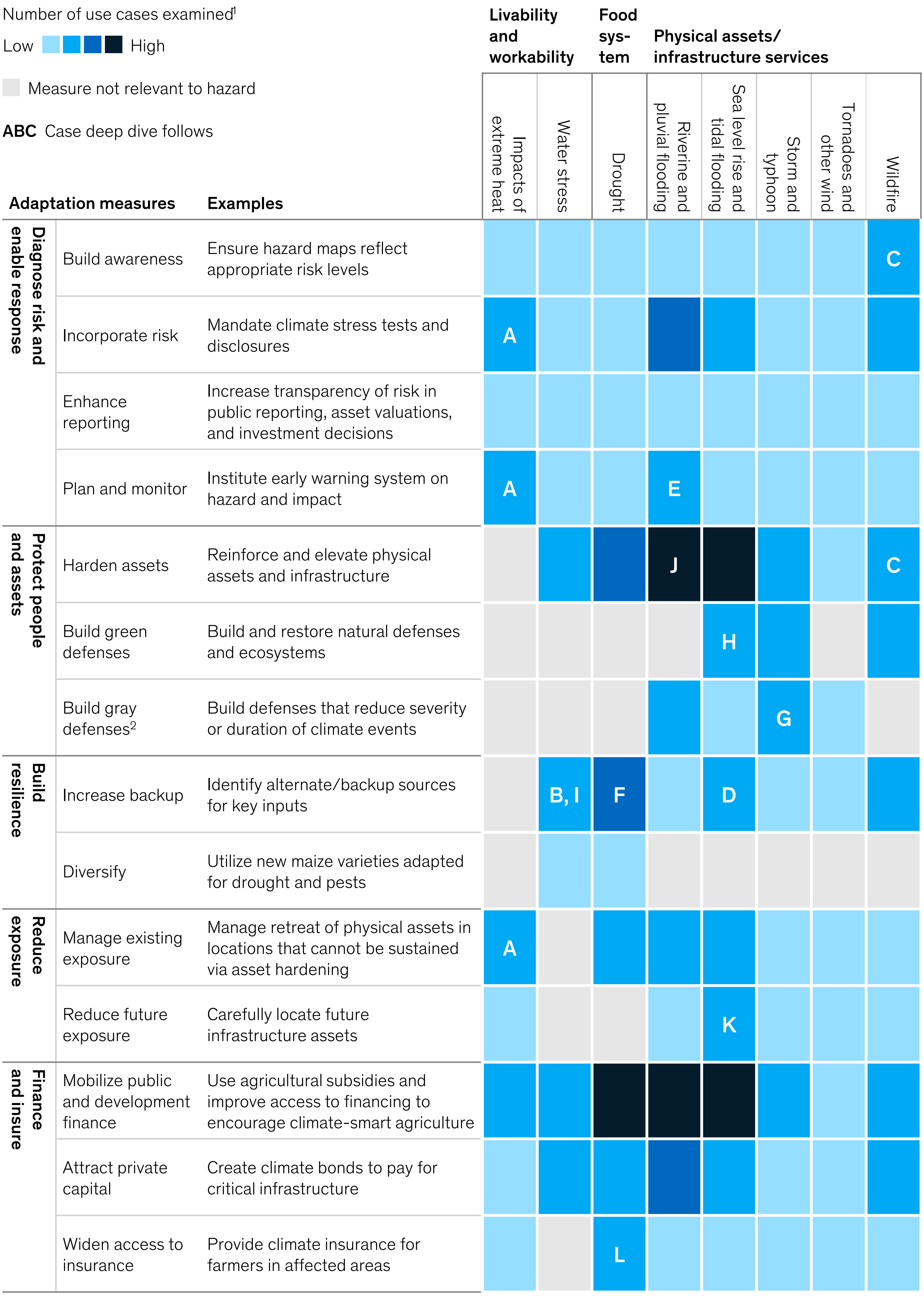
[30] Luke M. Brander et al., "Ecosystem service values for mangroves in Southeast Asia: A meta-analysis and value transfer application," *Ecosystem Services*, Volume 1, Issue 1, 2012, pp. 62–69.

[31] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1; David Archer, "Fate of fossil fuel CO_2 in geologic time," *Journal of Geophysical Research: Oceans*, March 2005, Volume 110, Issue C9; H. Damon Matthews and Susan Solomon, "Irreversible does not mean unavoidable," *Science*, April 2013, Volume 340, Issue 6131.

[32] Infrastructure investment is defined as fixed-asset investments in four sectors: transportation (road, rail, air, and ports), energy, telecommunications, and water and sanitation (including dams, irrigation, and flood control waterworks). *Meeting Asia's infrastructure needs*, ADB, 2017.

Exhibit E5

Adaptation measures for Asia vary according to specific climate hazards.



Number of use cases examined[1]

Low ░ ▒ ▓ █ High

□ Measure not relevant to hazard

ABC Case deep dive follows

	Adaptation measures	Examples	Livability and workability		Food system	Physical assets/ infrastructure services				
			Impacts of extreme heat	Water stress	Drought	Riverine and pluvial flooding	Sea level rise and tidal flooding	Storm and typhoon	Tornadoes and other wind	Wildfire
Diagnose risk and enable response	Build awareness	Ensure hazard maps reflect appropriate risk levels	░	░	░	░	░	░	░	▒ C
	Incorporate risk	Mandate climate stress tests and disclosures	▒ A	░	░	▓	▒	░	░	▒
	Enhance reporting	Increase transparency of risk in public reporting, asset valuations, and investment decisions	░	░	░	░	░	░	░	░
	Plan and monitor	Institute early warning system on hazard and impact	▒ A	░	░	▒ E	░	░	░	░
Protect people and assets	Harden assets	Reinforce and elevate physical assets and infrastructure	□	▒	▓	█ J	█	▒	░	▒ C
	Build green defenses	Build and restore natural defenses and ecosystems	□	□	□	□	▒ H	▒	□	▒
	Build gray defenses[2]	Build defenses that reduce severity or duration of climate events	□	□	□	▒	░	▒ G	░	□
Build resilience	Increase backup	Identify alternate/backup sources for key inputs	□	▒ B, I	▓ F	░	▒ D	░	░	▒
	Diversify	Utilize new maize varieties adapted for drought and pests	□	░	░	□	□	□	□	□
Reduce exposure	Manage existing exposure	Manage retreat of physical assets in locations that cannot be sustained via asset hardening	▒ A	□	▒	▒	▒	░	░	░
	Reduce future exposure	Carefully locate future infrastructure assets	░	□	□	░	▒ K	░	░	░
Finance and insure	Mobilize public and development finance	Use agricultural subsidies and improve access to financing to encourage climate-smart agriculture	▒	▒	█	█	█	▒	░	▒
	Attract private capital	Create climate bonds to pay for critical infrastructure	░	▒	▒	▓	▒	░	░	▒
	Widen access to insurance	Provide climate insurance for farmers in affected areas	░	□	▒ L	░	░	░	░	░

Exhibit E5 (continued)

Adaptation measures for Asia vary according to specific climate hazards (continued).

Adaptation case studies

A. India. Ahmedabad is a city of ~7 million residents. A deadly heat wave in May 2010 that killed 300 people in a single day (and 1,344 people in total) prompted development of a heat action plan as a framework for the implementation, coordination, and evaluation of extreme heat responses in Ahmedabad (including heat alert system and cool roof strategies).

B. India. Due to climate change, natural glaciers are shrinking in the Ladakh region, which relies on melting glacier water for irrigation. Engineer Sonam Wangchuk came up with the idea to collect water from melting snow and ice in the cold months, which would normally go to waste, and store it in the form of "ice stupa" until spring, when farmers need irrigation water the most.

C. Australia. The Victoria Department of Education and Training initiated a substantial and wide-ranging review of bushfire and emergency management arrangements. One significant project was the School Bushfire Protection Project, which aimed to improve bushfire protection for students and staff at schools in a practical and timely manner. The consortium included experts in fire risk modeling, threatened species assessments, and engineering solutions for bushfire-prone locations.

D. Bangladesh. Climate change has intensified riverine and tidal flooding. Each year, when the fields flood, farmers in Charbhangura, a village of 2,500 people in the Pabna district, cannot work. The strategy is to build a floating garden using aquatic weeds as a base on which vegetables can be grown. This garden consists of a duck coop, fish enclosures, and a vegetable garden moored by rope to the riverbank.

E. Japan. As climate change increases the possibility of flooding, the Tokyo Metro is working to minimize the disruption of subway operations, preventing water ingress and minimizing damage caused by floods in the Tokyo subways using precipitation data acquired from space, as well as enhancing station facilities and emergency response for passenger safety.

F. China. In the past 10 years, increasing water shortages and frequent drought in agricultural ecosystems have caused tremendous problems with crop yield in Yunnan and Guangxi provinces. With support from scientists, farmers are using participatory plant breeding to conserve, improve, and develop new maize varieties with satisfactory yields, agronomic traits, and palatability, which are better adapted to drought and pests than modern hybrids.

G. Philippines. In 2015, the International Organization for Migration and UNICEF launched a program to enhance the network of evacuation centers in Eastern Samar, one of the provinces hardest hit by Super Typhoon Haiyan. The program will construct 2 fit-for-purpose evacuation centers that will act as protective shelters from natural hazards such as floods, typhoons, and earthquakes, and, when not in use as evacuation centers, as multipurpose centers for community-based activities.

H. Vietnam. Over the past 30 years, Vietnam has lost half of its mangrove forests, notably to make way for shrimp ponds. Mangroves act as a natural barrier against storms, sea level rise, and erosion. To reduce the pressure on mangrove forests, SNV and the International Union for Conservation of Nature jointly developed the MAM project, which restores and protects mangrove forests while enhancing smallholder livelihoods and resilience.

I. South Korea. As global warming intensifies, increasing soil erosion and water shortages are leading to declining yields in crops. NextOn, an indoor vertical farm startup, rents a deserted tunnel (closed in 2002 due to the sharp curve deemed dangerous) in North Chungcheong to build a 2,000-foot-long vertical farm, growing salads, leafy greens, and strawberries.

J. Malaysia. Kuala Lumpur has experienced an increase in flash flooding, which now occurs almost annually. Malaysia's government controls flooding through increasing river channel capacity, by building a highway tunnel, and by channeling water to holding ponds. The whole project provides storage for 3 million cubic meters of water, sufficient to prevent most of the flooding.

K. Indonesia. The country is in a race against sea level rise, which threatens to submerge swaths of its capital city, Jakarta, by 2050. The plan, announced in 2019, is to move the capital from the island of Java to the island of Borneo. The new capital is to act as the center of government, while Jakarta would remain the country's business and economic center.

L. Thailand. Farmers in northeast Thailand were suffering significant revenue losses as a result of extreme weather events and other climate impacts. Sompo Japan Nipponkoa Insurance launched a new weather index insurance product that provides compensation and/or insurance payments to farmers when temperatures and rainfall breach certain thresholds or when other extreme weather events occur.

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1. Total 50 cases researched; some cases have more than 1 measure.
2. Gray defense refers to technological and engineering solutions to improve adaptation of territory, infrastructure, and people.

Source: McKinsey Global Institute analysis

More broadly, Asian countries are home to some of the largest populations of economically disadvantaged people, many of whom are highly vulnerable to the impacts of climate change. Therefore, it is crucial to ensure that the most vulnerable communities are protected and that decision making includes them. Adaptation measures must carefully be thought through so as not to further contribute to the regressive nature of climate risk. For example, if financing of adaptation needs to come from local communities or individuals themselves, the most vulnerable populations may be at further risk of not being able to finance adaptation investment.

These five adaptation measures are very relevant to Asian countries and in some cases are already deployed but can be expanded. Details of the measures include the following:

Diagnose risk and enable response
Adaptation measures cannot be successful without understanding and tracking intensifying climate risk. Decisive steps should be taken to adopt new mindsets and acquire the necessary tools and capabilities to model and diagnose climate risk that is continuously changing, is spatial (manifested locally), is systemic, and can lead to nonlinear impacts that are regressive. Importantly, planning and strategy building should reflect advanced modeling of climate risk probabilities and assess climate transition and liability risks as well as physical risk.

In Asia, many companies and public-sector organizations are beginning to assess their exposures. For example, as climate change increases the possibility of flooding, the Tokyo Metro is working to minimize the disruption of subway operations, preventing water ingress and minimizing damage caused by floods in the subways through precipitation data acquired from space, as well as enhancing station facilities and emergency response for passenger safety.[33] Yet more could be done. Organizations must take decisive steps to adopt new mindsets that incorporate climate risk, create tailored operating models, and acquire the necessary tools and capabilities.

Protect people and assets
Many Asian countries are dealing with similar challenges, such as how to implement adaptation measures when infrastructure is already in place and how to protect vulnerable populations. Across Asia, an opportunity therefore exists to share best practices so that countries and regions can learn from one another's experiences and adopt measures suitable for their context.

Measures to protect people and assets include: hardening assets, such as reinforcing or elevating physical assets and infrastructure; building green defenses, such as restoring natural defenses and ecosystems; and building gray defenses that reduce the severity or duration of climate events, such as disaster relief community shelters. For example, in a typical year, Kuala Lumpur experiences flash flooding. The Malaysian government has introduced flood controls by increasing river channel capacity, building a highway tunnel, and channeling water to holding ponds. The entire project provides storage for three million cubic meters of water, sufficient to offset most of the flooding in a typical year. [34]

Build resilience
Apart from asset hardening, the resilience of assets and communities can be enhanced by increasing alternate and backup sources or decentralizing resource distribution (diversification). Creating best practices for resilience building in the face of climate change would be beneficial. For example, Yunnan and Guangxi provinces in Southwest China are predominantly rural communities. Over the past ten years, pressure on water systems and frequent droughts have led to significant crop losses. One project to foster resilience helped farmers develop new maize varieties better adapted to drought and pests. In the Ladakh region of India, which relies on melting snow and ice from the Himalayas to irrigate its fields, as glaciers have shrunk, water supplies have declined. A solution was devised to store meltwater in huge standing structures, providing irrigation throughout the year.[35]

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[33] "Using radar to scan rainclouds in 3D to protect subways from flooding," The Government of Japan.
[34] *Special Unit for South-South Cooperation*, Kuala Lumpur, Malaysia, UNDP.
[35] *Ice stupas: Water conservation in the land of the Buddha*, India Water Portal, 2015.

In another case, in 2015, the International Organization for Migration and UNICEF launched a program to enhance the network of evacuation centers in Eastern Samar, one of the Philippine provinces hardest hit by Super Typhoon Haiyan two years previously.[36] The program supported construction of disaster-resilient community buildings. The design combined international best practices with local construction technology and materials, enabling sustainable replication of the template across the Philippines.

Reduce exposure

In the 50 case studies we investigated, reduction of exposure is not commonly practiced as an adaptation measure across Asia. But this should be reconsidered. In some cases, preferable adaptation strategies may include relocating or redesigning asset footprints. As we found in our micro analysis, selected regions in Asia are extremely exposed to intensifying climate risks. For example, in Australia, some of the most populated and capital dense areas (such as New South Wales) will see the steepest increase in number of high fire risk days.

One example of large-scale exposure reduction is the Indonesian government's 2019 decision to relocate the country's capital from Jakarta, parts of which may be submerged by 2050.[37]

Decisions about when to protect and when to relocate will require balancing which regions and assets to spend on, how much to spend, and what to do now versus in the future. The impact on individual home owners and communities must be weighed against the rising burden of repair costs and possible post-disaster aid. Asian countries are home to some of the world's largest populations of economically disadvantaged people, many of whom are highly vulnerable to the impacts of climate change. Therefore, it is crucial for Asian countries to ensure that the most vulnerable communities are protected and that their voices are included in decision making.

$1.7T

the amount needed to be invested in infrastructure in Asia by 2030

Finance and insure

The financing of adaptation measures is particularly important because of Asia's significant infrastructure needs. To maintain growth momentum, eradicate poverty, and respond to climate change, the region must invest $1.7 trillion a year in infrastructure through 2030, according to the Asian Development Bank. About 2 percent ($40 billion per year) is expected to be applied to climate risk adaptation.[38] The financial burden and opportunity could be shared between the public and private sectors, and will require a collaborative approach such as joint funding. Governments can leverage loans or guarantees to encourage private-sector investment or mechanisms, such as legislation, to either raise additional adaptation finance or encourage private-sector involvement. The Asian Development Bank's Climate Investment Funds, launched in 2008, are the largest source of financing for the bank's climate change program and of concessional climate finance for the Asia–Pacific region. The funds have built a strong private-sector portfolio and at the time of writing had about $1.6 billion under management. Financing sourced from the government, multilateral development banks, and the private sector augments and leverages the financial resources donors have pledged to the funds.[39]

Insurance is particularly important for Asia to minimize the impact of intensifying climate risks. This is another opportunity to crowd in the private sector. Three of the four Asian OECD countries and most non–OECD Asian countries did not achieve the average insurance penetration rate of OECD countries.[40] Underinsurance, or the absence of insurance, reduces resilience in Asia.

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[36] *Building safe spaces for the community*, UNICEF Philippines and International Organization for Migration, 2018.

[37] Paige Van de Vuurst and Luis E. Escobar, "Perspective: Climate change and the relocation of Indonesia's capital to Borneo," *Frontiers in Earth Science*, January 2020.

[38] *Meeting Asia's infrastructure needs*, ADB, 2017.

[39] ADB Climate Change and Disaster Risk Management Division, *Country fact sheets*, second edition, ADB and the Climate Investment Funds, 2016.

[40] *Insurance indicators: Penetration*, OECD.

Appropriate insurance can encourage behavioral changes by sending risk signals, for example discouraging development in certain locations. Instruments such as parametric insurance and catastrophe bonds can provide protection against climate events, minimizing financial damage and fostering speedy recovery after disasters. These products may help protect vulnerable populations. Asian initiatives include the weather index insurance product launched by Sompo Japan Nipponkoa Insurance in 2015.[41] This may, for example, pay farmers when temperatures and rainfall breach certain thresholds or when extreme weather events occur.

45%

Asia's share of global greenhouse gas emissions today

Asia is a focal point in global decarbonization efforts and has an opportunity to emerge as a leader

While adaptation is critical in the face of climate change, it is not sufficient. Climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas (GHG) emissions.[42] Asia has a key role to play in global mitigation efforts. Its share of global greenhouse gas emissions has grown to 45 percent in the past 30 years from about 25 percent.[43] The Paris Agreement aims to limit global temperature rise to well below 2.0 degrees Celsius above preindustrial levels in this century and preferably keep the increase to 1.5 degrees. The goal of 1.5 degrees Celsius requires staying within a global carbon budget of 570 gigatons (Gt) of CO_2.[44] One path to staying within the carbon budget requires the world to achieve 50 to 55 percent net emission reduction from 2010 levels by 2030 and net-zero emissions by 2050.[45] Given the substantial share of emissions from Asia as well as its expected economic and corresponding emissions growth, decisions made in Asia today will be a critical determinant of the global emissions pathway.

Our analysis of Asia's mitigation opportunities and challenges was built on four country- and sector-level decarbonization case studies: coal in India, steel in China, agriculture and deforestation in Indonesia, and transportation in Japan. With these case studies, we aim to cover the Four Asias as well as primary (in other words, carbon intensive) country sectors that could play a significant role in decarbonizing the region. These examples were not meant to be exhaustive; rather, the purpose was to understand current decarbonization trends, to identify potential opportunities for decarbonization, including availability and applicability of new technology, and to understand the extent and costs of transition risks associated with decarbonization. In some instances, decarbonizing a sector might require continuing to invest in new technologies that can be deployed at scale, for example the use of hydrogen for steel decarbonization. In other cases, technologies may be viable and scalable; however, other challenges and risks should be managed.

The good news is that, in many ways, Asia is well placed to lead global mitigation efforts. Significant opportunity lies in infrastructure development. As they build out their economies, policy makers in Frontier Asia and Emerging Asia can also exploit synergies between infrastructure needs and opportunities for emissions reductions (such as clean job creation

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[41] *Climate Resilience and the Role of the Private Sector in Thailand: Case Studies on Building Resilience and Adaptive Capacity*, BSR, September 2015.

[42] Net-zero emissions refers to a state in which total annual addition of greenhouse gases to the atmosphere is zero, because all emitting activities have ceased, all emitting technologies have been replaced with zero emissions technology, or remaining emissions are balanced by an equal quantity of negative emissions (for example, removing greenhouse gases from the atmosphere). For an overview of the amount of locked-in warming (called the Zero Emissions Commitment, or ZEC), the mechanics of climate stabilization, net-zero emissions, and carbon budgets, see H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1; H. Damon Matthews and Ken Caldeira, "Stabilizing climate requires near zero emissions," *Geophysical Research Letters*, February 2008, Volume 35, Issue 3; and Myles R. Allen et al., "Warming caused by cumulative carbon emissions towards the trillionth tonne," *Nature*, April 2009, Volume 458, Issue 7242.

[43] Based on AR5GWP20.

[44] Our analysis draws on the work of the Intergovernmental Panel on Climate Change (IPCC) by using a remaining carbon budget of 570 metric gigatons (Gt) CO_2 as of January 1, 2018. Remaining within this budget would equate to a 66 percent chance of limiting warming to 1.5° Celsius. For more about the IPCC methodology and how it differs from other carbon budget estimates (for example, 420 $GtCO_2$ for a 66 percent chance, and 580 $GtCO_2$ for a 50 percent chance), see Myles R. Allen et al., *Special report: Global warming of 1.5°C*, IPCC, 2018; and Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020.

[45] Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020.

and sustainable economic development). Stakeholders can also embrace collaboration between the public and private sectors and explore new approaches to incorporate climate factors into planning. More broadly, Asia is home to some of the world's largest and most innovative companies, and almost half of R&D investment globally takes place in Asia. Over the past decade, the region accounted for the largest share of global growth in key technology metrics—namely, technology company revenue, venture capital funding, spending on research and development, and number of patents filed.[46] With concerted effort, Asian countries can help manage their own exposure to climate risk and can lead the way on global mitigation efforts.

We find four major decarbonization opportunities in Asia (Exhibit E6). They are: shifting from coal to renewable energy; decarbonizing industrial operations and advancing carbon capture, utilization, and storage (CCUS); transforming agriculture and forestry; and electrifying our lives to decarbonize road transportation and buildings. These opportunities cover carbon-emitting sectors. The challenges are very real. In the case of coal, the transition to renewables must take into account recent large-scale investment in newly built coal plants. Here we highlight each opportunity in more detail.

90%

of Asia's emissions from the power sector come from coal

Shift from coal-powered energy to renewables

Asia is uniquely positioned to accelerate coal decarbonization, given its critical mass of regional production capacity and scale to drive down the cost of renewables. Furthermore, about half of global investment in power by 2040 is expected to occur in Asia. At the same time, the power sector accounts for about 35 percent of the region's total CO_2 emissions, and 90 percent of those emissions come from coal (compared to 70 percent globally).

A shift to renewables is under way. China is already the largest renewable market worldwide (more than 750GW of the total 2,500GW global capacity), and its investment in renewable power and fuel in 2018 accounted for 47 percent of total global investment.[47] However, the decarbonization challenge in the coal sector depends on the age profile of a country's power plants as well as the outlook of the country's power demands. Major economies in Asia, such as China and India, have a larger share of newly built coal plants and expect more plants to be built. Decommissioning new plants while meeting growing power demand by renewables alone requires significant investment and a dramatic ramp-up in manufacturing capacity for renewable deployment as well as addressing the difficulty of matching supply and demand when sun or wind is limited. And while it is possible to retrofit coal plants with either biomass or carbon capture and storage, it is a challenge to do so at scale because of the high capital costs and the limited availability of biomass.

In our case study of the coal fired power sector in India, we examined various scenarios, including an aggressive scenario where carbon emissions from power generation in 2050 could be cut in half to 500 $MtCO_2$ from 1,070 $MtCO_2$.[48] This will require decommissioning of about 110GW of subcritical coal plants. It would also require massive up-front investment, including a combination of solar and wind power and battery storage as well as the cost of potential payments to coal asset owners for retiring their assets before the assets reach the end of their lifetime, totaling up to about $310 billion in additional costs by 2050, compared with our reference case.[49] In the absence of effective measures, the scenarios we explore also require overcoming implementation challenges, such as a significant risk of electricity price growth caused by the capital expenditures needed to install renewables and potential job losses by coal plant workers, who may find transitioning to growing sectors (including renewable plants) challenging.

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[46] See Oliver Tonby, Jonathan Woetzel, Noshir Kaka, Wonsik Choi, Jeongmin Seong, Brant Carson, and Lily Ma, *How technology is safeguarding health and livelihoods in Asia*, McKinsey & Company, May 2020.

[47] *Renewable capacity statistics 2020*, International Renewable Energy Agency, March 2020; BloombergNEF; *BP statistical review of world energy 2019*, BP, 2019.

[48] The Global Energy Perspective reference case describes major transitions in the global energy landscape, such as the rise of renewables, a move towards electrification, and shifts in the thinking on climate change and decarbonization. This outlook is based on contributions from hundreds of McKinsey experts from around the world, from fields including oil and gas, automotive, renewable energy, and basic materials. Through this global network, McKinsey's Energy Insights team is able to incorporate a diverse set of views into one consensus reference case. Throughout this report, we refer to this reference case as *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019.

[49] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019.

Exhibit E6

Asia has unique decarbonization opportunities across key carbon-heavy sectors.

Total Asia GHG emissions, 2016, $MtCO_2e$[1]

Low ░ ▒ ▓ █ High

Country[2]	Power	Industry	Agri-culture	Defores-station	Trans-portation	Buildings	Waste	CO_2	Non-CO_2	GHG
	By sector							**Total emissions**		
China	4,023	7,732	1,689	4	970	628	1,017	10,338	5,726	16,064
India	1,060	1,327	1,912	34	288	141	758	2,249	3,271	5,520
Indonesia	181	742	456	1,115	147	26	237	1,630	1,274	2,904
Japan	484	422	64	0	244	118	31	1,214	148	1,363
Australia	188	512	290	10	111	15	88	441	773	1,215
Pakistan	43	183	470	0	50	19	90	192	662	854
South Korea	279	233	37	0	153	53	46	675	127	803
Thailand	93	220	186	15	92	7	59	320	352	672
Myanmar	7	44	226	321	5	4	28	345	289	635
Vietnam	78	209	193	3	42	12	60	233	364	597
Malaysia	106	199	24	52	73	5	46	288	218	506
Philippines	54	77	176	1	38	6	81	130	304	435
Bangladesh	34	76	226	5	12	9	71	86	348	434
New Zealand	3	19	111	1	18	2	18	37	134	171
Total	**6,634**	**11,995**	**6,061**	**1,561**	**2,242**	**1,046**	**2,631**	**18,178**	**13,992**	**32,170**

Key statistics	Power emits **~20%+** of GHGs. **~90%** of power emissions in Asia are from coal (vs ~70% globally).	Industrial GHGs per unit of GDP in Asia are **~60%** higher than global. Asia emits **~80%** of global CO_2 emissions in steel and cement.	Asia agriculture and deforestation emit **20%+** of GHGs. Agriculture emits **~20%** of global methane emissions.	**1/3** of global transportation and buildings' GHGs come from Asia.
Key dicarbon-ization areas	**Shift from coal to renewable energy in power mix.** Critical mass of regional production capacity and scale to drive down costs of renewables (eg, ~50% of global power investment by 2040 expected in Asia).	**Decarbonize industrial operations and advance CCUS.**[3] Biggest indus-trial sector worldwide (eg, China alone accounts for ~50% of global steel production). Rapid investment and large carbon storage potential for CCUS.	**Transform agriculture and forestry.** Major breadbaskets for global crop production (eg, ~90% of rice, 30%+ of corn/wheat from Asia). Significant reforestation potential (~45GtCO_2 could be absorbed).	**Electrify daily life to decarbonize road transportation and buildings.** Technology leadership especially in EVs/FCVs (eg, dominant global share of EVs/batteries, governmental initiatives to accelerate FCV adoption).[4]
Example challenges for Asia	**Large share of newly built plants.** Decarbonization heavily depends on age profile of country's power plants; significant capital expenditures required to retire newly built plants in Asia and decarbonize.	**Dominant global share in steel and cement.** Scaling new solutions (eg, CCUS, hydrogen, bioenergy) is required to accelerate decarboniza-tion and still meet global production demand.	**People's high depen-dency on agriculture.** Securing livelihoods of people dependent on agriculture while decarbonizing the sector is required.	**Massive infrastructure investment.** A challenge exists to scale significant infrastructure required to shift from ICEs to BEV/FCVs.

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1. Greenhouse gases. Non-CO_2 emissions converted into CO_2e using AR5 GWP20 values.
2. The objective of this heat map is to show the largest emitting country-sectors in the region, so Cambodia and Laos are not included. The 14 countries included here account for >95% of total GHGs in the region.
3. Carbon capture, utilization, and storage.
4. Electric vehicles, fuel cell vehicles.

Note: Figures may not sum to 100% because of rounding.

Source: EDGAR 2008, 2015; FAOSTAT, 2015; McKinsey Global Energy Perspective 2019: Reference case, McKinsey Energy Insights, 2019; McKinsey 1.5C Scenario analysis; McKinsey Global Institute analysis

Decarbonize industrial operations and advance carbon capture, utilization, and storage

The industrial sector is the largest greenhouse gas emitter in Asia, accounting for over 35 percent of the region's annual CO_2 emissions.[50] Furthermore, Asia's ratio of industrial GHG emissions to unit of GDP is about 60 percent higher than the global average.[51] Today, Asia generates about 80 percent of global CO_2 emissions in the steel and cement industries.[52] Consequently, structural shifts within these two industries in Asia are critical to success in decarbonizing the world's industrial sector. This could be done in a number of ways. First, reduce demand for and consumption of carbon-intensive intermediate products, improve energy efficiency, and electrify both industries. Second, new sources of energy, especially bioenergy and hydrogen, as well as investment in CCUS would also play a key role.

Leading steelmakers in China already invest in hydrogen metallurgy, and the cost of green hydrogen could fall by an estimated 30 percent and become cash cost competitive between 2030 and 2040.[53] CCUS is considered most applicable for heavy industries such as cement and steel. We believe that Asia has massive potential carbon storage; for example, China's onshore and offshore basins represent a total estimated theoretical CO_2 geological storage capacity of 3,088 gigatons.[54] But the challenge of achieving decarbonization of the steel and cement industries is that accelerating the shift requires significant investment in new technologies. In our China and steel industry case study, assuming an accelerated scenario, China's emissions from the steel industry could decrease by 440 $MtCO_2$ by 2030 from 1,720 $MtCO_2$ in 2020 with a decline in demand, improved energy efficiency, and increased scrap electric arc furnace (EAF) production. Among the new technologies, hydrogen-based steel production using an EAF is most technically feasible and already considered to be part of a potential long-term solution for decarbonizing the steel industry on a large scale.

We identify a number of external factors that will shape future development and time to adoption of green hydrogen–based steel.[55] These include: the need for a significant capacity increase in electricity from renewables; the availability of green hydrogen on an industrial scale; changes in raw materials; new production technology; demand for hydrogen-based steel; and financing and access to capital.

20%

the share of global methane emissions from Asian agriculture

Transform agriculture and forestry

Decarbonizing agriculture in Asia and preventing deforestation are a significant mitigation opportunity; agriculture and deforestation combined account for 10 percent of CO_2 emissions in Asia and over 40 percent of CH_4 emissions. Furthermore, methane emissions from agriculture alone in Asia account for almost 20 percent of global total methane emissions. Key strategies to reduce emissions in this sector include: promoting a shift from a diet rich in animal protein to plant-based protein; improving farming practices (such as dry direct seeding, improved rice paddy water management, and improved fertilization of rice) and promoting sustainable forestry (ending deforestation and scaling reforestation). According to one estimate, as of 2016, annual tree cover loss in Asia amounted to about 63,000 square kilometers, nearly equivalent to the size of Sri Lanka. Stopping deforestation would require a combination of actions (regulation, enforcement, and incentives such as opportunity-cost payments to farmers). Additionally, a massive mobilization to reforest Asia would be necessary. The total potential area of reforestation is approximately 90 million hectares, which could absorb up to about 45 Gt of CO_2 emissions.[56] Coordinated government actions to determine the land use for sustainable forestry would be needed for reforestation to take place at scale.

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[50] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019; Emissions Database for Global Atmospheric Research (EDGAR), 2015; FAOSTAT, FAO, 2015.

[51] Based on AR5GWP20.

[52] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019.

[53] *The future of hydrogen: Seizing today's opportunities*, Organisation for Economic Co-operation and Development, June 2019.

[54] Xiaochun Li et al., "CO_2 point emission and geological storage capacity in China," *Energy Procedia*, February 2009, Volume 1, Issue 1.

[55] Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, *Decarbonization challenge for steel*, McKinsey & Company, 2020.

[56] Jean-Francois Bastin et al., "The global tree restoration potential," *Science*, July 2019, Volume 365, Issue 6448.

Based on the top three contributors to Indonesia's agriculture GHG emissions—rice cultivation, manure management, and enteric fermentation—we find six cost-efficient measures with high $MtCO_2e$ mitigation potential (these are measures related to agricultural production, vs. other measures like diet shifts, that entail shifts in consumer behavior). Three are in cultivation of rice, which has a significant socioeconomic impact in Indonesia, and three in meat production.[57] Evaluated according to global abatement costs, four of the six measures result in cost savings.[58]

The biggest challenge, however, would be the transition to low-carbon farming practices from current practices—which support the lives and livelihoods of billions of people in the region. In Indonesia, for example, the agricultural sector accounts for 13 percent of national GDP and 30 percent of total employment. About 93 percent of Indonesia's farmers work on small family farms, with about 50 percent of annual household income from farm activities.[59]

Decarbonization efforts in Indonesia must move beyond the farm to restoration of carbon sinks. This is because unsustainable agricultural practices have significantly contributed to deforestation. For example, forest clearing for palm oil and timber harvesting accounts for about 40 percent of deforestation in Indonesia. Indonesia has lost 40 percent of its mangroves since the 1970s, mainly due to unsustainable aquaculture and palm oil cultivation.

Indonesia may need to consider introducing more sustainable farming practices to promote decarbonization. However, the country also needs to secure the food industries that are vital to Indonesians' livelihoods. Therefore, the primary measures to stop deforestation include not only strengthened law enforcement to prevent forest fires and land clearing, but also the enhancement of reforestation and efforts to restore degraded lands.

30%

the share of global greenhouse gas emissions from transportation and buildings in Asia

Electrify our daily life to decarbonize road transportation and buildings

More than 30 percent of global GHG emissions from transportation and buildings comes from Asia.[60] At the same time, Asia is a leader in technology such as electric vehicles and fuel cell vehicles (EVs and FCVs). Strategies to decarbonize in the transportation sector include: improving the fuel efficiency of internal combustion engine (ICE) vehicles, EV/FCV penetration in multiple vehicle types, and decreasing the distance driven by road transportation (for example, with a shift to public transportation and ride sharing). In electric vehicle adoption, China already has the largest EV market for passenger cars, with nearly half of global plug-in hybrid electric vehicles and battery electric vehicles (BEV) sales.[61] Asian governments are also taking initiatives to accelerate FCV adoption. For example, the Japanese government's Basic Hydrogen Strategy calls for replacing 1,200 ICE buses and 800,000 ICE vehicles with FCVs by 2030.

The big challenge is to scale the massive infrastructure required to shift from ICEs to BEVs and FCVs. In our Japanese case study, we found that Japan's transportation sector could achieve an annual reduction of about 70 $MtCO_2$ by 2030 compared to 2016 by improving the fuel efficiency of ICEs, raising BEV penetration in most commercial vehicle segments, and decreasing the distance driven on the road through greater use of public transport and ride sharing, for example. This reduction in emissions would help Japan meet its Paris Agreement target in 2030. However, we also found that the decarbonization of the transportation sector requires about $120 billion in incremental investment by 2030 in order to deploy technology for transportation electrification and scale the infrastructure needed, such as EV charging stations.[62] These shifts would also prompt a rapid increase in demand for batteries, challenging that industry to scale more quickly. In addition, electrification of road transportation would require car owners to switch their purchasing behavior and decision-

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[57] Although abatement costs are generalized from our analysis and not specific to Indonesia, we believe they provide a useful guide for each measure.

[58] *Agriculture and climate change: Reducing emissions through improved farming practices*, McKinsey and Company, April 2020.

[59] "Indonesia: Share of economic sectors in the gross domestic product (GDP) from 2008 to 2018," Statista, 2020; "Employment in agriculture (% of total employment) (modeled ILO estimate)," World Bank, 2019.

[60] Based on AR5 GWP20.

[61] China Association of Automobile Manufacturers (CAAM); The Electric Vehicle World Sales Database, EV Volumes.

[62] For details, see *Meeting Japan's Paris Agreement targets—more opportunity than cost*, McKinsey & Company, 2020.

making criteria. The higher up-front cost of BEVs could pose an adoption barrier even if total cost of ownership (TCO) parity is reached, requiring governments and automotive manufacturers to introduce incentives (such as subsidies, tax credits, and preferential number-plate policies) and innovative financing programs to help consumers overcome this barrier.

While electrification is the most promising decarbonization measure for road transportation, decarbonizing buildings would also help overall mitigation efforts. Space and water heating, which typically relies on fossil fuels, is the primary emission contributor, and electrifying these two processes would be the primary decarbonization driver in Asia. Also, by expanding the use of district heating and by blending hydrogen or biogas into gas grids for cooking and heating, emissions attributable to buildings could be further reduced.

Much of Asia is already responding to the adaptation and mitigation challenges of climate change. By building on those efforts, sharing best practices, and galvanizing support, Asia can emerge as a leader in one of the most monumental challenges facing the world. We hope this report helps to point the way. While we recognize that the challenges are large, Asia is well positioned to meet the challenges and capture the opportunities.

Malaysians walking through flooded streets.

© Teh Eng Koon/AFP/Getty Images

1. Understanding physical climate risk in Asia

Signs of vulnerability to a changing climate are emerging across Asia. A changing climate is creating new risks that are significant today and will grow over the coming decade and beyond. To understand the extent of climate risk, we focus on physical risks that encompass both the physical impacts of a changing climate and the effects on socioeconomic systems including people, natural and physical capital, communities, and economic activity (see Box 1, "Our research methodology"). We explore risks today and to 2050 for 16 countries in Asia that account collectively for 54 percent of the global population and one-third of global GDP. The countries are: Australia, Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, New Zealand, Pakistan, the Philippines, South Korea, Thailand, and Vietnam. We also use a Four Asias framework to understand different patterns in exposure to physical climate risk.

2.3°C

the increase in global average temperatures expected by 2050 above the preindustrial average, under RCP 8.5, in the absence of mitigation

As the climate warms, Asian climate hazards are intensifying

Over the past 140 years, Earth has been getting warmer. Following millennia of relative stability, the average temperature has risen by about 1.1 degrees Celsius relative to pre-industrial periods, with significant regional variations.[63] The current rate of warming is unprecedented on geological time scales and is accelerating. In the absence of mitigation, global temperatures are set to rise to 2.3 degrees Celsius above the preindustrial average by 2050 (different climate models predict a range of about 2.0 to 2.8 degrees), translating to local temperature increases of between 1.5 and 5.0 degrees under RCP 8.5.[64]

The primary cause of global warming is increasing volumes of greenhouse gases (GHG) in the atmosphere. Since the mid–18th century, humans have released nearly 2.5 trillion tonnes of CO_2, raising atmospheric CO_2 concentrations from about 280 parts per million by volume (ppmv) to 415 ppmv. Science tells us that between 98 and 100 percent of observed warming since 1850 is attributable to the rise in atmospheric GHG concentrations, and approximately 75 percent is attributable to CO_2 directly.[65]

Climate science also tells us that as a result of global warming, Asia faces a range of climate hazards, with potentially different impacts depending on geography. Indeed, climate scientists have already found direct evidence of the growing effect of climate change on the likelihood and intensity of extreme events. In China, the 2017 Hunan province floods affected 7.8 million people and resulted in $3.55 billion of direct economic loss, including severe infrastructure damage.[66] Researchers estimate that climate change made the floods twice as likely. Researchers have examined the likelihood of fires in Australia and found that the risk of weather conditions that result in fires as severe as those observed in 2019–20 (measured using a fire weather index) has increased by at least 30 percent since 1900.[67]

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[63] Goddard Institute Surface Temperature (GISTEMP), NASA, 2019; and Nathan J. L. Lenssen et al., "Improvements in the GISTEMP uncertainty model," *Journal of Geophysical Research: Atmospheres*, June 2019, Volume 124, Number 12.

[64] Michael Prather et al., "Climate system scenario tables," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[65] Karsten Haustein et al., "A real-time Global Warming Index," *Scientific Reports*, November 2017; Richard J. Millar and Pierre Friedlingstein, "The utility of the historical record for assessing the transient climate response to cumulative emissions," *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Number 2119.

[66] Yin Sun et al., "Anthropogenic influence on the heaviest June precipitation in southeastern China since 1961," *Bulletin of the American Meteorological Society*, January 2019, Volume 100, Number 1.

[67] Geert Jan van Oldenborgh et al., "Attribution of the Australian bushfire risk to anthropogenic climate change," *Natural Hazards and Earth System Sciences* preprint, March 2020.

Box 1

Our research methodology

We measure the impact of climate change based on the extent to which it could affect human beings, human-made physical assets, and the natural world. While McKinsey & Company employs many scientists, including climate scientists, we are not a climate modeling institution. Our focus in this report is on translating climate science data into an assessment of physical risk and its implications for stakeholders. Most of the climatological analysis was undertaken by Woodwell Climate Research Center (formerly Woods Hole Research Center), and in other instances we relied on publicly available climate science data. Woodwell's work draws on the most widely used and thoroughly peer-reviewed ensemble of climate models to estimate the probabilities of relevant climate events.

Our analysis is based on climate models, the primary inputs for which are values for the amount of greenhouse gases in the atmosphere. In mainstream modeling, there are four baseline scenarios for emissions, expressed as Representative Concentration Pathways (RCP). These run from RCP 2.6 to RCP 8.5. The RCP 8.5 scenario delivers a temperature increase of about 2.3 degrees Celsius above preindustrial levels by 2050, compared with 1.8 degrees Celsius for RCP 4.5.[1] Under RCP 4.5, 2.3 degrees Celsius warming would be reached in the year 2080. RCP 8.5 has been criticized for assuming unrealistically high use of coal and therefore projecting emissions in the second half of the century that are too high. However, our report considers a more limited time frame, to 2050. In that context, RCP 8.5 is the best available description for an "inherent risk" scenario over the next two to three decades.[2] By inherent risk, we mean risk absent adaptation and mitigation. This assessment allows us to understand the full magnitude of the problem and the scale of potential response.

We highlight the following key methodological choices:

Case studies
To link Asian physical climate risk to socioeconomic impact, we investigate six cases that illustrate Asia's exposure to climate change extremes and proximity to physical thresholds. They cover a range of sectors and geographies and provide the basis of a "micro-to-macro" approach that is a characteristic of MGI research. We find that these hazards affect five key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

The case studies show that the direct risk to socioeconomic systems is determined by the severity of the hazard and its likelihood, the exposure to hazards of various stocks of capital (people, physical capital, and natural capital), and the resilience of the stocks—for example, the ability of physical assets to withstand flooding. They also help illustrate the specific characteristics and features of physical climate risk, as well as measures to manage the risk.

Geospatial analysis
We use geospatial data to provide a perspective on direct impacts of climate change in countries in Asia over the next 30 years. For each of the five systems in our framework, we identify one or more measures to define the direct impact of climate change: **Livability and workability**—the share of the population living in areas experiencing a nonzero annual probability of lethal heat waves, annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, and water stress, measured as the annual demand for water as a share of the annual supply of water; **Food systems**—annual probability of a change in agricultural yields for major crops;[3] **Physical assets** and **Infrastructure services**—annual share of capital stock at risk of riverine flooding; and **Natural capital**—share of land surface changing climate classification, known as biome shift.[4] We attempt to include impacts from a wide range of hazards. However, due to difficulties in obtaining sufficiently granular and robust data across countries, we are unable to include the potential impact of some hazards, including pluvial flooding and hurricanes.

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[1] Ben Kirtman et al., "Near-term climate change: Projections and predictability," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[2] For a full discussion of our choice of RCP 8.5 and details of our methodology, see the technical appendix of our global report, *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020. See also Christopher R. Schwalm, Spencer Glendon, and Philip B. Duffy, "RCP8.5 tracks cumulative CO_2 emissions," *Proceedings of the National Academy of Sciences*, August 2020.

[3] Major crops are rice, corn, soy, and wheat.

[4] The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. We have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.

Following standard practice, we define future states as the average climatic behavior over multidecade periods. Unless otherwise noted, the climate state today is defined as the average conditions between 1998 and 2017. In 2030 it is defined as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Unless otherwise noted, projections are from Woodwell analysis of 20 CMIP5 General Circulation Models.[5]

For the purposes of this cross-country analysis, we combine the categories of physical assets and infrastructure services. Both derive from physical capital impacts. Data limitations affected our ability to assess infrastructure effects regionally. We often report results as relative measures, compared with a baseline of population, physical capital stock, or GDP in the areas affected by the hazard in question.

What this report does not do

Since the purpose of this report is to understand the physical risks and disruptive impacts of climate change, there are many areas that we do not address:

— We do not assess the efficacy of climate models but instead draw on best-practice approaches from climate science literature and highlight key uncertainties.

— We do not examine in detail areas and sectors that are likely to benefit from climate change.

— We do not undertake a detailed bottom-up cost-benefit analysis of adaptation and mitigation.

— While we attempt to draw out the knock-on effects of direct physical impacts of climate change, we recognize the limitations given the complexity of socioeconomic systems.

— We do not provide projections or deterministic forecasts, but rather assess risk. The climate is the statistical summary of weather patterns over time and is therefore probabilistic in nature. Following standard practice, our findings are therefore framed for the most part as “statistically expected values.”

How we deal with uncertainty

One of the main challenges in understanding the physical risk arising from climate change is the range of uncertainties involved. Risks arise as a result of long causal chains. Emissions influence both global climate and regional climate variations, which in turn influence the risk of specific climate hazards (such as drought and sea level rise). These influence the risk of physical damage (such as crop shortages and infrastructure damage), which finally influence the risk of financial harm. Our analysis relies on assumptions made along the causal chain. The further one goes along the chain, the greater the intrinsic model uncertainty.

Taking a risk-management approach, we have developed a methodology to provide decision makers with an outlook over the next three decades on the inherent risk of climate change—that is, risk absent any adaptation and mitigation response. In our case studies, we outline how this risk could be reduced via an adaptation response. We believe this approach is appropriate to help stakeholders understand the potential magnitude of the impacts of climate change and the commensurate response required. The key uncertainties include the emissions pathway and pace of warming, climate model accuracy and natural variability, the magnitude of direct and indirect socioeconomic impacts, and the socioeconomic response. Assessing these uncertainties, we find that our approach likely results in conservative estimates of inherent risk because of the skew in uncertainties of many hazard projections toward worse outcomes as well as challenges with modeling the many potential knock-on effects associated with direct physical risk.[6]

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[5] The hazard data taken from external organizations includes data on today’s river flood plains from the World Resources Institute Aqueduct Global Flood Analyzer, water stress projections from the World Resources Institute Water Risk Atlas, and climate classification shift data from Franz Rubel and Markus Kottek, “Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification,” *Meteorologische Zeitschrift (Contributions to Atmospheric Sciences)*, April 2010, Volume 19, Number 2.

[6] For further details, see *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.

We list below some of Asia's key climate hazards under RCP 8.5 to 2030 and to 2050.[68]

- **Average temperatures.**[69] Under RCP 8.5, Asia is expected to see an increase in average temperature of more than two degrees Celsius by 2050 compared with preindustrial levels, with the magnitude and pace of warming varying across locations (Exhibit 1).[70] Climate science predicts significant temperature increases, for example, in parts of China, Australia, and the Indian subcontinent. These effects will start to accumulate over the coming decade.
- **Lethal heat waves**.[71] Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature exceeds the survivability threshold for a healthy human resting in the shade.[72] Under RCP 8.5, large cities in parts of India, Bangladesh, and Pakistan could be among the first places in the world to experience heat waves that exceed the survivability threshold (Exhibit 2).[73]
- **Extreme precipitation**.[74] Under the RCP 8.5 scenario, the likelihood of extreme precipitation events, defined as once-in-50-year occurrences in the 1950–81 period, could increase three- or fourfold by 2050 in areas including eastern Japan, central and eastern China, parts of South Korea, and Indonesia (Exhibit 3).
- **Severe typhoons**.[75] While climate change is unlikely to increase the frequency of typhoons in Asia, it could boost their average severity (and thus increase the frequency of severe events). The likelihood of severe typhoon precipitation—an event that had a 1 percent annual likelihood in the 1981–2000 period—is expected to triple by 2040 in some parts of Asia, including coastal areas of China, South Korea, and Japan (Exhibit 4).

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[68] Following standard practice, we define future states as the average climatic behavior over multidecade periods. 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 as the average between 2041 and 2060. Unless otherwise noted, projections are from Woodwell analysis of 20 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models.

[69] Royal Netherlands Meteorological Institute (KNMI) Climate Explorer, 2019, using the mean of the full CMIP5 ensemble of models.

[70] We define the preindustrial period as 1880 to 1910.

[71] Modeled by Woodwell using the mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 global climate models. Models were independently bias corrected using the ERA-Interim data set. High levels of atmospheric aerosols provide a cooling effect that masks the risk.

[72] Wet-bulb temperature is the lowest temperature to which air can be cooled by the evaporation of water at a constant pressure. We took the average wet-bulb temperature of the hottest six-hour period across each rolling three-day period as the relevant threshold. Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature exceeds the survivability threshold for a healthy human resting in the shade, 34°C wet-bulb. 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-degree wet-bulb heat waves over the 35-degree 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 four to five 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. A global analysis of 419 major cities showed that the average daytime temperature difference between urban areas and their immediate surroundings is +1.5°C ± 1.2°, with some outliers up to 7.0°C warmer. Shushi Peng et al., "Surface urban heat island across 419 global big cities," *Environmental Science & Technology*, January 2012, Volume 46, Issue 2. If a nonzero probability of lethal heat waves in certain regions occurred in the models for today, it was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. For details, see the technical appendix of *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.

[73] Some research has documented occurrences of 35° Celsius wet-bulb in some parts of the world for a short duration and finds that extreme humid heat overall has more than doubled in frequency since 1979. See Colin Raymond, Tom Matthews, and Radley M. Horton, "The emergence of heat and humidity too severe for human tolerance," *Science Advances*, May 2020, Volume 6, Number 19.

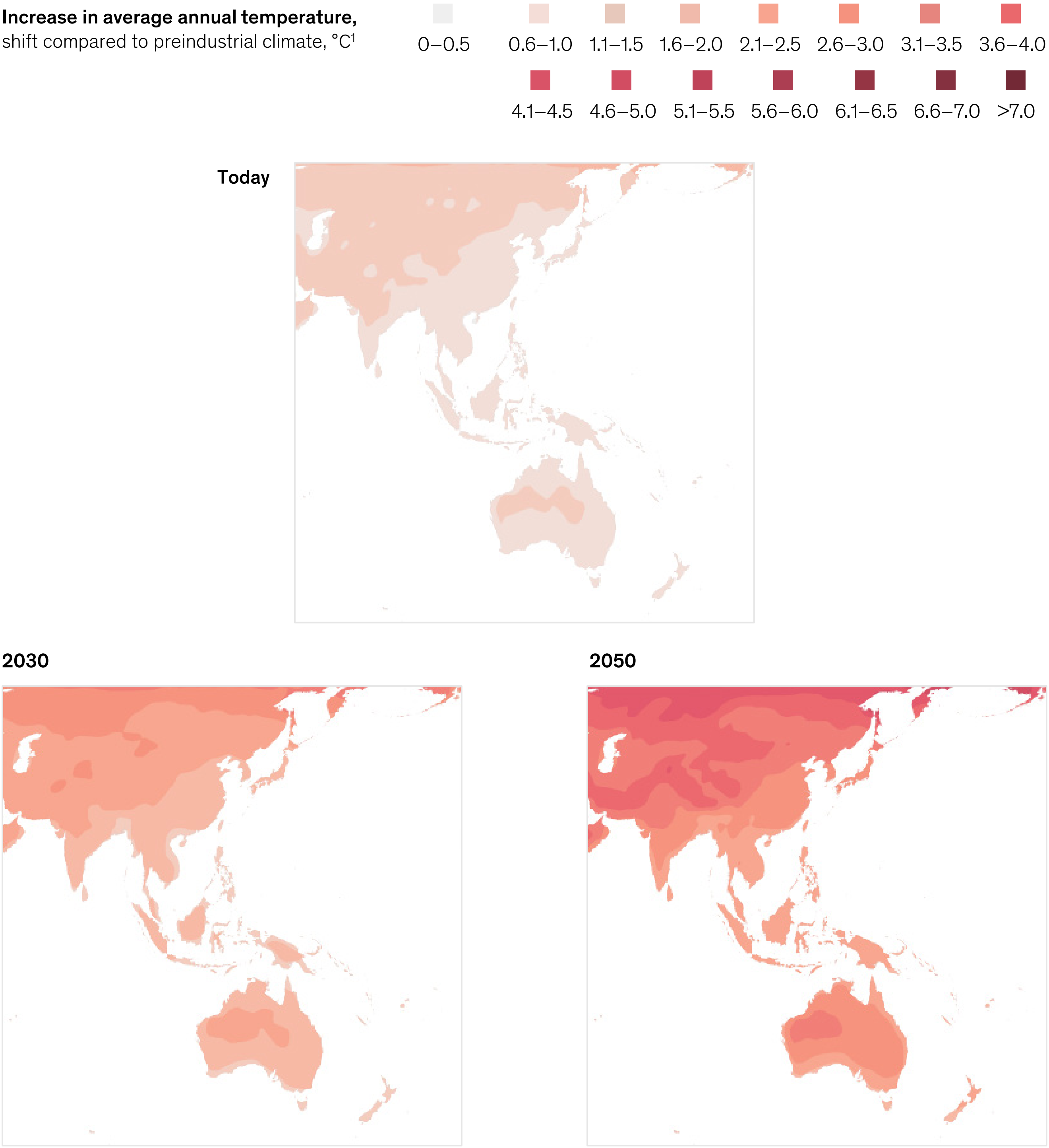
[74] Modeled by Woodwell using the median projection from 20 CMIP5 global climate models.

[75] Modeled by Woodwell using the Coupled Hurricane Intensity Prediction System (CHIPS) model. Kerry Emanuel, *The Coupled Hurricane Intensity Prediction System (CHIPS)*, MIT, 2019. Time periods available for the hurricane modeling were 1981–2000 (baseline) and 2031–50 (future). These are the results for one of the main hurricane regions of the world. Others, for example those affecting the Indian subcontinent, have not been modeled here.

Exhibit 1

Average temperatures are projected to increase in many parts of Asia.

Based on RCP 8.5



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1. From KNMI Climate Explorer, 2019, using the mean of the full CMIP5 ensemble of models.

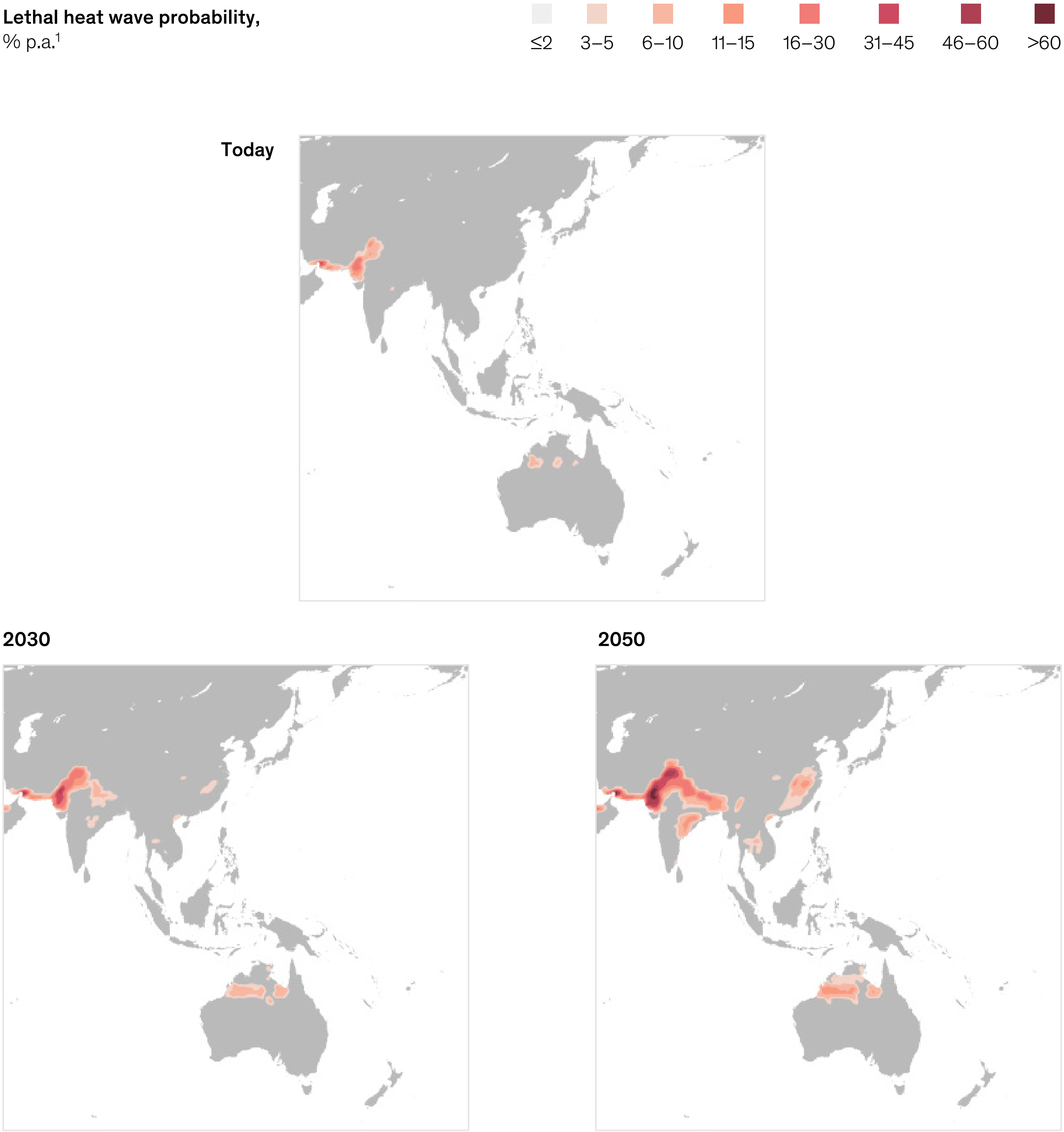
Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, climate 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: KNMI Climate Explorer, 2019; Woodwell Climate Research Center; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Exhibit 2

The likelihood that parts of Asia could experience lethal heat waves is increasing.

Based on RCP 8.5



1. Lethal heat wave defined as 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb, where wet-bulb temperature is defined as lowest temperature to which parcel of air can be cooled by evaporation at constant pressure. Threshold chosen because 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 35°C threshold. Under these conditions, a healthy, well-hydrated human being resting in shade would see core body temperatures rise to lethal levels after roughly 4–5 hours of exposure. Projections subject to uncertainty related to future behavior of atmospheric aerosols and urban heat island or cooling island effects. Modeled by Woodwell Climate Research Center using mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 global climate models.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: KNMI Climate Explorer, 2019; Woodwell Climate Research Center; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

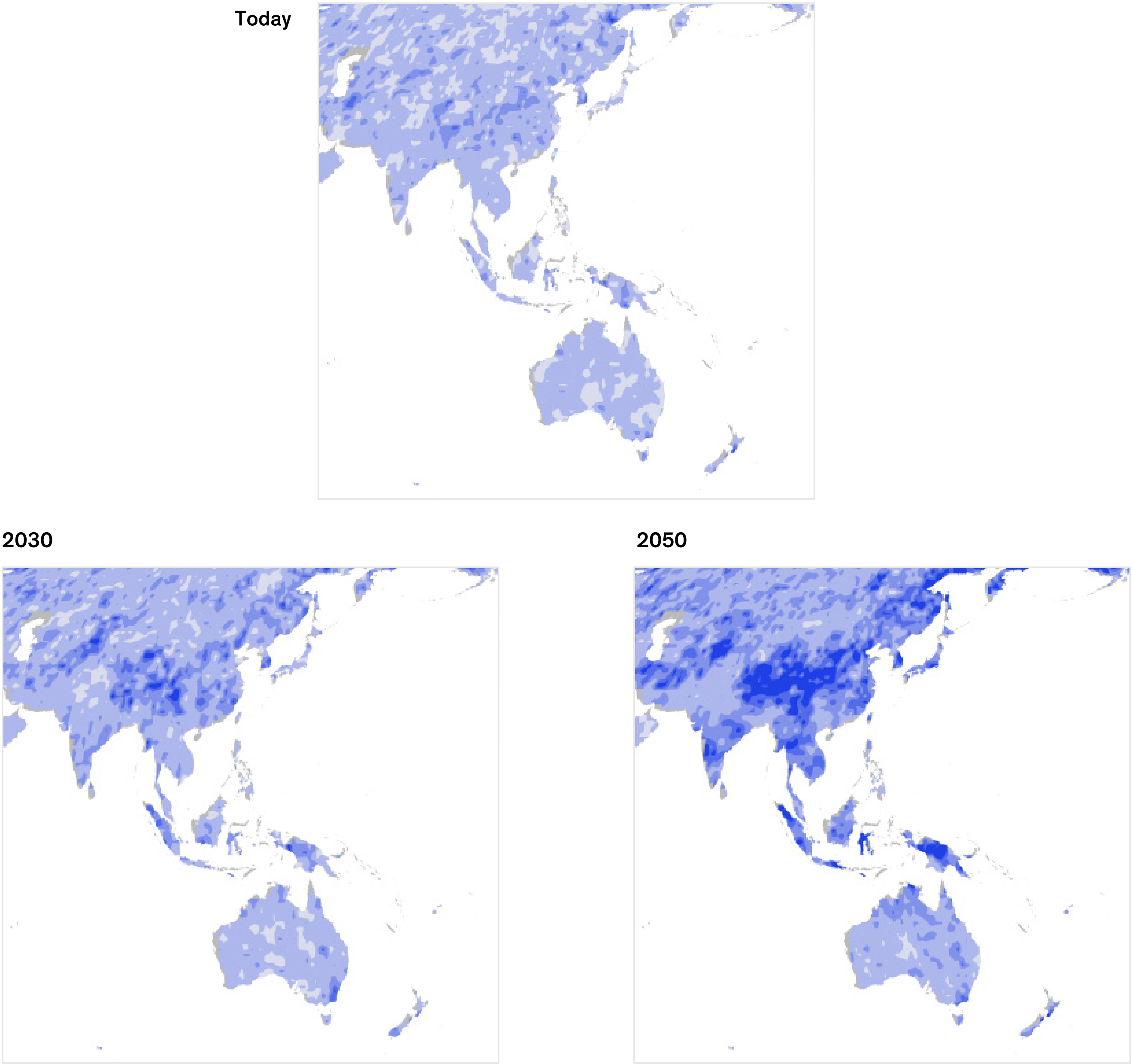
Exhibit 3

In some areas of Asia, the likelihood of extreme precipitation could potentially rise three- to fourfold.

Based on RCP 8.5

Extreme precipitation,
change of likelihood compared to a 1950–81 50-year precipitation event[1]

▨ ≤1x ▨ 1–2x ▨ 2–3x ▨ 3–4x ▨ >4x



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1. Modeled by Woodwell Climate Research Center using median projection from 20 CMIP5 global climate models.

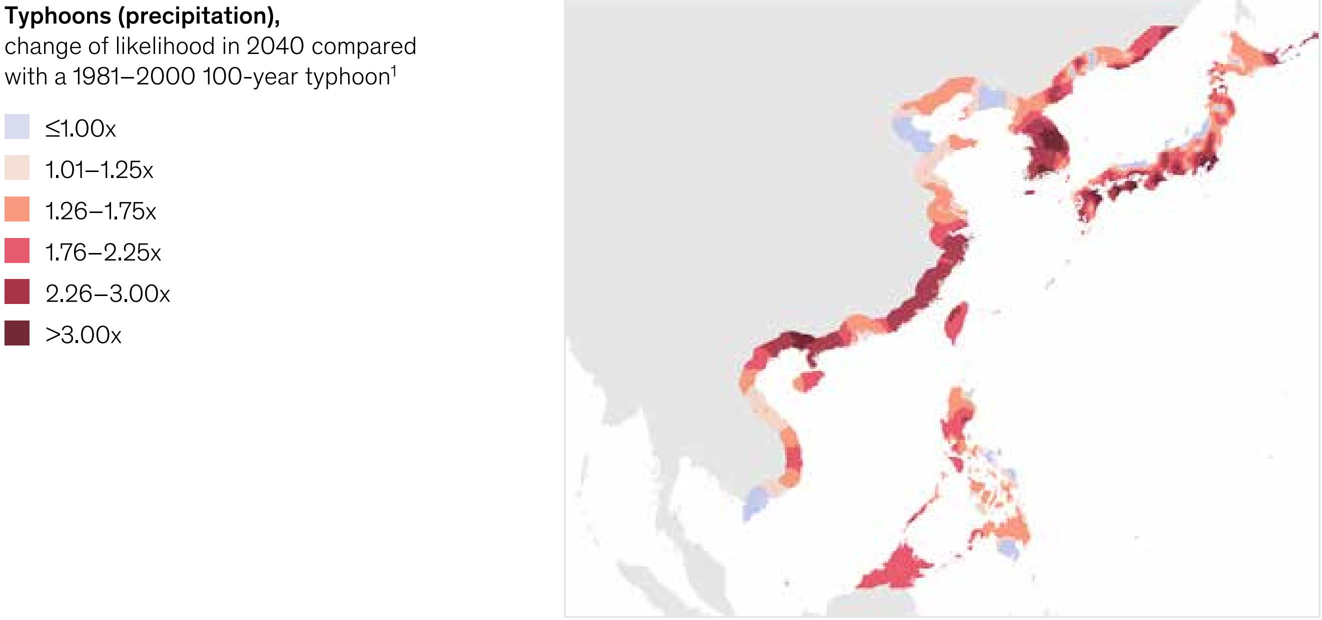
Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, climate 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; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Exhibit 4

The likelihood of severe typhoons in Asia could increase.

Based on RCP 8.5



1. Time periods available for hurricane modeling were 1981–2000 baseline and 2031–50 future. Results represent a main global hurricane region. Others, for example those affecting Indian subcontinent, not modeled here.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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 using Coupled Hurricane Intensity Prediction System (CHIPS) model from Kerry Emanuel , MIT, 2019; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

- **Drought.**[76] As the Earth warms, the spatial extent of and share of time spent in drought conditions is projected to increase (Exhibit 5). The share of time spent in drought in southwestern Australia could grow to more than 80 percent by 2050, and to 40 to 60 percent in some parts of China.

- **Changes in water supply.**[77] The renewable freshwater supply will be affected by factors including rainfall patterns and evaporation (Exhibit 6). In several parts of Australia, mean annual surface water supply could significantly decrease by 2050. Conversely, in parts of China, water supply could increase by more than 20 percent. Parts of the Indian subcontinent could also see an increase in water supply.

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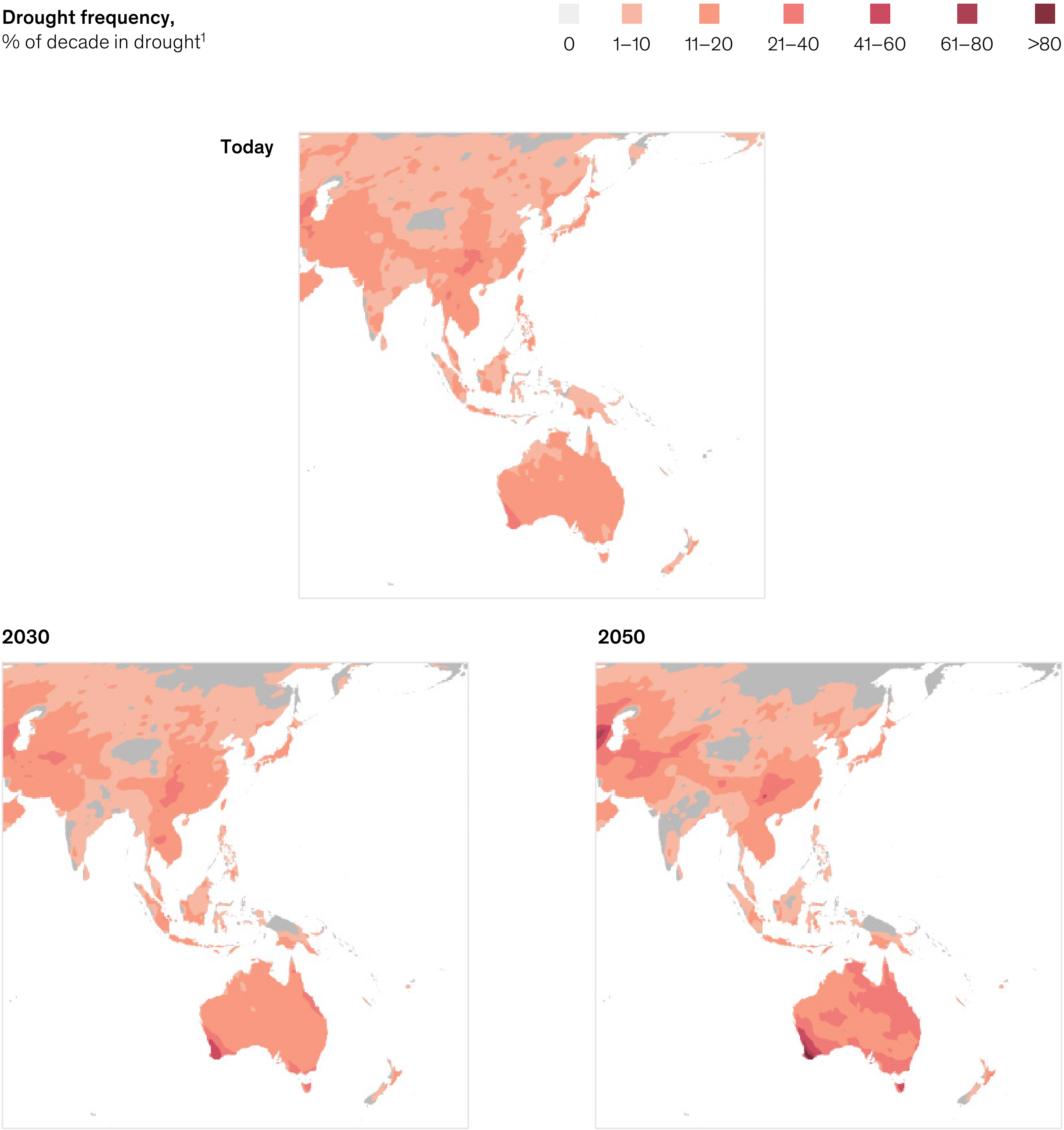
[76] Modeled by Woodwell using the median projection of 20 CMIP5 global climate models, using the self-correcting Palmer Drought Severity Index. Projections were corrected to account for increasing atmospheric CO_2 concentrations.

[77] Taken from the World Resources Institute Water Risk Atlas, 2018, which relies on six underlying CMIP5 models. Time periods in this raw data set are the 20-year spans centered on 2020, 2030, and 2040. Data for 1998–2017 and 2041–60 were linearly extrapolated from the 60-year trend provided in the base data set. Note that this is a measure of surface water supply and does not account for changes in demand for water.

Exhibit 5

Drought could become more frequent in some parts of Asia and less frequent in other parts.

Based on RCP 8.5



Drought frequency,
% of decade in drought[1]

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[1] Measured using 3-month rolling average. Drought is defined as rolling 3-month period with average Palmer Drought Severity Index (PDSI) <-2. PDSI is temperature- and precipitation-based metric calculated based on deviation from historical mean. Values generally range from +4 (extremely wet) to -4 (extremely dry). Modeled by Woodwell Climate Research Center using median projection of 20 CMIP5 global climate models, using the self-correcting PDSI. Projections corrected to account for increasing atmospheric CO_2 concentrations.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

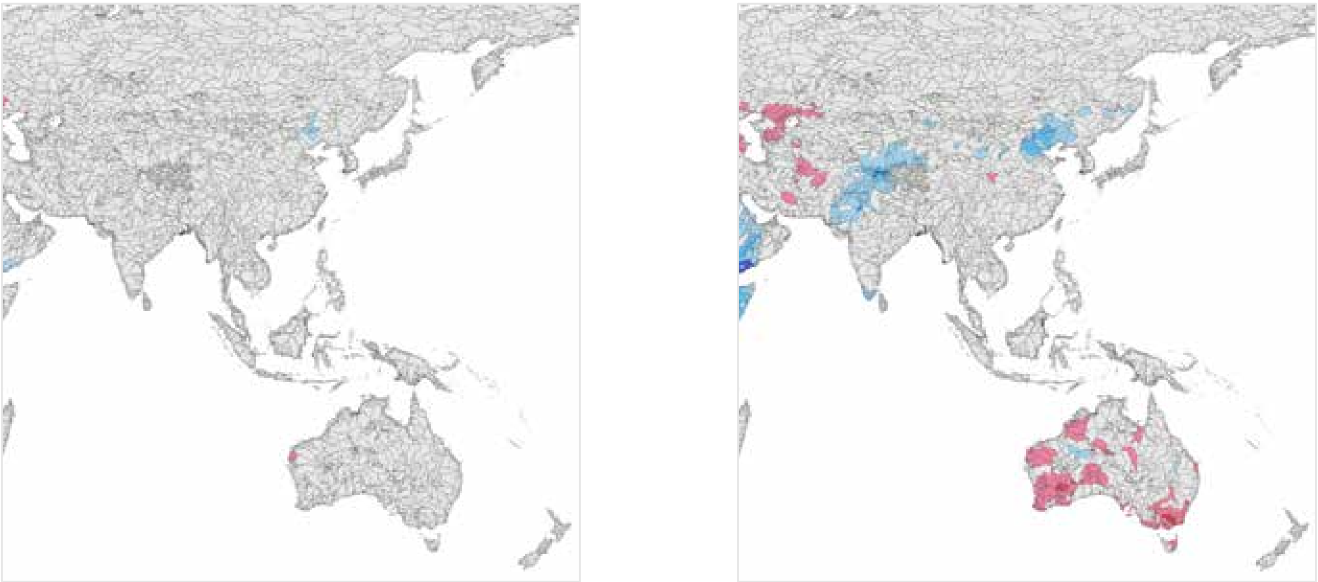
Exhibit 6

Water supply may increase in some parts of Asia and decrease in others.

Based on RCP 8.5

Water supply,
change in surface water compared with 2018
(map boundaries represent water basins), %[1]

■ -70 to -40
■ -40 to -20
■ -20 to 20
■ 20–40
■ 40–70
■ >70



2030

2050

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1. Taken from the World Resources Institute Water Risk Atlas, 2018, which relies on 6 underlying CMIP5 models.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: World Resources Institute Water Risk Atlas, 2018; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

In many ways, Asia may face more severe socioeconomic impacts than global averages, absent adaptation and mitigation

In this analysis, we use geospatial data to provide a perspective on climate change across 16 countries over the next 30 years. These countries account collectively for about 95 percent of Asia's population and GDP. We examined six indicators for the five socioeconomic systems in our analytical framework.

The systems are the following:

- **Livability and workability.** The three indicators in this system are the share of population living in areas experiencing a nonzero probability of lethal heat waves, annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, and water stress, measured as the annual demand for water as a share of the annual supply of water.[78]
- **Food systems.** The indicator we use is the annual probability of a change in agricultural yields for four major crops.[79]
- **Physical assets** and **Infrastructure services**, considered together. The indicator we use for both of these systems is annual share of capital stock at risk of riverine flooding.[80]
- **Natural capital.** The indicator is the share of land surface changing climate classification, known as biome shift.[81]

Our results show that all 16 countries studied would see an increase in potential direct impacts from climate change for at least one indicator by 2050. Twelve countries would see an increase in three or more indicators by 2050. We expect most countries to see rising impacts for the annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, annual share of capital stock at risk of flood damage, and the share of land surface changing climate classification.

Our analysis finds that the socioeconomic impacts could in many cases be more severe in Asia than elsewhere, in the absence of adaptation and mitigation (Exhibit 7).[82] Under RCP 8.5, between 600 million and one billion people in the region will live in areas with a nonzero annual probability of lethal heat waves by 2050. For them, the probability of being exposed to a lethal heat wave at least once in the decade centered on 2050 could increase to 80 percent.[83] That compares with a global total of 700 million to 1.2 billion exposed. On the same timeline, between $2.8 trillion and $4.7 trillion of GDP in Asia will be at risk annually from loss of effective outdoor working hours because of increased heat and humidity. That would amount to more than two-thirds of the total annual global GDP impact. Finally, about $1.2 trillion in capital stock in Asia could be damaged by riverine flooding in a given year by 2050, equivalent to about 75 percent of the global impact. For other systems, Asia might be somewhat less exposed to climate risks than the world, although risks in these areas are still expected to increase by 2050. For food systems, we find the risk of a grain yield decline

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[78] Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone, and not the impacts of increased population and GDP growth. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.

[79] Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using the median of nitrogen limited crop models from the AgMIP ensemble. Yield changes are measured relative to the mean yield for the 1998–2017 period.

[80] For estimation of capital stock at risk of riverine flooding we used a country level Urban Damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under a business-as-usual scenario (RCP 8.5, SSP 2) and existing levels of flood protection.

[81] The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. We have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.

[82] In this report, we look at 16 countries that account collectively for about 95 percent of Asia's population and GDP: Australia, Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, New Zealand, Pakistan, the Philippines, South Korea, Thailand, and Vietnam. They make up 54 percent of global population and one-third of global GDP.

[83] The ranges in the number of people exposed to extreme heat and lethal heat waves in 2030 and 2050 are based on the ranges of population projections from the UN World Population Prospects and the UN World Urbanization Prospects, to bound population growth based on high and low variants and based on urban and total population growth rate. The calculated probabilities of exposure to lethal heat waves are approximations. They assume that the annual probability of X percent applies to every year in the decade centered on 2030 or 2050. We first calculate the cumulative probability of a heat wave not occurring in that decade, which is 1-X10. The cumulative probability of a heat wave occurring at least once in the decade is then 1 minus that number.

of greater than 5 percent in a given year could be 1.4 times higher by 2050 compared with today; the global number is 1.9 times. For natural capital, the share of land area projected to experience biome shift by 2050 is 40 percent for Asia, slightly less than the global average of 45 percent.

Exhibit 7

People, physical assets, and GDP may be more at risk from climate change in Asia than globally, but food systems and natural capital slightly less so.

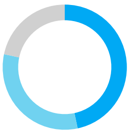
Based on RCP 8.5

First-order impact only, by 2050

Livability and workability

GDP at risk annually due to labor productivity affected by extreme heat and humidity[1]

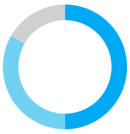
Globally **$4T–$6T**



Asia **$2.8T–$4.7T**

People living in areas with >0% annual probability of lethal heat waves[2]

Globally **0.7B–1.2B**

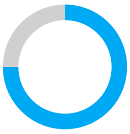


Asia **0.6B–1.0B**

Physical assets/infrastructure

Capital stock that could be damaged from riverine flooding in given year by 2050[3]

Globally **$1.6T**



Asia **$1.2T**

Food systems

	Globally	Asia
Increased risk of >5% grain yield decline in given year, vs today[4]	**1.9x**	**1.4x**

Natural capital

	Globally	Asia
Land area projected to experience biome shift, affecting ecosystems and livelihoods[5]	**~45%**	**~40%**

1. Defined as risk from outdoor working hours affected by extreme heat and humidity in climate-exposed regions annually. Heat and humidity reduce labor capacity because workers must take breaks to avoid heatstroke and because the body naturally limits its efforts to prevent overexertion. Range here is based on pace of sectoral transition across countries.
2. Lethal heat wave defined as 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. Threshold chosen because 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 35°C threshold. Projections subject to uncertainty related to future behavior of atmospheric aerosols and urban heat island or cooling island effects. Range based on range of population projections from UN World Population Prospects and UN World Urbanization Prospects, to bound population growth based on high and low variants, and based on urban and total population growth rates.
3. For estimation of capital stock at risk of riverine flooding, we used country-level urban damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under business-as-usual scenario (RCP 8.5, Shared Socioeconomic Pathways 2) and existing levels of flood protection. Risk values calculated based on expected values, ie, probability-weighted value at risk.
4. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits.
5. Biome refers to naturally occurring community of flora and fauna inhabiting a particular region. Changes in the Köppen Climate Classification System used as indicative proxy for shifts in biome.

Source: Rubel and Kottek, 2010; Woodwell Climate Research Center; World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

We identify four Asias, with different climate profiles, exposures, and responses to climate risk

We divide the 16 countries in our analysis into four groups, reflecting the diversity of a region that is home to four billion people and a variety of governments, economic systems, and demographics. The groups were developed in McKinsey's Future of Asia research and reflect measures of scale (including GDP and population), economic development, regional integration and trade, and global connectedness.[84] While impacts vary across as well as within countries, we broadly find that physical climate risks will play out differently across the Four Asias.

The Four Asias are:

- **Frontier Asia**, consisting of Bangladesh, India, and Pakistan. These economies historically have seen low levels of regional integration and have a more diverse global base of trading partners and investors than other regional economies. They are urbanizing rapidly.
- **Emerging Asia**, comprising Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Thailand, and Vietnam. These culturally diverse countries see a high share of regional flows, and are a major source of labor.
- **Advanced Asia**, made up of Australia, Japan, New Zealand, and South Korea. All are significant providers of capital and technology to the region.
- **China** is large and distinct enough to stand in its own category. It acts as an anchor economy and as a connectivity and innovation platform for neighboring countries.

We use the Four Asias framework to contextualize climate hazards, their socioeconomic impacts, and potential responses (Exhibit 8).

The rapidly urbanizing economies of Frontier Asia (Bangladesh, India, and Pakistan) could see extreme increases in heat and humidity, which may significantly affect workability and livability. Frontier Asia could face a greater likelihood of lethal heat waves than the rest of Asia by 2050. We estimate that by 2050, between 500 million and 700 million people in Frontier Asia could live in regions that have an annual probability of a lethal heat wave of about 20 percent. Rising heat and humidity could also affect human beings' ability to work outdoors, as they tire more easily or need more breaks. We estimate that by 2050, in an average year, 7 to 13 percent of GDP could be at risk as a result. By 2050, these countries could see extreme precipitation events more frequently than in the second half of the 20th century and may experience less drought. Based on analysis by the World Resources Institute, we find that the amount of capital stock at risk from riverine flooding could rise from 0.5 percent of the total today to 3 percent in 2050, for a total of $800 billion of stock at risk.[85] Climate change would also have the biggest negative impact on Asian crop yield in this group of countries. For example, the annual probability of a yield decline of 10 percent or more for four major crops (rice, corn, soy, and wheat) is expected to increase from 12 percent today to 39 percent by 2050 for India, and from 40 percent to 53 percent for Pakistan. Annual probability of a yield improvement of 10 percent or more for the four major crops is expected to decrease from 17 percent today to 5 percent by 2050 for India, and from 38 percent to 27 percent for Pakistan. Frontier Asia is also expected to see an increase in the share of land changing climate classification between today and 2050.

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[84] Our Four Asias framework is based on a methodology developed in McKinsey's Future of Asia research. For a detailed discussion of the Four Asias, see *The future of Asia: Asian flows and networks are defining the next phase of globalization*, McKinsey Global Institute, September 2019.

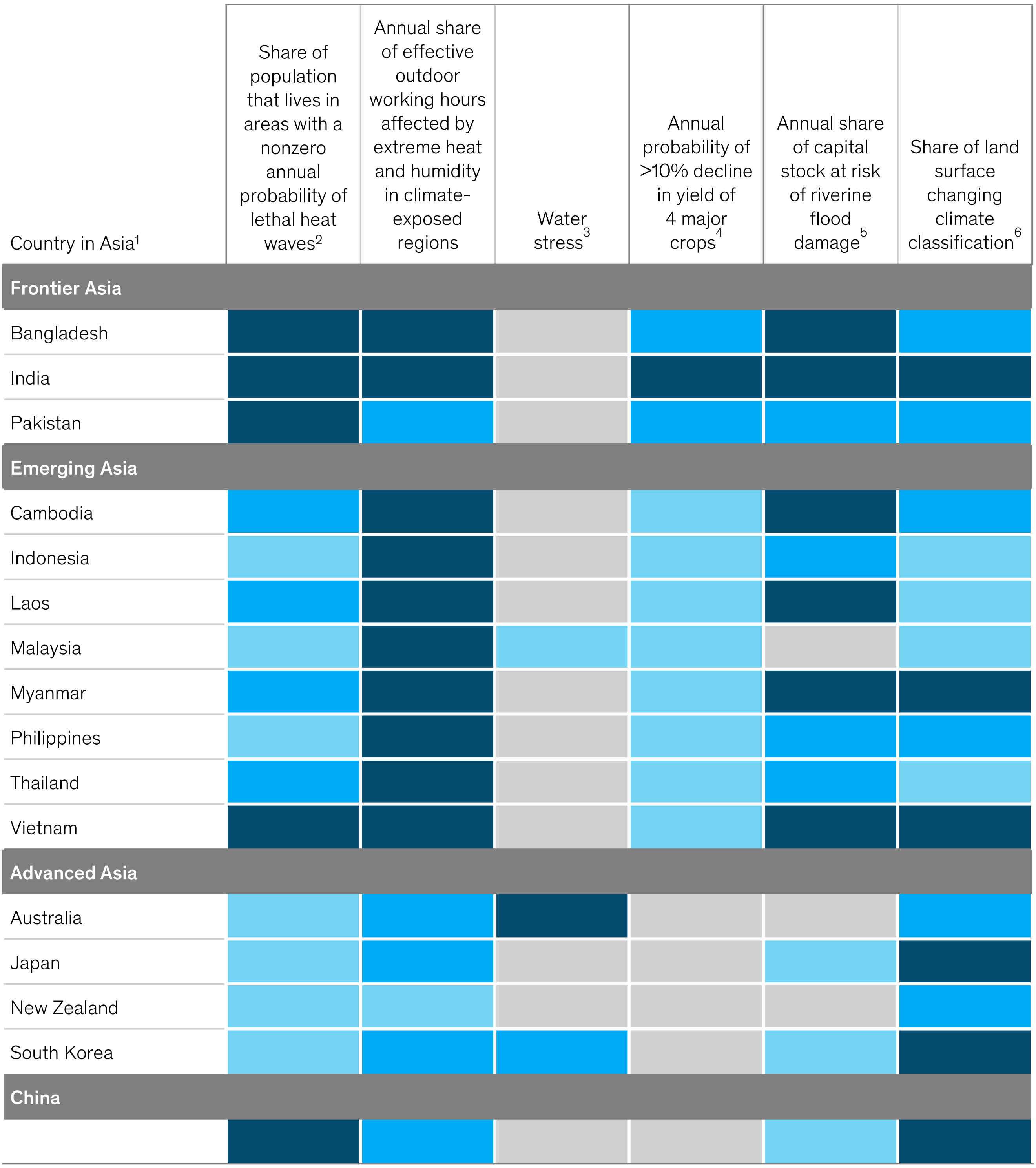
[85] By capital stock at risk, we mean expected damages—that is, damage incurred should an event occur times the likelihood of an event occurring.

Exhibit 8

We identify different types of socioeconomic impacts across the Four Asias.

Based on RCP 8.5

○ Risk decrease ◔ No or slight risk increase ◑ Moderate risk increase ● High risk increase



	Livability and workability			**Food systems**	**Physical assets/ infrastructure services**	**Natural capital**
Country in Asia[1]	Share of population that lives in areas with a nonzero annual probability of lethal heat waves[2]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions	Water stress[3]	Annual probability of >10% decline in yield of 4 major crops[4]	Annual share of capital stock at risk of riverine flood damage[5]	Share of land surface changing climate classification[6]
Frontier Asia						
Bangladesh	●	●	○	◑	●	◑
India	●	●	○	●	●	●
Pakistan	●	◑	○	◑	◑	◑
Emerging Asia						
Cambodia	◑	●	○	◔	●	◑
Indonesia	◔	●	○	◔	◑	◔
Laos	◑	●	○	◔	●	◔
Malaysia	◔	●	◔	◔	○	◔
Myanmar	◑	●	○	◔	●	●
Philippines	◔	●	○	◔	◑	◑
Thailand	◑	●	○	◔	◑	◔
Vietnam	●	●	○	◔	●	●
Advanced Asia						
Australia	◔	◑	●	○	○	◑
Japan	◔	◑	○	○	◔	●
New Zealand	◔	◔	○	○	○	◑
South Korea	◔	◑	◑	○	◔	●
China						
	●	◑	○	○	◔	●

Exhibit 8 (continued)

We identify different types of socioeconomic impacts across the Four Asias (continued).

Based on RCP 8.5

■ Risk decrease ■ No or slight risk increase ■ Moderate risk increase ■ High risk increase

	Livability and workability			Food systems	Physical assets/ infrastructure services	Natural capital
	Share of population that lives in areas with a nonzero annual probability of lethal heat waves[2]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions	Water stress[3]	Annual probability of >10% decline in yield of 4 major crops[4]	Annual share of capital stock at risk of riverine flood damage[5]	Share of land surface changing climate classification[6]
Change in potential impact 2018–50 (percentage points)						
Risk decrease	n/a	n/a	<0	<0	<0	n/a
No or slight risk increase	0.0–0.5	0.0–0.5	0–3	0–10	0–0.1	0–5
Moderate risk increase	0.5–5.0	0.5–5.0	3–7	10–20	0.1–0.5	5–10
High risk increase	>5.0	>5.0	>7	>20	>0.5	>10

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1. For our analysis in this report, we look at 16 countries that account collectively for about 95% of Asia's population and GDP: Australia, Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, New Zealand, Pakistan, Philippines, South Korea, Thailand, and Vietnam. Collectively, these 16 countries make up 54% of global population and one-third of global GDP.
2. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. 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. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
3. Water stress measured as annual demand for water as share of annual supply of water. For this analysis, we assume demand for water stays constant over time, to measurement of impact of climate change alone. Water stress projections for arid, low-precipitation regions excluded due to concerns about projection robustness.
4. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits. Countries grouped for some analyses to ensure modeling robustness. Yield changes are measured relative to the mean yield for the 1998–2017 period.
5. For estimation of capital stock at risk of riverine flooding, we used country-level urban damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under business-as-usual scenario (RCP 8.5, Shared Socioeconomic Pathways 2) and existing levels of flood protection. Risk values calculated based on expected values, ie, probability-weighted value at risk.
6. The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. For this report, we have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.

Note: See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: Rubel and Kottek, 2010; Woodwell Research Center; World Resources Institute Aqueduct Global Flood Analyzer, 2019; World Resources Institute Water Risk Atlas, 2018; McKinsey Global Institute analysis

Like Frontier Asia, Emerging Asia is expected to see increases in heat and humidity. By 2050, in an average year, between 8 and 13 percent of GDP could be at risk as a result of rising heat and humidity. The region could also experience growing exposure to extreme precipitation events and flooding. The socioeconomic impacts of these hazards could potentially be severe. Based on analysis by the World Resources Institute, we find that capital stock at risk from riverine flooding in Emerging Asia countries is expected to double from 0.7 percent today to 1.5 percent by 2050, meaning a total of $220 billion in stock would be at risk. Drought could become less frequent in this region. Volatility in agriculture could increase. In crop yields, the annual probability of a 10 percent decline will increase from 2 percent today to 8 percent by 2050. At the same time, the annual probability of a 10 percent yield increase will decrease from 5 percent today to 1 percent.

Overall, the countries we classify as Advanced Asia (Australia, Japan, New Zealand, and South Korea) are expected to see slightly lower impacts of climate change along many dimensions than Frontier Asia and Emerging Asia countries. Under RCP 8.5, for some countries in the region, the impact on water supply and drought are the main challenges. Indeed, by 2050, the share of a decade southwestern parts of Australia spend in drought conditions is expected to top 80 percent. One potential impact the region is likely to see is biome shift, or the share of land changing climate classification. Under RCP 8.5, biome shift is projected to climb in Japan and South Korea by an average of 27 percentage points between today and 2050, as measured against a 1901–25 baseline. Typhoon and extreme precipitation risk could also increase in some parts of Japan and South Korea, as noted earlier. In agriculture crop yield, no significant risk increase has been observed for this group. Rather, by 2050, the annual probability of a 10 percent yield increase could increase; it could rise from 21 percent today to 45 percent for the Australia and New Zealand region.

China is climatically heterogeneous, due to its location on a wide range of latitudes. Still, the country in aggregate is projected to become hotter. In addition, eastern parts could see threats of extreme heat, including lethal heat waves. Central, northern, and western China could experience more frequent extreme precipitation events. In the country overall, the average share of effective outdoor working hours lost each year to extreme heat and humidity in exposed areas would increase from 4.5 percent in 2020 to as much as 6.0 percent in 2030 and 8.5 percent in 2050. As a result, the share of China's GDP that could be lost to heat and humidity, currently 1.5 percent, could rise to 2 to 3 percent by 2050—equivalent to $1 trillion to $1.5 trillion in GDP at risk in an average year. China is expected to see a growing biome shift by 2050, with an increase of about 27 percentage points in the share of land changing climate classification, measured against a 1901–25 baseline. The country is expected to be an agricultural net beneficiary from climate change in the near term, with increasing statistically expected yields and volatility skewed toward positive outcomes. China could see expected yields increase by about 2 percent by 2050 relative to today. The annual probability of a breadbasket failure of greater than 10 percent relative to a baseline today would decrease from 5 percent to 2 percent by 2050, while the annual probability of a bumper year with an increase in yield of greater than 10 percent would increase from 1 percent to approximately 12 percent by 2050.

Each of the Four Asias will need to take steps to manage their exposure to physical climate risk, and pay particular attention to the areas of risk highlighted above. Frontier Asia, Emerging Asia, and China are still building out large parts of their infrastructure and rapidly urbanizing. They will need to ensure that climate risk is embedded into forward-looking capital and urban planning decisions. For example, Emerging Asia is expected to see an influx of labor-intensive industries as manufacturing migrates away from China, and the countries will need to focus on the impact of rising heat and humidity, as well as potential impacts of flooding, on those industries. Given China's role in regional and global trade, and the potential exposure of many of its industries and geographies, companies in China will need to pay particular attention to increasing resiliency in supply chains.

Climate science finds that Asia is already experiencing an increase in both severity and frequency of climate hazards, such as drought, wildfires, typhoons, and floods. This trend will only continue and risks rise, without adaptation and mitigation. In that case, the socioeconomic impacts could be large—for example, at least 600 million and perhaps as many as one billion people could live in areas with a nonzero annual probability of lethal heat waves by 2050. In the following chapter, we look more closely at six case studies in Asia and highlight the extent to which a changing climate could affect the economy and society and the nature of physical climate risk, as well as the types of adaptation measures that are needed.

Australian wildfires.
© Andrew Merry/Moment/Getty Images

2. Physical climate risk: A micro view

In this chapter, we examine how climate hazard becomes risk for socioeconomic systems. We examine six case studies from across Asia to assess risks to specific sectors, locations, and markets. The cases were chosen based on their exposure to the extremes of climate change and their proximity today to key physical and biological thresholds. Each case is specific to a regional geography and an exposed system, and as such is not representative of an "average" environment or level of risk across the world. As noted, these cases are based on an RCP 8.5 climate scenario. By understanding the impact of climate change in a leading-edge case, we provide a methodology to assess risk in future instances of rising climate change.

Our case studies cover each of the five systems we consider directly affected by physical climate risk, across countries and sectors (Exhibit 9). The cases include the following:

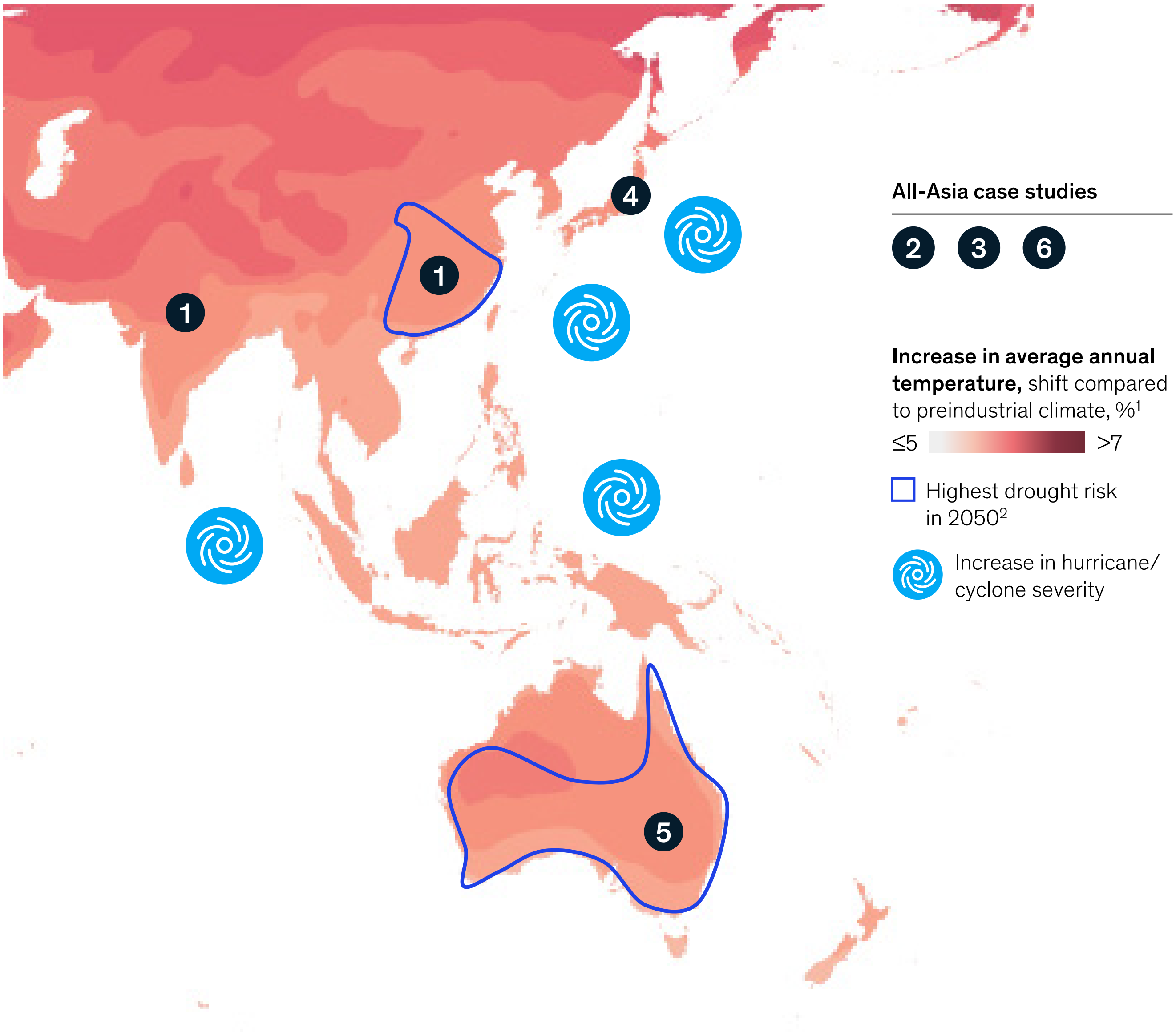
- **Livability and workability.** We examine the risk of exposure to extreme heat and humidity in India and China and what that could mean for urban populations and outdoor-based sectors.
- **Food systems.** We focus on the likelihood of a multiple-breadbasket failure affecting rice, corn, soy, and wheat in six major breadbaskets in Asia.
- **Physical assets and infrastructure services.** For these two systems, we examine 17 types of infrastructure asset for their vulnerability to climate hazards and present deep dives on the potential impacts of flooding in Tokyo and wildfires in Australia.
- **Natural capital.** We examine the potential impacts of climate change on three natural capital systems in Asia: glaciers, oceans, and forests.

At the end of this chapter, we present a country-level view of socioeconomic impacts in a series of individual country dashboards that combine the findings from our geospatial analysis and case studies.

Exhibit 9

We selected six case studies of climate change impacts across geographies and systems in Asia.

Based on RCP 8.5



Livability and workability	1	Will Asia get too hot to work? (India and China)
Food systems	2	Will breadbaskets in Asia become less reliable?
Physical assets/infrastructure services	3	Will infrastructure in Asia bend or break under climate stress?
	4	Can coastal cities turn the tide on rising flood risk?
	5	Will Australian capital stock be more exposed to wildfires?
Natural capital	6	Could climate change accelerate the destruction of natural capital?

1. Taken from KNMI Climate Explorer, 2019, using mean of full CMIP5 ensemble of models.
2. Drought risk defined based on time in drought according to Palmer Drought Severity Index.

Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: KNMI Climate Explorer, 2019; Woodwell Climate Research Center; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Seven core characteristics of climate risk stand out from our case studies

Our case study analysis helps to reveal the magnitude of the physical climate risk facing specific countries and regions in Asia. We find that physical climate risk has seven core characteristics. We originally determined these characteristics from nine case studies in our global report and have confirmed them in our six Asia-specific cases in this report.[86] These characteristics are:

- **Increasing.** In each of our six cases, the level of climate risk increases by 2030 and further by 2050.
- **Spatial.** Climate hazards manifest locally. The direct impacts of physical climate risk therefore should be understood in the context of a geographically defined area. For example, absent further adaptation, our research suggests that the impact of extreme heat could differ, reflecting variations in exposure and severity. In India and China, rising temperatures may affect outdoor work and diminish labor productivity much more than in other regions.
- **Nonstationary.** As the Earth continues to warm, physical climate risk is ever-changing or nonstationary. Between 1990 and 2017, a shock to corn and wheat production across Asia of greater than 15 percent was a one-in-100-year event. By 2050 we expect the probability to rise to one-in-20 for corn and one-in-33 for wheat.
- **Nonlinear.** The socioeconomic impacts of climate risk are nonlinear: once hazards exceed certain thresholds, the affected physiological, human-made, or ecological systems work less well or break down and stop working altogether. This is because the systems have evolved or been designed and optimized for historical climates. Rising heat and humidity levels, for example, could affect the human body's ability to work outdoors as well as the survivability of healthy human beings. In Tokyo, the average flooded depth from a one-in-100-year flood event would be 1.7 times higher by 2050 than today.[87] However, real estate and infrastructure damage would be 30 percent more than the increase in flood depth.
- **Systemic.** While the direct impact of physical climate risk is local, it can have knock-on effects through interconnected socioeconomic systems. Our past research on Ho Chi Minh City found that direct infrastructure damage from a 100-year flood could be between \$500 million and \$1 billion by 2050, but knock-on costs could be between \$1.6 billion and \$8.4 billion.[88]
- **Regressive.** The poorest communities in our case studies typically are the most vulnerable. These communities rely more on outdoor work and natural capital than wealthier communities, which could be affected by a changing climate, and have fewer financial means to adapt quickly.
- **Underprepared.** The pace and scale of adaptation will need to significantly increase. For now, Asian countries have insufficient adaptation measures in place for hazards such as extreme heat and typhoons. Adaptation is likely to entail rising costs and tough choices. Moreover, adaptation costs could rise over time; for example, in cities including Jakarta, Mumbai, and Tokyo, the cost of building new sea walls and other protection from flooding hazards is likely to increase as sea levels rise.

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[86] For more details of our case studies, please see the Country dashboards, page 75.

[87] The compound flood event of all three sources of flooding (fluvial, pluvial, and coastal) is modeled as the flood extent caused by one-in-100-year rainfall, streamflow, and storm surge events occurring simultaneously.

[88] Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Peter Cooper, *Can coastal cities turn the tide on rising flood risk?*, McKinsey & Company, April 2020.

10M–45M

the number of people in China that could be exposed to extreme heat and lethal heat waves by 2030

Rising temperatures could affect working hours in major Asian economies and cause regressive impacts on countries

As discussed in chapter 1, parts of Asia could become hotter and more humid in the years ahead. Here, we take a closer look at changing livability and workability in China and India.

China is highly exposed to hot weather. By 2030, extreme heat and lethal heat waves could affect between ten million and 45 million people.[89] The average person in that group could face a roughly 25 percent chance of experiencing a lethal heat wave at least once in the decade around 2030 (without factoring in air-conditioning), compared with zero chance at present. By 2050, the number of people exposed to extreme heat and lethal heat waves could climb to between 110 million and 250 million. For this group, the probability of being exposed to a lethal heat wave at least once in the decade around 2050 could rise to 35 percent. A hotter China will be a less livable China. One way to adapt is to increase air conditioner penetration, currently at 60 percent.[90] However, more air-conditioning could mean higher emissions; the design of new systems must be carefully undertaken.[91]

Chronic exposure to heat and humidity can reduce labor productivity and effectively thus reduce the number of hours that people are physically able to work outdoors. This could affect more than half of China's working population, 26 percent of which works in the agricultural sector.[92] In addition, some 28 percent of industrial employment in China takes place at least partially outdoors. We estimate that the average share of outdoor working hours effectively lost each year to extreme heat and humidity could increase from 4.5 percent in 2020 to as much as 6.5 percent in 2030 and 8.5 percent in 2050 in exposed areas (Exhibit 10). The consequences in some major cities could be significant. In Dongguan, Guangzhou, Nanjing, Shenzhen, and Wuhan, the average share of effective outdoor working hours lost each year to extreme heat and humidity could increase by more than 5 percentage points.

In India, 160 million to 200 million people (of whom an estimated 80 million to 120 million do not have air-conditioning) are expected to live in urban areas with a nonzero probability of life-threatening heat waves by 2030.[93] This could rise to between 310 million and 480 million by 2050, without factoring in air conditioner penetration, which at current rates of growth could rise to cover the full population by that time.[94] As heat and humidity increase and workers take breaks to avoid heatstroke, labor productivity could fall. We estimate that the effective number of outdoor working hours lost in an average year because of diminished labor productivity could rise by about 15 percent by 2030 (24 percent of outdoor working hours lost compared with 21 percent today in exposed areas) (Exhibit 11).[95]

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[89] Jonathan Woetzel, Kimberly Henderson, Mekala Krishnan, Haimeng Zhang, and Grace Lam, *Leading the battle against climate change: Actions for China*, McKinsey & Company, 2020. Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature exceeds the survivability threshold for a healthy human resting in the shade, 34°C wet-bulb. Wet-bulb temperature is the lowest temperature to which air can be cooled by evaporation of water into the air at a 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-degree wet-bulb heat waves over the 35-degree 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 four to five 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.

[90] *The future of cooling in China*, International Energy Agency, 2019.

[91] For more detail about considerations surrounding air conditioners, see *Will India get too hot to work?*, McKinsey Global Institute, November 2020.

[92] People's Republic of China Ministry of Human Resources and Social Security; "Distribution of the workforce across economic sectors in China from 2009 to 2019," Statista, June 2020.

[93] *Will India get too hot to work?*, McKinsey Global Institute, November 2020.

[94] Estimates are based on the range of population projections from the UN World Population Prospects and the UN World Urbanization Prospects, to bound population growth based on high and low variants, and based on urban and total population growth rates.

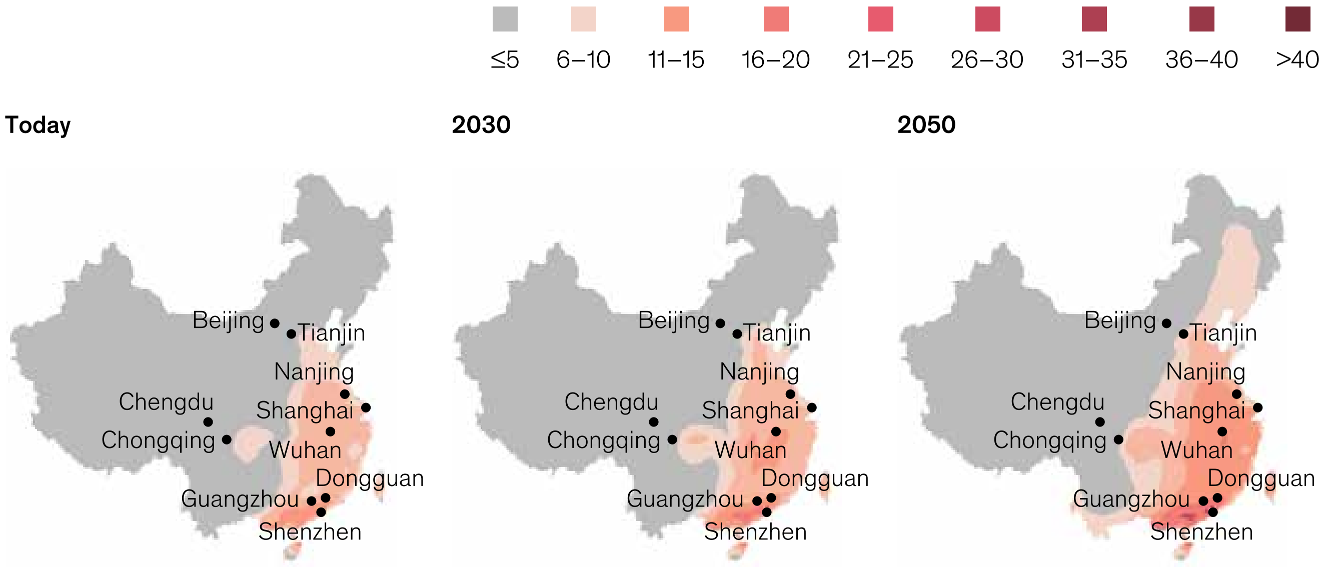
[95] Lost working hours are calculated according to the methodology of Dunne et al., corrected using empirical data from Foster et al. John P. Dunne et al., "Reductions in labour capacity from heat stress under climate warming," *Nature Climate Change*, February 2013, Volume 3; Josh Foster et al., "A new paradigm to quantify the reduction of physical work capacity in the heat," *Medicine & Science in Sports & Exercise*, June 2019, Volume 51, Issue 6S.

Exhibit 10

In China, the average share of annual outdoor working hours effectively lost due to heat and humidity change could increase from 4 percent today to 9 percent in 2050.

Based on RCP 8.5

Share of effectively lost working hours due to extreme heat and humidity, %[1]



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

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

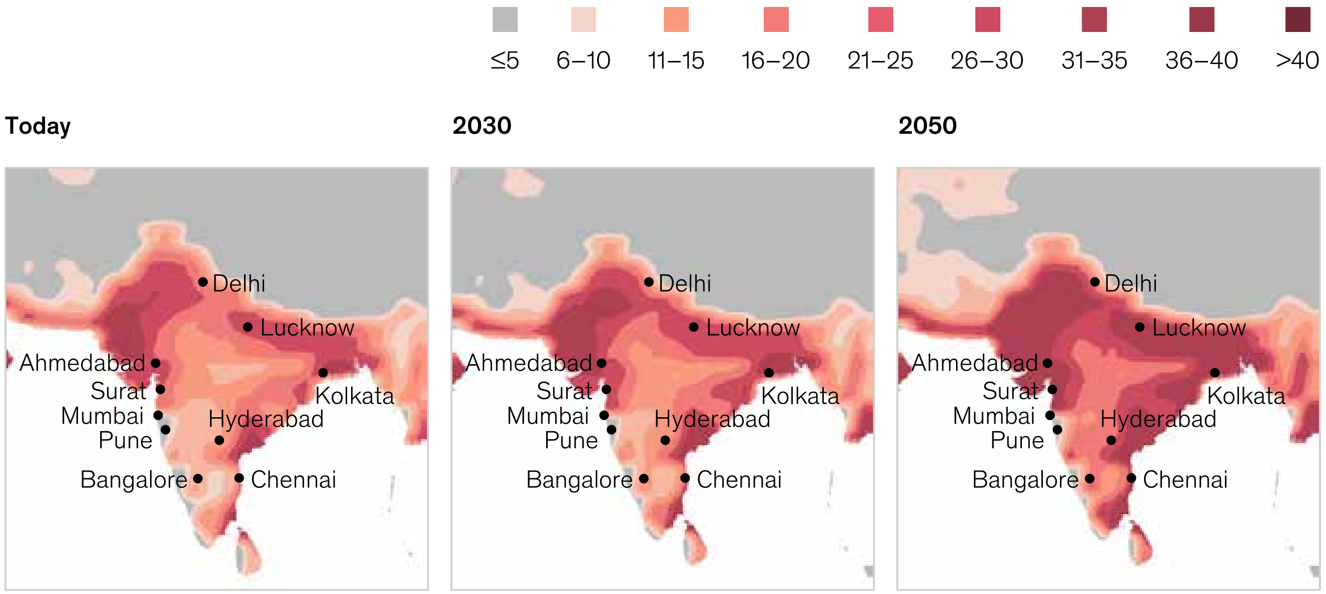
Source: Woodwell Climate Research Center; McKinsey Global Institute CityScope Database; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Exhibit 11

In India, the affected area and intensity of extreme heat and humidity are projected to increase, leading to a higher expected share of effectively lost working hours.

Based on RCP 8.5

Share of effectively lost working hours due to extreme heat and humidity, %[1]



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

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

Source: Woodwell Climate Research Center; McKinsey Global Institute CityScope Database; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

The urban poor without access to cooling systems and those engaged in outdoor activities will be disproportionately affected. By 2050, in four of the five most populated cities—Bangalore, Chennai, Delhi, and Kolkata—the average share of outdoor working hours effectively lost each year to extreme heat and humidity would increase by 5 to 10 percentage points.

Vulnerable populations are more susceptible in both countries for a number of reasons. First, they may be more likely to provide manual labor in outdoor-based industries such as agriculture, mining, and construction (these industries account for a sizable share of each country's economy today: about 16 percent of China's GDP and 26 percent of India's). Second, adaptation is expensive and may be out of reach for the most economically vulnerable. Third, livelihoods could be affected by multiple climate hazards. For example, Indian agriculture may be hit not only by lost hours from extreme heat and humidity but also by potential yield declines.

We find that climate risk is regressive within countries and between countries. In our macro analysis, we find that countries with lower levels of per capita GDP are most at risk from the impacts of climate change (see Box 2, "The least developed countries in Asia may face the greatest climate risk").

Concerted adaptation could reduce the risk from extreme heat and humidity. Given the inherent risk of rising wet-bulb temperatures, China and India could consider adapting through capacity and knowledge building, material investment in adaptive technology and infrastructure, and supporting the economy's transition away from outdoor work. In particular, they may consider a number of measures, from cooling plans to government policies.

The Indian government is already taking steps related to cooling plans. 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.[96] Action is also under way at the local level.

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. Future investment in capacity and knowledge building could focus on incorporating the impact of humidity into heat-wave projections and policy, to aid in identification of high-risk regions and communities.

Transitioning away from outdoor work and the rate at which these countries invest in adaptation could significantly reduce the economic risk of lost hours as well as the toll on life from heat waves. 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 China and India face 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. For the poorest urban segments, air-conditioned emergency shelters and additional similar solutions will likely have to be provided, possibly complemented by targeted affordable air-conditioned housing programs. Additionally, the GHG intensity of current air-conditioning technology will need to be addressed to avoid further exacerbating climate change.

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[96] 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.

Box 2

The least developed countries in Asia may face the greatest climate risk

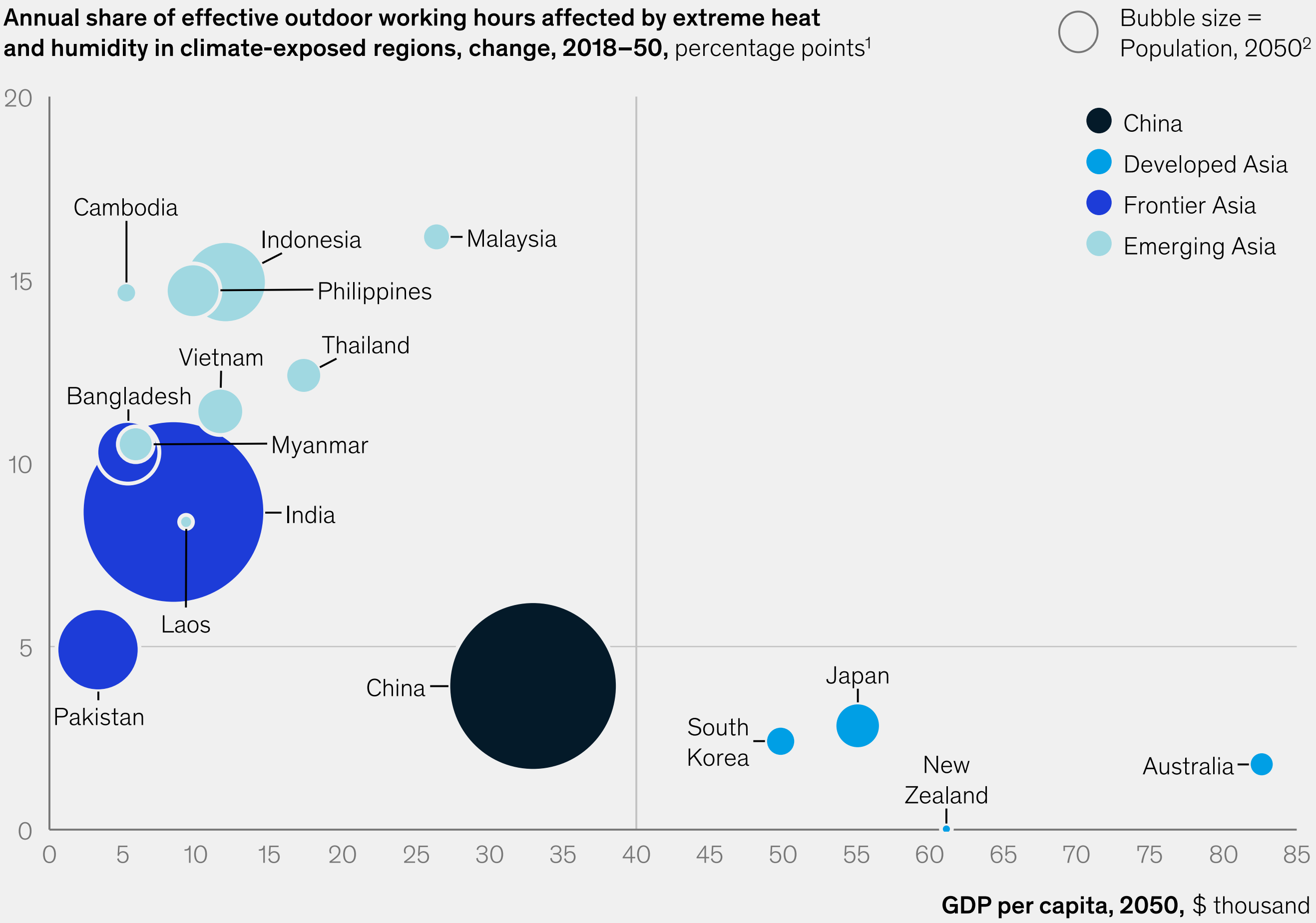
Countries with generally lower levels of per capita GDP, namely those in Frontier Asia and Emerging Asia, are most at risk from the impacts of climate change (Exhibit 12). Relying more on outdoor work and natural capital, they are closer to physical thresholds and have fewer financial means to adapt.

For example, analysis reveals that the least developed parts of Asia face disproportionate workability impacts from extreme heat and humidity. By 2050, under RCP 8.5, there could be an increase in 7 to 12 percentage points of share of working hours in climate-exposed regions effectively lost due to rising heat and humidity on average across Frontier Asia and Emerging Asia, compared to 2 to 5 percentage points for Advanced Asia and China.[1] Frontier Asia and Emerging Asia countries are expected to account for more than 35 percent of the region's GDP growth from 2018 to 2050, and also raise incomes for millions of people. It is therefore critical for these countries to address climate risks effectively.

Exhibit 12

The least developed parts of Asia may face greater impacts from the increasing risk of extreme heat and humidity.

Based on RCP 8.5



1. Defined as risk from outdoor working hours affected by extreme heat and humidity in climate-exposed regions annually, considering an average year. Heat and humidity reduce labor capacity because workers must take breaks to avoid heatstroke and because the body naturally limits its efforts to prevent overexertion.
2. UN World Population Prospects 2019, Medium fertility scenario.

Note: See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: IHS Real GDP data; UN World Population Prospects, 2019; Woodwell Climate Research Center; McKinsey Global Institute analysis

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[1] These numbers represent the regional average across countries. The range comes from considering hotter- and cooler-than-average years.

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 measures, such as mandating the development of heat-action plans or multiple-stakeholder coordination. 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. Commuting times have to be adapted, changes in lifestyle are necessary, and schools and shops have to open at different hours. Stakeholders will need to consider the end to end response needed.

A changing climate could increase the volatility of crop yields, potentially causing price spikes

Asia plays a significant role in global crop production, accounting for about 90 percent of rice, 30 percent of corn, 10 percent of soybeans, and 40 percent of wheat production.[97] Both chronic hazards, such as increasing temperatures, and acute hazards, including storms and floods, could have significant impacts on production. The Asian food system is also vulnerable to climate change because of a high geographic concentration of production. For example, 88 percent of Indian wheat production takes place in five states in the north.[98] In China, the eight largest grain-producing provinces, accounting for 57 percent of production, are in the east.[99]

To quantify the impact of climate change on agricultural yields, we identify six regional breadbaskets in Asia: China, India, Southeast Asia, the Indian subcontinent, Australia and New Zealand, and Japan and South Korea.[100] Working with Woodwell scientists, we estimated the probability of yield change by 2030 and by 2050 due to increased likelihood of chronic climate stress (Exhibit 13).[101]

Our analysis reveals simultaneous impacts in a sufficient number of breadbaskets to potentially undermine production in the region, particularly for certain crops. Corn would see a 5 percent risk of a yield decline of more than 15 percent by 2050, compared to 1 percent today. Rice would see little impact by 2030. However, a change in yields of more than 5 percent would become 1.5 times as likely by 2050. Wheat would also see higher production volatility. The probability of a change in yield (increase or decrease) of more than 15 percent would increase: a 2 percentage point increased likelihood of a yield decline, and a 5 percentage point increased likelihood of a yield failure by 2050 relative to today. Other crops will likely see rising yields. Soy could benefit from higher temperatures—the ideal daytime temperature for soybeans is about 30 degrees Celsius, which is higher than the ideal temperature for corn.[102] The cultivation period for rice could be extended as a result of increasing irrigation water temperatures induced by climate change. This could lead to higher production.

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[97] USDA, 2019–20 annual production based on crop year.

[98] *Statistical Year Book India 2017*, Government of India, Ministry of Statistics and Programme Implementation, 2017.

[99] *China Statistical Yearbook 2018*, National Bureau of Statistics of China, 2017; "Grain production in China in 2018, by region," Statista, October 2019.

[100] This analysis builds on *Will the world's breadbaskets become less reliable?*, McKinsey Global Institute, May 2020.

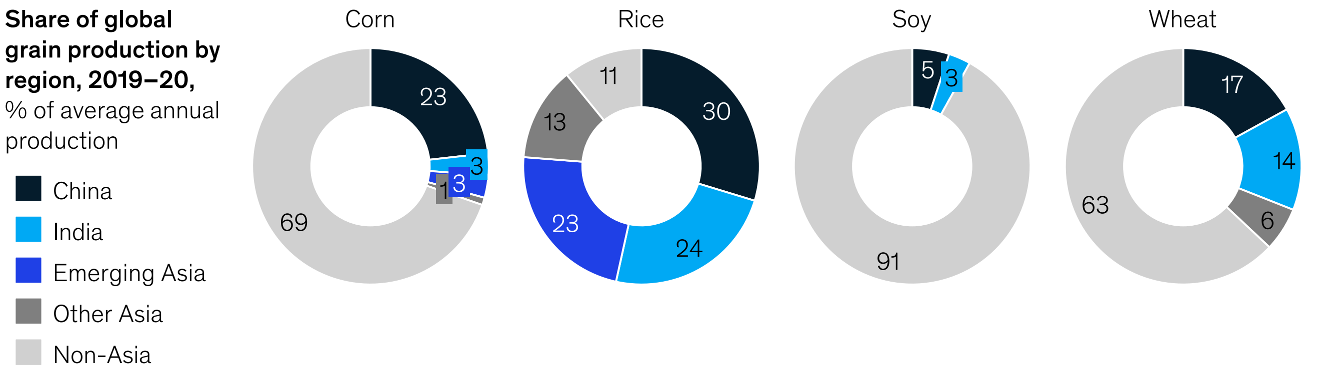
[101] To estimate the likelihood of harvest failure, we employ crop models from the AgMIP model library that translate outputs from climate models into crop yields for each modeled grid cell. Using all available climate models for the period from 1998 to 2060, we construct a probability distribution of yields for each crop in each grid cell. For the purpose of this analysis, we focus on grid cells in the six highest-producing breadbasket regions in Asia for each crop. By the nature of the choice of agricultural models, these results do not account for specific extreme events such as flash flooding or individual heat waves. All crop modeling has been done under the assumption that historic increases in CO_2 fertilization continue to increase with atmospheric CO_2 content. Uncertainty related to this assumption would lead to overestimating yields and underestimating the likelihood of breadbasket failures. We take into account potentially positive effects on plant growth from higher CO_2 levels (CO_2 fertilization). However, those benefits could be mitigated as increased CO_2 levels cut the protein and micronutrient content of crops, which would require humans to eat more volume to achieve the same level of nutrition (an effect we do not take into account). A related factor is that increased precipitation and water availability will generally act to improve yields, but only up to a limit. Yield changes are measured relative to the mean yield for the 1998–2017 period.

[102] "High temperature effects on corn, soybeans," *Farm Progress*, 2012.

Exhibit 13

The impact of climate change on crop yields will vary across crops.

Based on RCP 8.5



Share of global grain production by region, 2019–20, % of average annual production

Asia grain yields, once-a-year probability in a given year, %

🟥 Declining ⬛ Increasing

Asia grain yield decline

		Corn	Rice	Soy	Wheat
>5% decline	Today	26	11	21	27
	2030	26	⬛ 9	⬛ 8	🟥 36
	2050	🟥 35	🟥 17	⬛ 5	🟥 28
>10% decline	Today	6	2	6	12
	2030	🟥 8	⬛ 0	⬛ 1	12
	2050	🟥 15	2	⬛ 0	⬛ 10
>15% decline	Today	1	0	1	1
	2030	⬛ 0	0	⬛ 0	🟥 2
	2050	🟥 5	0	⬛ 0	🟥 3

Asia grain yield improvement

		Corn	Rice	Soy	Wheat
>5% improvement	Today	32	14	18	17
	2030	🟥 17	🟥 10	⬛ 35	17
	2050	🟥 26	⬛ 22	⬛ 50	⬛ 36
>10% improvement	Today	5	1	1	2
	2030	🟥 1	1	⬛ 7	⬛ 5
	2050	⬛ 9	⬛ 3	⬛ 25	⬛ 13
>15% improvement	Today	0	0	0	0
	2030	0	0	⬛ 1	⬛ 1
	2050	⬛ 1	0	⬛ 10	⬛ 5

1. Emerging Asia includes Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, and Vietnam.

Note: Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using the median of nitrogen-limited crop models from the AgMIP ensemble. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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. In some regions we see trends of improving then declining yields or vice versa by 2030 and 2050. This is driven by region specific combinations of climate conditions. For example, in China, a shift of expected corn yields to worse outcomes by 2030 is explained by larger potential increases in temperature relative to precipitation and by 2050 the effect is reversed—larger increases in precipitation relative to additional warming lead to improved corn yields. Figures may not sum to 100% because of rounding. Yield changes are measured relative to the mean yield for the 1998–2017 period.

Source: Woodwell Climate Research Center; United States Department of Agriculture; McKinsey Global Institute analysis

We find that certain countries are more exposed than others because of their climatic conditions and composition of crops (Exhibit 14). In China, we expect growing volatility of crop production due to changes in patterns of precipitation and temperature. We find that rice, corn, and wheat could experience a shift in yield distribution toward worse outcomes and an increase in volatility skewed toward worse outcomes by 2030 due to more severe climate hazards. But that shift could reverse by 2050, with yield distribution shifting toward better outcomes and increased volatility skewed toward better outcomes.[103] Soy could see lower risk through 2030 and through 2050. A yield shock from increased production volatility in China could have significant knock-on effects, given that the country produces nearly a third of the world's rice, 23 percent of corn, 5 percent of soybeans, and 17 percent of wheat.[104]

In Frontier Asia, Indian crops would be most affected in the time period to 2030 and 2050. All four crops would face increasing probability of a yield decline of more than 10 percent, and no crop would see an increased probability of an improvement of more than 10 percent. Agriculture accounts for 15 percent of India's GDP, suggesting that the economic impact could be significant. India is the second-largest crop producer in Asia (accounting for a 27 percent share of rice and 37 percent of wheat, based on 2019–20 annual production). Moreover, a concurrent climate shock in India and elsewhere could trigger higher food prices or even disruptions to food supply. Similarly, the Indian subcontinent (Bangladesh and Pakistan) would see a rising probability of a yield decline of more than 10 percent across crops; the probability of a rice and wheat yield decline of more than 10 percent would increase by more than 10 percent by 2050. Moreover, the two countries may also experience a decreasing probability of a yield improvement of greater than 10 percent by 2050 for rice and corn.

In Emerging Asia, we find an increased probability of a yield change (increase or decrease) of more than 10 percent in the production of rice, corn, and soy by 2050. Since Emerging Asia produces about 26 percent of Asia's rice and 10 percent of its corn, this could have a significant impact on price volatility.

In Advanced Asia (Australia, Japan, New Zealand, and South Korea), climate change could boost the yields of some crops to 2030 and to 2050. In Japan, the rice cultivation period would be extended as a result of increasing irrigation water temperatures. This would allow greater planting flexibility and lead to a reduction in the frequency of cool-summer damage in northern districts.

Importantly, the discussion above reveals that climate risks will not necessarily reduce agricultural yields for some breadbaskets or crops; however, they will likely increase production volatility, destabilizing farmers' incomes.[105] Both oversupply and undersupply could have negative effects. Oversupply could affect farmers who may face lower prices for their crops, while undersupply could lead to food shortages and price spikes. Even limited reductions in stock-to-use ratios have in the past triggered food price spikes. In 2008, cereal prices rose by 100 percent, although global production of grains barely changed.[106]

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[103] Multidirectional impacts of climate change to 2030 and to 2050 are observed in China. This is mainly driven by the multidirectional nature of specific climate factors that could affect crop yields both positively and negatively. For example, intensifying climate hazards in China reduce yields of rice and wheat through 2030, whereas accumulated CO_2 in the atmosphere serves as fertilizer to improve yields to 2050. In corn cultivation, China may experience increases in precipitation which improves the yields in the 2030–50 period compared to the period from today to 2030.

[104] USDA, based on 2019–20 annual production of crops by country.

[105] We also found this to be the case in Africa. For more detail, see *How will African farmers adapt to changing patterns of precipitation*?, McKinsey Global Institute, May 2020.

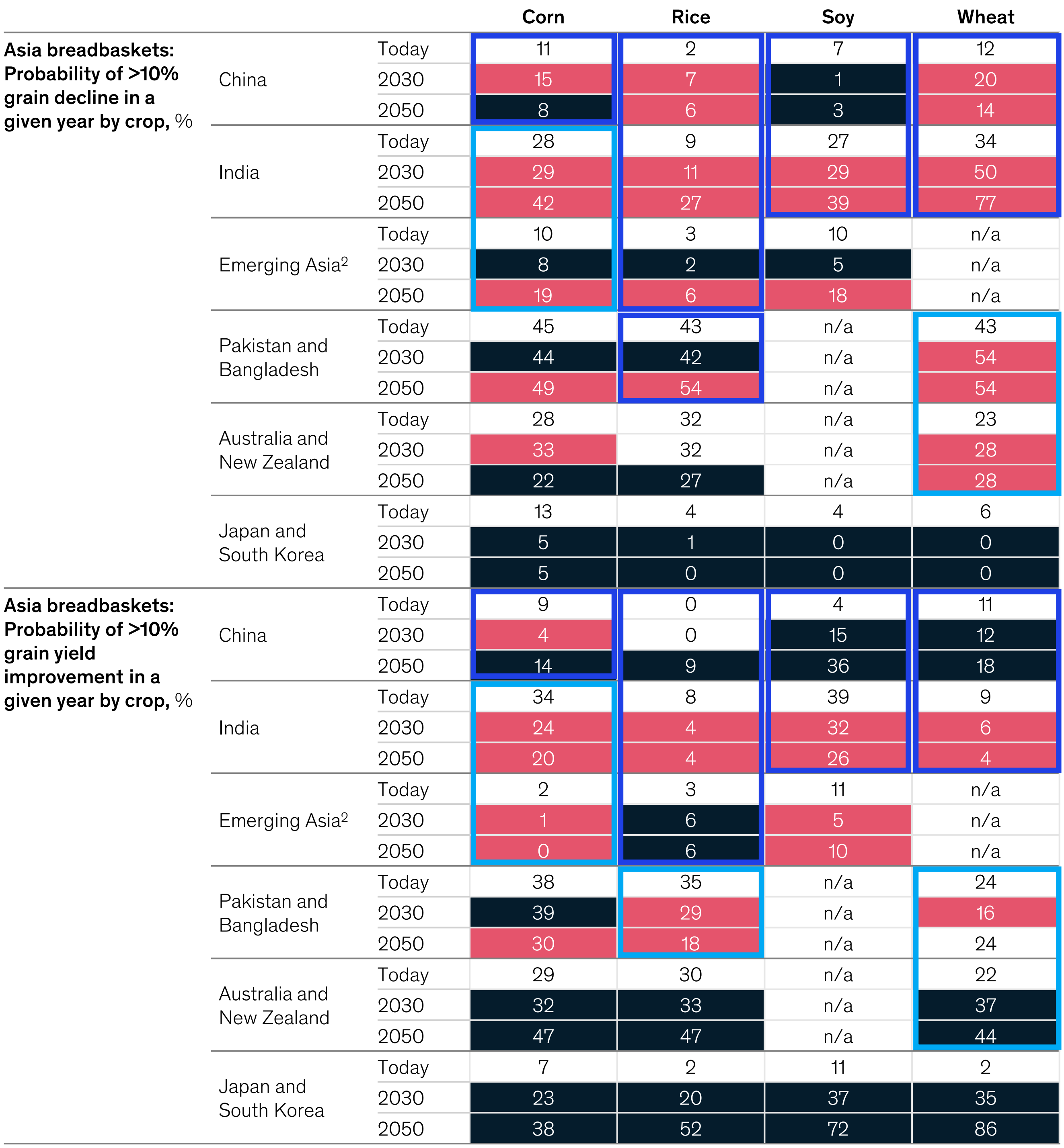
[106] FAOSTAT, FAO.

Exhibit 14

Climate change is expected to have different impacts across crops and breadbaskets.

Based on RCP 8.5

Yields vs today 🟥 Declining ⬛ Increasing **Region's share of total Asia production**[1] ☐ >5% ☐ >15%



			Corn	Rice	Soy	Wheat
Asia breadbaskets: Probability of >10% grain decline in a given year by crop, %	China	Today	11	2	7	12
		2030	15	7	1	20
		2050	8	6	3	14
	India	Today	28	9	27	34
		2030	29	11	29	50
		2050	42	27	39	77
	Emerging Asia[2]	Today	10	3	10	n/a
		2030	8	2	5	n/a
		2050	19	6	18	n/a
	Pakistan and Bangladesh	Today	45	43	n/a	43
		2030	44	42	n/a	54
		2050	49	54	n/a	54
	Australia and New Zealand	Today	28	32	n/a	23
		2030	33	32	n/a	28
		2050	22	27	n/a	28
	Japan and South Korea	Today	13	4	4	6
		2030	5	1	0	0
		2050	5	0	0	0
Asia breadbaskets: Probability of >10% grain yield improvement in a given year by crop, %	China	Today	9	0	4	11
		2030	4	0	15	12
		2050	14	9	36	18
	India	Today	34	8	39	9
		2030	24	4	32	6
		2050	20	4	26	4
	Emerging Asia[2]	Today	2	3	11	n/a
		2030	1	6	5	n/a
		2050	0	6	10	n/a
	Pakistan and Bangladesh	Today	38	35	n/a	24
		2030	39	29	n/a	16
		2050	30	18	n/a	24
	Australia and New Zealand	Today	29	30	n/a	22
		2030	32	33	n/a	37
		2050	47	47	n/a	44
	Japan and South Korea	Today	7	2	11	2
		2030	23	20	37	35
		2050	38	52	72	86

1. Annual production in 2019–20.
2. Emerging Asia consists of Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, and Vietnam.

Note: Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using the median of nitrogen-limited crop models from the AgMIP ensemble. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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. In some regions we see trends of improving then declining yields or vice versa by 2030 and 2050. This is driven by region specific combinations of climate conditions. For example, in China, a shift of expected corn yields to worse outcomes by 2030 is explained by larger potential increases in temperature relative to precipitation and by 2050 the effect is reversed—larger increases in precipitation relative to additional warming lead to improved corn yields. Figures may not sum to 100% because of rounding. Yield changes are measured relative to the mean yield for the 1998–2017 period.

Source: Woodwell Climate Research Center; United States Department of Agriculture; McKinsey Global Institute analysis

To make food systems more resilient, private and public research could be expanded, for example to make crops more resistant to abiotic and biotic stresses. This may include conventional breeding, gene editing, and other biological or physical approaches. Potential adaptation measures for rice include increasing investment in irrigation infrastructure, leveraging water-efficiency technologies, or shifting sowing dates. For improved and stable yields of soybeans, stakeholders could develop new varieties to cope with drought and excess water. Key measures in corn production may include heat-tolerant cultivars, erosion protection, and planting of trees to protect crops from sun. To offset the risk of a harvest failure of greater than 15 percent, the current global stock-to-use ratio could be increased to 35 to 40 percent, making use of periods of surplus and low prices.

Assets and infrastructure could increasingly come under threat from hazards like floods and wildfires

We find a growing risk from climate change across all 17 types of infrastructure we examined in the areas of transportation, telecommunications, energy, and water (Exhibit 15).

Each infrastructure asset type has unique vulnerabilities to climate hazards. In transportation, for example, only a few millimeters of airport runway flooding can cause disruption. Rail and roads are affected by flooding because of the vulnerability of signaling systems to water exposure and the impacts of even small amounts of water; traffic can slow by 30 percent with just a few centimeters of water on the road.

Telecommunications infrastructure is less climate exposed, although cell phone towers and cables are vulnerable to high winds. In the Indian state of Odisha in 2019, cyclonic storm Fani caused $7 million to $11 million of damage to such assets, according to Indian government estimates.[107] Freshwater infrastructure assets such as reservoirs, wells, and aquifers are vulnerable to sustained drought conditions. Fluvial, pluvial, and coastal flooding can also overwhelm and damage wastewater treatment infrastructure and water treatment systems. Twelve out of 14 wastewater treatment plants in Ho Chi Minh City are expected to be within inundation zones in both regular and extreme flood events by 2050.[108] The power grid is also vulnerable. Extreme heat can lead to the combined effects of efficiency losses and increase in peak load from greater use of air-conditioning. In this section, we look more closely at flood risk in Tokyo and wildfire risk in Australia.

While the average flood depth in Tokyo could increase 1.7 times by 2050, the real estate and infrastructure damage from the same event would be 2.2 to 2.4 times higher

In urban areas, extreme floods could cause significant damage to infrastructure and real estate. Tokyo is vulnerable to all three sources of flooding: fluvial, pluvial, and coastal. To simulate a worst-case scenario and avoid underestimating flood risk, we analyzed a compound flood event based on simultaneous one-in-100-year rainfall, streamflow, and storm surge events.[109] Each of these 100-year events respectively is equivalent to a 28-year rainfall, 32-year storm surge, and 71-year streamflow event in 2050.[110] We forecast significant increases in both flooded areas and depth by 2050 (Exhibit 16). The flooded area in the modeled geography would increase from 64 percent today to 81 percent by 2050. Average flood depth would increase by 1.7 times, from 0.28m today to 0.48m by 2050. We estimate that direct real estate damage from the modeled flood event could be $5.9 billion today. This could rise to $13.1 billion in 2050, assuming no new adaptation. Infrastructure

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[107] Nirmalya Behera, "Cyclone Fani demolishes mobile infra, losses could touch Rs 800 cr," *Business Standard*, May 11, 2019.

[108] *Ho Chi Minh City adaptation to climate change*, ADB, 2013.

[109] To simulate the worst-case scenario, all three flood sources were used as inputs to model the 24-hour compound flood event. In this context, the compound flood event is defined as the flood extent caused by the 1-in-100-year rainfall, streamflow, and storm surge events occurring simultaneously. The 1-in-100-year rainfall, streamflow, and storm surge values were calculated independently from each other using various data sources. However, this does not mean that the rainfall, streamflow, and storm surge events are probabilistically independent of each other. The probability of an extreme storm surge event can be higher when conditioned on the occurrence of extreme precipitation compared to the probability of extreme storm surge estimated when assuming the two events are independent, for example. Therefore, in order to avoid underestimating flood risk, all three flood sources were modeled together to provide a realistic estimate of the 1-in-100-year flood event. See technical appendix for further details.

[110] We do not expect significant intensification of streamflow by 2050 due to a potential decrease in snowpack.

damage is also expected to increase, from $400 million today to $1.1 billion in 2050. This suggests damage increases of about 2.2 to 2.4 times.

The measures for reducing inundation risks are classified broadly into those that improve river channels—such as expansion of the channels, excavation of riverbeds, and building of embankments—and measures for controlling flooding, such as dams and flood control facilities. For all measures, the impacts on communities and the natural environment should be considered.

In response to the increasing threat of flooding, the city of Tokyo has developed a number of adaptation measures, including a super levee, or a robust, broad river embankment with special seismic reinforcement that is resistant to overflow, seepage, and even earthquakes. It differs from a conventional dike in its width (a super levee is ten meters high and about 300 meters wide). Super levees are well suited to dense urban areas, allowing development on top while integrating multifunctional structures. Compared to traditional levees, super levees allow easy access to rivers and reconnection with urban water ecosystems. The super levee built along Tokyo's Ara River combines a broad dike with a park and a small high-rise, whereas the Sumida River super levee combines a broad dike and floodwall with a promenade and a large high-rise.[111] Given the intensifying floods in Tokyo that climate models project, it is extremely important to assess the potential impacts and build the defenses accordingly. Also, infrastructure should be located in areas where assets that are vulnerable to inundation face relatively low risks.

$13.1B

the amount of direct real estate damage from a 100-year flood in Tokyo by 2050

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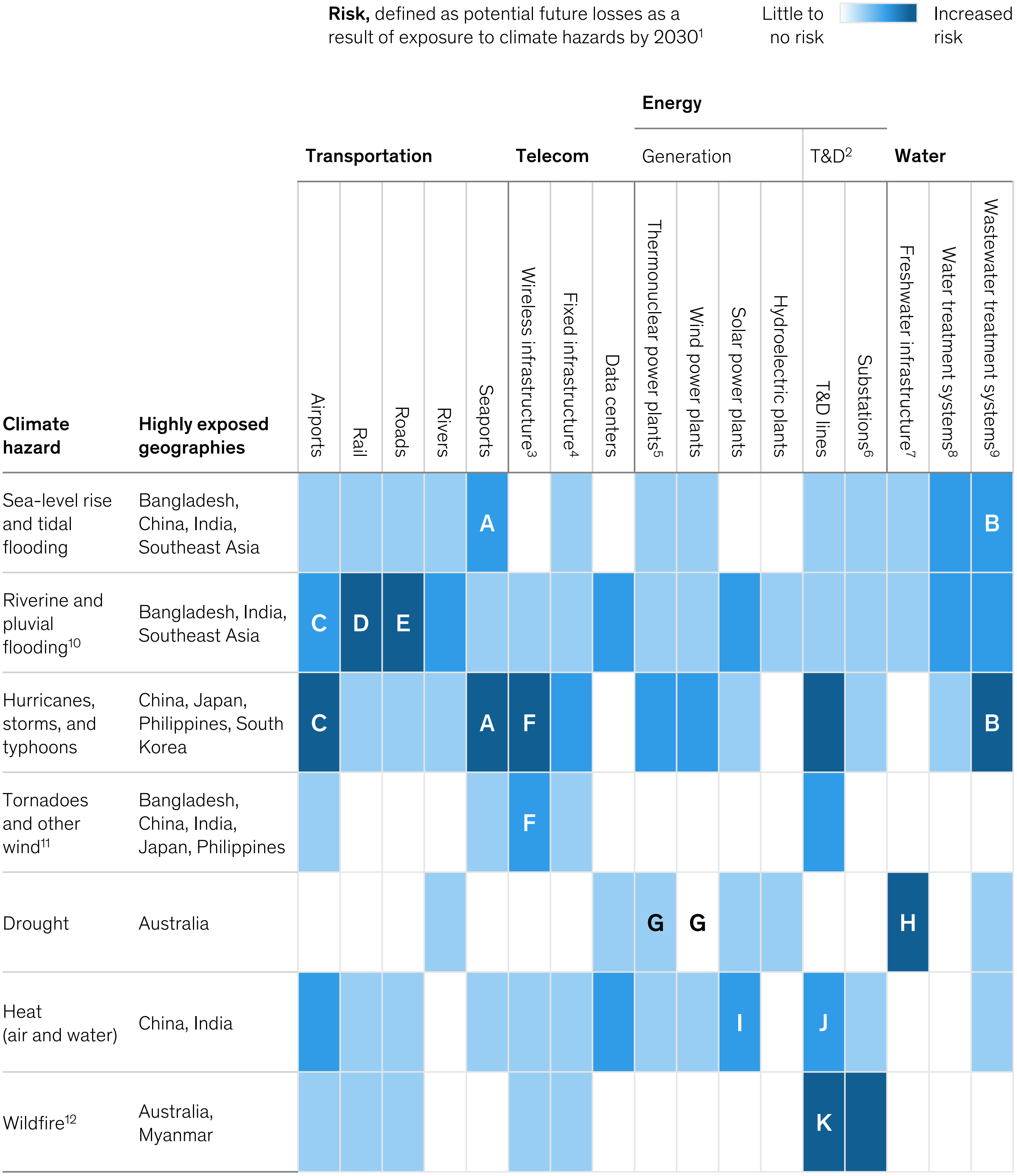
[111] "Case study: Tokyo—Super levees," in *Good practice guide: Climate change adaptation in delta cities*, C40 Cities, 2016.

Exhibit 15

Infrastructure assets across Asia are vulnerable to climate hazards such as flooding, hurricanes, and wildfires.

Based on RCP 8.5



Risk, defined as potential future losses as a result of exposure to climate hazards by 2030[1]

										Energy								
		Transportation					Telecom			Generation				T&D[2]		Water		
Climate hazard	**Highly exposed geographies**	Airports	Rail	Roads	Rivers	Seaports	Wireless infrastructure[3]	Fixed infrastructure[4]	Data centers	Thermonuclear power plants[5]	Wind power plants	Solar power plants	Hydroelectric plants	T&D lines	Substations[6]	Freshwater infrastructure[7]	Water treatment systems[8]	Wastewater treatment systems[9]
Sea-level rise and tidal flooding	Bangladesh, China, India, Southeast Asia	░	░	░	░	▒ A		░		░	░			░	░	░	▒	▒ B
Riverine and pluvial flooding[10]	Bangladesh, India, Southeast Asia	▒ C	▓ D	▓ E	▒	░	░	░	▒	░	░	▒	░	░	░	░	▒	▒
Hurricanes, storms, and typhoons	China, Japan, Philippines, South Korea	▓ C	░	░	░	▓ A	▓ F	▒		▒	▒	░		▓	░		░	▓ B
Tornadoes and other wind[11]	Bangladesh, China, India, Japan, Philippines	░				░	▒ F	░						▒				
Drought	Australia				░				░	░ G	G	░	░			▓ H		░
Heat (air and water)	China, India	▒	░	░		░	░	░	▒	░	░	▒ I		▒ J	░			░
Wildfire[12]	Australia, Myanmar	░	░	░			░	░						▓ K	▓			

Exhibit 15 (continued)

Infrastructure assets across Asia are vulnerable to climate hazards such as flooding, hurricanes, and wildfires (continued).

Based on RCP 8.5

A. Seaports, by definition, are exposed to risk of all types of coastal flooding. Typically, seaports are resistant and can more easily adjust to small sea level rise. However, powerful hurricanes are still a substantial risk. Sea levels in some major ports in India (eg, Diamond Harbor in West Bengal) are rising rapidly, endangering the ports, increasing the chances of coastal flooding in low-lying areas, and affecting livelihoods of millions of people who live near the seashore and river deltas. Shanghai is the busiest port in the world, handling 647 million tons of cargo volume every year. To future-proof it against rising storm surges and other climate effects would cost $400 million–$650 million.

B. Wastewater treatment plants often adjoin bodies of water and are highly exposed to sea level rise and hurricane storm surge. Wastewater plants in Ho Chi Minh City will be exposed to inundation from projected regular and extreme flooding. Twelve out of 14 wastewater treatment plants in Ho Chi Minh City are expected to be within inundation zones in both regular and extreme flood events by 2050.

C. Many airports are near water, increasing their risk of precipitation flooding and hurricane storm surge. In 2014, Japan's Kansai International Airport, built on a reclaimed island near Osaka, was hit by Typhoon Jebi. The runway was flooded, and fully restoring airport operations took 17 days, at a high cost to the region's economy and to dozens of airlines that had to cancel flights.

D. Rail is at risk of service interruption from flooding. Disruption to signal assets in particular can significantly affect rail reliability. In 2019, Typhoon Hagibis caused serious destruction in Japan and led to disruption of train service, damaging 10 bullet trains (120 carriages). Trains partially submerged by floodwater had to be scrapped.

E. Roads are vulnerable to major damage from significant flood depths and flows. In August 2017, heavy monsoon rains caused intense flooding across more than one-third of Bangladesh, damaging 1,214 km of roads, 100 bridges and culverts, and 15 km of rail tracks between Dinajpur and Dhaka.

F. Cell phone towers are at risk from high wind speeds. Cyclonic storm Fani damaged the telecom infrastructure in the Indian state of Odisha in 2019, causing a loss of $7.1 million–$11.4 million.

G. Wind power plants are highly resistant to drought; thermoelectric power plants, which regularly use water for cooling (seen in >99% of CJS plants), are at risk during significant shortages. Water shortage problems led to 61 coal plant shutdowns in India in 2013–17.

H. Freshwater infrastructure and associated supplies are highly vulnerable to impact of drought. In Chennai, 3 of the city's 4 main reservoirs dried up in 2019 due to drought caused by 2 years of deficient monsoon rainfall, leaving millions of people without consistent access to water.

I. Solar panels can lose efficiency through heat, estimated at 0.1–0.5% lost per 1°C increase.

J. T&D suffers 2 compounding risks from heat. Rising temperatures drive air-conditioning use, increasing load. Concurrently, heat reduces grid efficiency. Recent temperatures that soared to 47°C in 2014 in Uttar Pradesh in India caused power demand to spike at 11,000 MW—far higher than the state's 8,000 MW capacity—triggering blackouts that shut down fans, city water pumps, and air conditioners.

K. T&D networks are highly vulnerable to wildfires. In 2019, wildfires in Australia damaged thousands of kilometers of network, and more than 5,000 power poles were destroyed or required replacement.

1. Losses defined as asset interruption, damage, or destruction.
2. Transmission and distribution.
3. Base substations and radio towers.
4. Including above- and below-ground cable.
5. Including nuclear, gas, and oil.
6. Including large power transformers.
7. Reservoirs, wells, and aquifers.
8. Plants, desalination, and distribution.
9. Plants and distribution.
10. Pluvial flooding is flooding caused by extreme precipitation, independent of actions of rivers and seas.
11. Including both rain and wind impacts.
12. Wildfire is derivative risk primarily driven by drought.

Source: Asian Development Bank; Asia Research & Engagement; *Business Standard*; *Climate risk and response*, McKinsey Global Institute, January 2020; Energy Networks Australia; India Climate Dialogue; India government; Institute for Energy Economics & Financial Analysis; *Railway Technology*; *Economic Times*; The Weather Channel; UNICEF; McKinsey Global Institute analysis

Exhibit 16

Flooding in Tokyo is expected to become more frequent and intense by 2050 due to climate change in the absence of adaptation and mitigation.

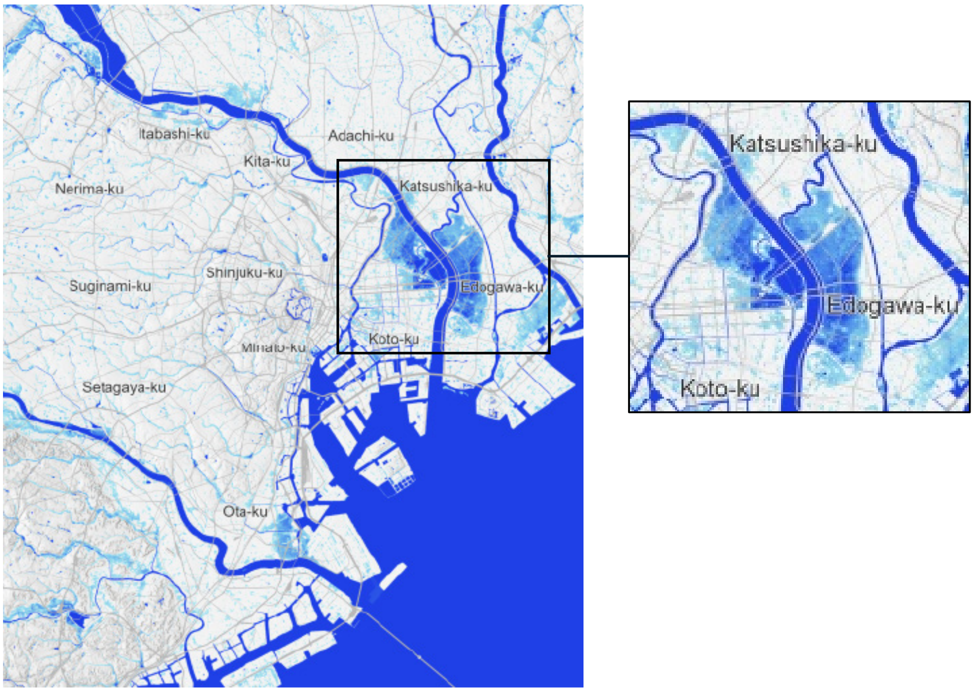
Based on RCP 8.5

Combined flood effects from 100-year rainfall, storm surge, and streamflow in Tokyo

Water level
15 cm ▨ 2+ meters

Today, 100-year event

100-year event in each category today is equivalent to
28-year rainfall, 32-year storm surge, and 71-year streamflow event in 2050



2050, 100-year event

100-year event in each category in 2050 is equivalent to
484-year rainfall, 307-year storm surge, and 152-year streamflow event today

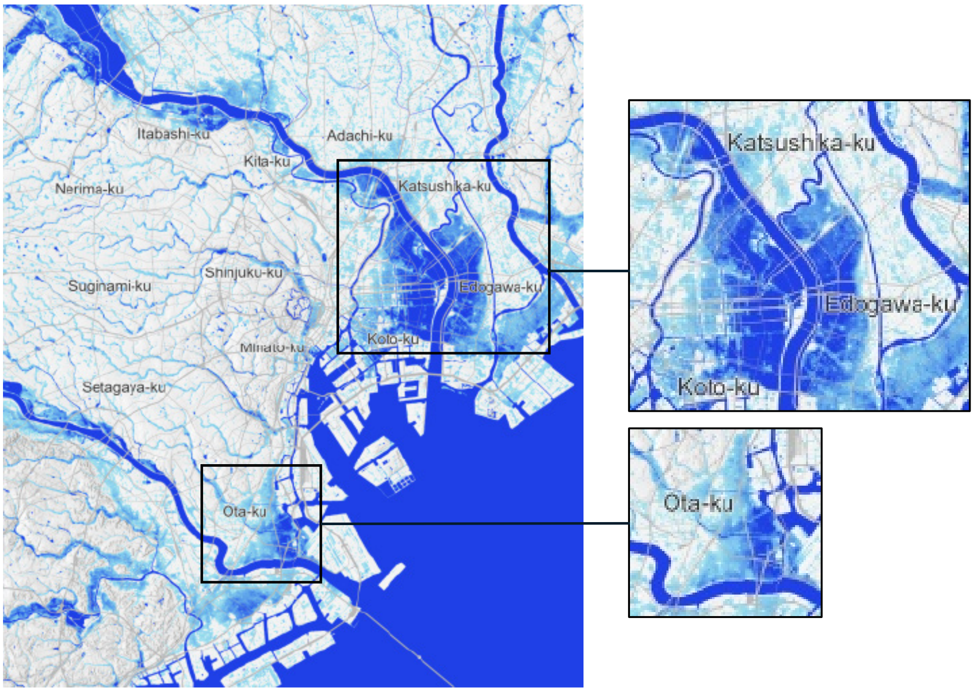
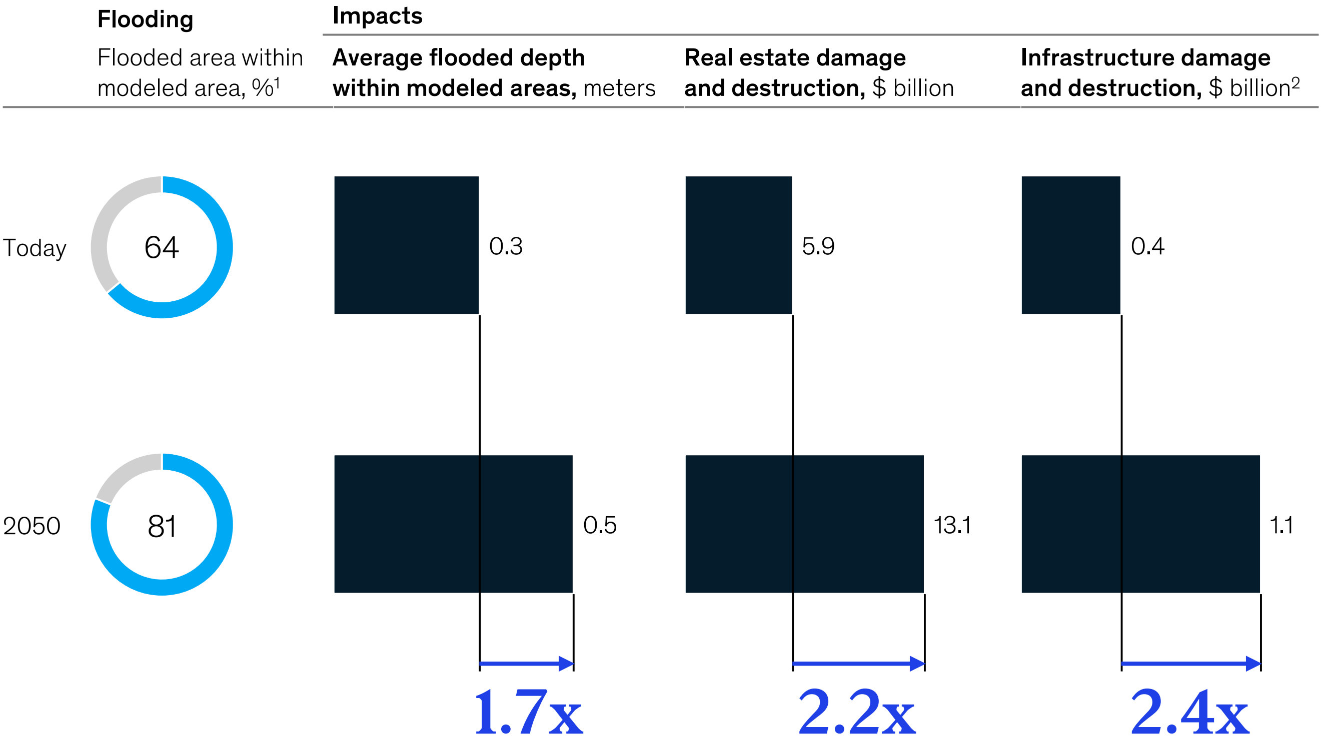


Exhibit 16 (continued)

Flooding in Tokyo is expected to become more frequent and intense by 2050 due to climate change in the absence of adaptation and mitigation (continued).

Based on RCP 8.5

Combined flood effects from 100-year rainfall, storm surge, and streamflow in Tokyo



One-third of Australia may see the number of high fire risk days per year increase by more than 20 days

Wildfires could cause substantial damage to infrastructure assets. In Australia, their severity is already significant. In the 2019–20 season, wildfires burned more than 46 million acres (72,000 square miles). Thirty-four people died and at least 3,500 homes and thousands of other buildings were destroyed.[112] Climate science tells us that climate change made southeastern Australia's devastating wildfires in 2019–20 at least 30 percent more likely.[113] Our case study reveals how high wildfire risk days (high fire weather index days) would increase to 2030 and to 2050 (Exhibit 17).[114]

Fire occurrence is a function of prevalence of fire risk conditions, but also ignition events and the prevalence of combustible materials. Woodwell scientists model precipitation, air temperature, wind speed, relative humidity, snow cover, latitude, and time of year, all of which are influenced by climate change. This shows the risk of fire occurring based on climatic conditions, though it is important to note that this may be different from the actual occurrence of fires, since they do not account for the occurrence of ignition events or the prevalence of combustible materials. This explains why we may see a discrepancy between maps of historical fire events and maps with high fire risk days.

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[112] *2019–2020 Australian Bushfires*, Center for Disaster Philanthropy, 2020.

[113] Geert Jan van Oldenborgh et al., "Attribution of the Australian bushfire risk to anthropogenic climate change," *Natural Hazards and Earth System Sciences* preprint, March 2020.

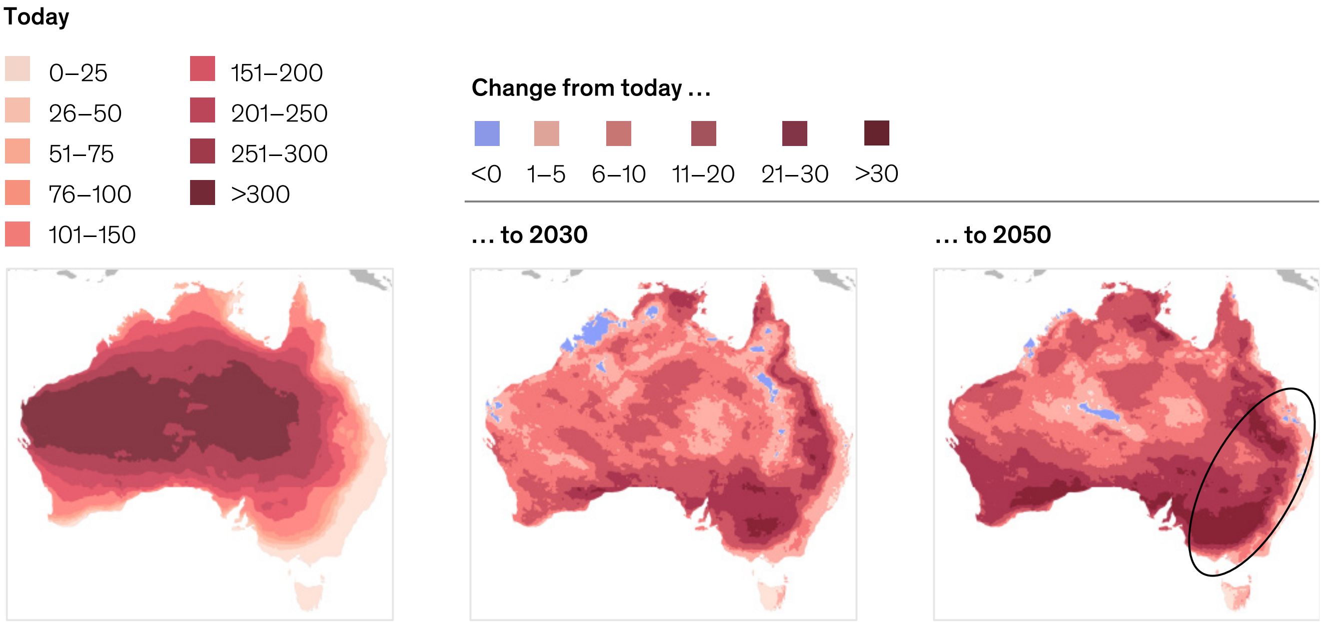
[114] Defined as a day when the fire weather index is high enough to account for the majority (79 percent) of observed historical fires. A fire weather index is a general index of fire danger used globally and is a function of precipitation, air temperature, wind speed, relative humidity, snow cover, latitude and time of year. See the technical appendix for detailed methodologies.

Exhibit 17

Wildfires are expected to become more frequent in Australia by 2030 and 2050 without adaptation or mitigation.

Based on RCP 8.5

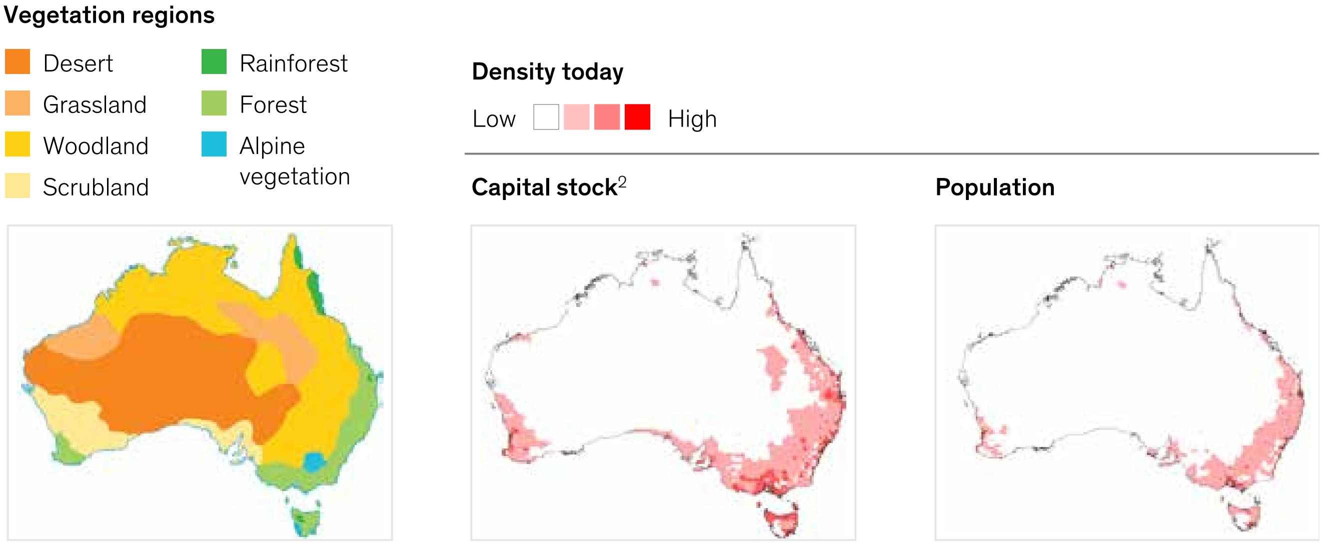
Number of high fire risk days per year[1]



Most populated and capital-dense areas of Australia

30% of country area will see an increase of 20+ days in number of high fire risk days per year

Australia today



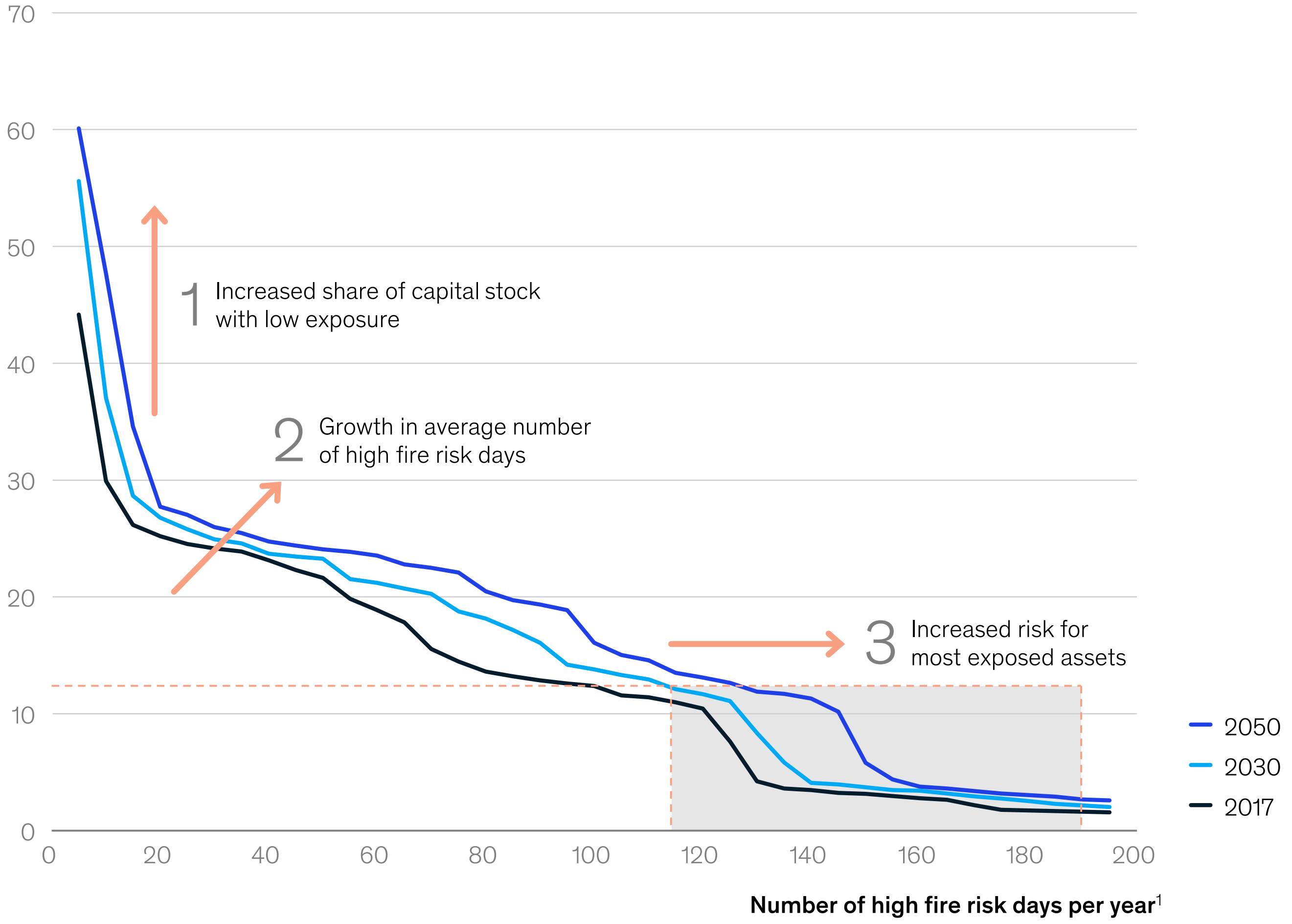
Some of the most populated and capital-dense areas (eg, New South Wales) will see the steepest increase in number of high fire risk days

Exhibit 17 (continued)

Wildfires are expected to become more frequent in Australia by 2030 and 2050 without adaptation or mitigation (continued).

Based on RCP 8.5

Share of capital stock at risk of wildfires (cumulative), %[3]



Number of high fire risk days per year[1]

	1 Share of capital stock exposed to at least 5 high fire risk days, %	2 Weighted based on all capital stock	3 Weighted based on 10% most exposed capital stock
Today	44	28	154
2030	56	32	164
2050	60	37	178

Columns 2 and 3: **Average number of high fire risk days per year,** weighted average based on capital stock value

1. Defined as day when fire weather index is high enough to account for majority (79%) of observed historical fires. Fire weather index is general metric of fire danger used globally and is a function of precipitation, air temperature, wind speed, relative humidity, snow cover, latitude, and time of year.
2. Capital stock value is defined as sum of replacement value of industrial, residential, and commercial buildings. Capital stock density is defined as total capital stock value by statistical area 2 (SA2) divided by SA2 area.
3. Based on capital stock value.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company. See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: Australian Geography Teachers Association; Geoscience Australia; UN Office for the Coordination of Humanitarian Affairs; Woodwell Climate Research Center; McKinsey Global Institute analysis

46%

the increase in the Australian population living in an area with more than 10 high fire risk days a year by 2050

Modeling suggests that 30 percent of Australia will see the number of high fire risk days per year increase by more than 20 days.[115] While today most risk is in central and less populated areas, in the future it will affect wider areas with higher concentrations of population and vegetation. This implies that the risk of an actual fire event will be much higher to 2030 and to 2050 because of the increased probability of ignition events, due to proximity to humans as well as combustible materials. The share of the population that lives in an area with more than ten high fire risk days per year would increase to 46 percent by 2050, from 26 percent today.[116]

Furthermore, Exhibit 17 shows Australia's growing exposure of capital stock to wildfires absent adaptation. The share of capital stock exposed to five high fire risk days per year could increase from 44 percent today to 56 percent by 2030.[117] The average number of fire risk days per year (weighted average based on capital stock value) could increase from 28 days today to 37 days by 2050. Finally, 10 percent of the most exposed capital stock would see high fire risk days increase from 154 days today to 178 days by 2050. These shifts would cause sizable socioeconomic impacts, especially in some areas with high concentrations of population and capital stock (for example, New South Wales). In the wildfires of 2019–20, the majority of deaths and buildings destroyed were in New South Wales. Many of the lost structures were farm buildings, adding to the challenge of agricultural recovery that is already complex because of ash-covered farmland accompanied by historic levels of drought. In the 2030 and 2050 time frames, the increasing frequency and extent of wildfires would cause intensifying risks to various types of vulnerable infrastructure, which could have even more severe socioeconomic impacts than today. For example, energy infrastructure assets, like T&D lines, are most vulnerable to wildfires because those assets are critical everywhere communities exist. Other vulnerable infrastructure assets include transportation (airports, rail, and roads) and telecommunications equipment (base substations, radio towers, and cable).

To adapt to the increasing risks from wildfires, asset owners need to take action at all stages of the risk management life cycle: 1) prevention, 2) detection, 3) fire management, 4) restoration, and 5) remediation. Given the destruction from past fire events, prevention is critical. Asset owners could harden existing assets by enhancing them (burying lines underground, for instance) or moving them. They could use advanced analytics to improve assessments of the likelihood and cost of risks and could build climate risk into future capital plans, business cases, and engineering standards. Detection could also be conducted through monitoring (of temperature, humidity, wind, and vegetation around the assets). In the event of wildfires, it is critical to have a fire management plan in place. T&D players should be able to ensure available backup power from third parties for critical load and prepare fire response plans (including communication strategies and operational procedures). Most importantly, asset owners could build restoration and remediation plans for after wildfires (even before the events).

Local governments have started to respond to the growing risks from wildfires. The Victoria Climate Change Adaptation Plan 2017–2020 includes measures to address bushfires, for example, and the Victoria Department of Education and Early Childhood Development initiated a substantial and wide-ranging review of bushfire and emergency management arrangements. Through the new School Bushfire Protection Project, the department aims to improve bushfire protection for students and staff at schools in high bushfire risk locations. The effort uses experts in fire risk modeling, threatened species assessment, and engineering solutions for bushfire-prone locations to find solutions that improve safety, reduce bushfire hazards, and minimize the impact of bushfire on school sites. Given the growing risks of hazards across the country, adaptation measures could further be accelerated.

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[115] Note that we project risk of wildfires based on climatic conditions (precipitation, air temperature, wind speed, relative humidity, snow cover, latitude, and time of year) but do not consider the ignition events that eventually cause fires (such as human error) nor the existence of materials that burn (for instance, forests and agricultural lands). For example, wildfire risk is high in the central areas of Australia because of climate conditions, but actual fires are rare due to low population density and burnable materials.

[116] Assuming the distribution of population in Australia stays at today's levels.

[117] To conduct this analysis, we relied on geospatial data, including climate hazard and capital stock data from: Woodwell Climate Research Center; Geoscience Australia's National Exposure Information System.

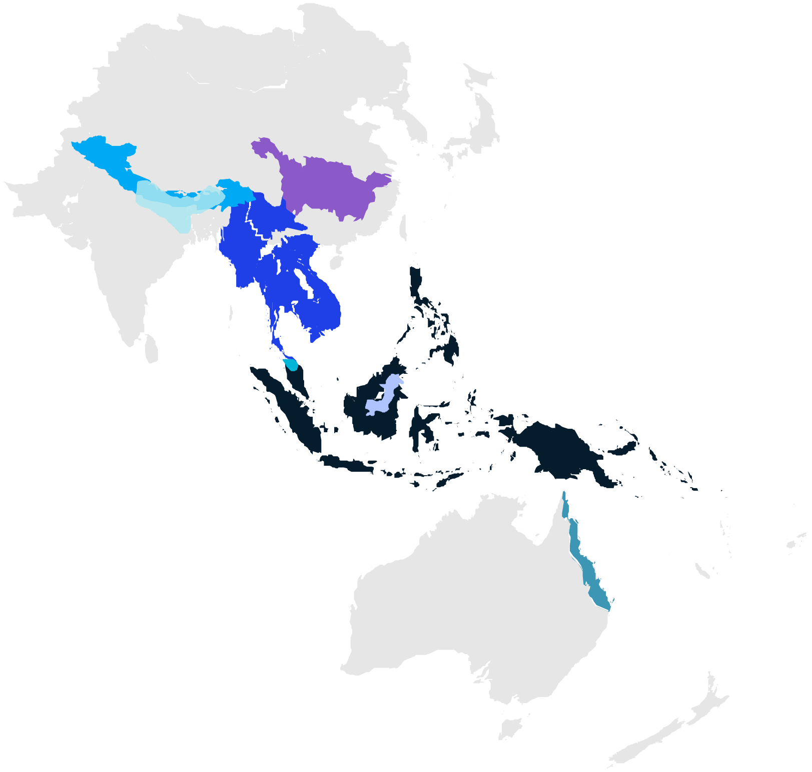
Climate change is already having an impact on natural capital and could increasingly affect the services the assets provide

The Asia–Pacific region is rich with natural capital and home to some of the largest and most diverse ecosystems that are critical to societies and economies. According to the World Bank, 47 percent of national wealth in low income countries comes from natural capital, compared with 3 percent in OECD countries (Exhibit 18).[118]

Exhibit 18

The diverse ecosystems of Asia and the Pacific are critical to the regions' social and economic activities.

Seven key ecosystems in the Asia–Pacific region



Coral Triangle
Harbors 76% of world's coral species. Natural resources provide livelihood for 120 million people.

Himalaya Mountain Range
160+ globally endangered species. 1 in 5 people on the planet depend on freshwater from the Himalayas.

Greater Mekong Subregion
524 new species discovered in 1997–2016. World's largest inland fishery (worth $2.5 billion per year).

Great Barrier Reef
Makes up 10% of the world's coral reef ecosystems. Contributes more than $6.4 billion per year to the Australian economy.

Heart of Borneo
Home to 6% of world's total biodiversity. Secures livelihood of 11 million Borneans.

Yangtze River
Home of iconic giant panda and rare river dolphin. Accounts for 40% of China's freshwater resources.

Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company. Sources: WWF, Australian Government.
Source: *Climate risk and response*, McKinsey Global Institute, January 2020; World Wildlife Fund; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

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[118] World Bank, *The Changing Wealth of Nations 2018: Building a Sustainable Future*, Washington, DC: World Bank, 2018.

Human activities are depleting natural capital and curtailing ecosystem services at an unprecedented rate. Some of these activities involve the conversion of natural capital into other forms of productive capital, such as clear-cutting forestland so it can be farmed. Others degrade natural capital stock without direct socioeconomic benefit. Climate change accelerates the depletion of natural capital and ecosystem services because it changes geophysical conditions—average surface temperatures, ocean body temperatures, precipitation patterns, the oxygen content and acidity of seawater—too quickly for natural systems to adapt. When these changes reach thresholds, natural capital and ecosystem services often degrade on a nonlinear path.[119] To understand the magnitude of the risks involved, we examine glaciers, oceans, and forests, and the potential extent of their degradation in the absence of adaptation and mitigation (Exhibit 19).

Exhibit 19

Climate change intensifies degradation of already endangered natural capital in Asia–Pacific.

Based on RCP 8.5

Climate risk impact by 2050 in the Asia–Pacific region

Glacier melt

20–40%

decrease of glaciers in Hindu Kush Himalayan region

Ocean warming …

Up to 90%

of coral will suffer severe degradation in Coral Triangle and Great Barrier Reef under climate change scenarios with 2°C global mean temperature increase

… and acidification

8%

decrease in catch rate due to fish migrating to higher latitudes to engage in seasonal behaviors at different times than in past

Note: See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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: IPBES 2018; IPCC; World Wildlife Fund; *The future of Asia* and *Climate risk and response*, McKinsey Global Institute; McKinsey Global Institute analysis

By 2050, glaciers in the Hindu Kush Himalayan region could shrink by 20 to 40 percent, affecting about 750 million people

The Hindu Kush Himalayan region includes eight countries, from Afghanistan in the west to Myanmar in the east. Its glaciers provide water for irrigation, energy generation, and other economic activities for the region's 240 million residents and about 750 million people in total. The rate of melting of Himalayan glaciers has doubled since 2000, and more than a quarter of glacial ice in negatively affected regions has been lost in the past four decades.[120] Glacial mass in this region could drop by about 10 to 25 percent by 2030, and by 20 to 40 percent by 2050 in some subregions. The region already faces severe danger of catastrophic flooding.[121] Climate change has been the main cause of these developments.[122] On the Tibetan Plateau, glacial retreat has caused hydrological changes, including an increase in river runoff of more than 5 percent and a 0.2-meter annual rise in water levels.[123] While runoff from 45 percent of the world's glaciers, including the source of the Brahmaputra River, has already peaked, runoff from 22 percent of glacier-fed basins is predicted to increase. The headwaters of

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[119] Virginia R. Burkett et al., "Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications," *Ecological Complexity*, December 2005, Volume 2, Number 4.

[120] J. M. Maurer et al., "Acceleration of ice loss across the Himalayas over the past 40 years," *Science Advances*, June 2019, Volume 5, Number 6.

[121] Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, 2019.

[122] Damian Carrington, "Himalayan glacier melting doubled since 2000, spy satellites show," *Guardian*, June 19, 2019.

[123] Tandong Yao et al., "Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding regions," *Arctic, Antarctic, and Alpine Research*, November 2007, Volume 39, Number 4; Guoqing Zhang et al., "Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009)," *Remote Sensing of Environment*, July 2011, Volume 115, Number 7.

the Ganges River and the Indus River are expected to peak in 2050 and 2070, respectively.[124] Pre-monsoon flows are forecast to decline, compromising irrigation, hydropower, and ecosystem services. Erratic weather, such as the disappearance of expected rainfall and more frequent heat waves, could magnify the effects on river flows.[125]

These changes may have significant consequences, particularly for rural communities that rely on rivers. The risk of floods poses an immediate threat to human populations. Climate-dependent sectors, such as agriculture, may also be threatened.[126] The consequences could be severe for countries such as India, which has the world's 13th-highest level of water stress (driven primarily by water management challenges and growing demand) and a population three times greater than the total population of the 17 other countries with high water stress.[127]

More than

40%

of all coral reefs in the Coral Triangle have vanished over the past 40 years

Ocean warming threatens sea life, which supports the livelihood of hundreds of millions of people in the region

Climate change has made the oceans warmer, less oxygenated, and more acidic. From 1950 to 2009, the average surface temperature in the Indian Ocean rose by 0.65 degree Celsius, while in the Pacific it rose by 0.31 degree.[128] Ocean warming is increasing the frequency and duration of marine heat waves, which can deplete carbon-absorbing seagrass and kelp forests. Ocean warming also causes seawater to release stored oxygen. More CO_2 in the atmosphere causes the ocean to absorb more CO_2, which makes seawater more acidic. The oceans have absorbed roughly 30 percent of the CO_2 emitted by human activities since the preindustrial period, leading to a 0.1 pH decrease, a pace of change that is unprecedented in the past 65 million years.[129]

The rate of CO_2 absorption is slowing due to rising ocean temperatures.[130] In addition, warming, deoxygenation, and acidification change the oceans' circulation patterns and chemistry. Fish and zooplankton are migrating to higher latitudes and changing behaviors.[131] This in turn exerts stress on traditional fisheries. Between 1930 and 2010, seafood yields in the Sea of Japan fell by 35 percent.[132]

Coral reefs are threatened by small changes in ocean temperature. The Great Barrier Reef, which supports a $5 billion-a-year tourism industry in Australia and has suffered four mass bleaching events since 1998 (with half of its reef corals bleaching and dying in 2016–17), is likely to experience bleaching twice each decade by 2035 and annually by midcentury, in large part induced by rising water temperatures.[133] The warmer ocean could cause the reef systems in the Coral Triangle, home to more than half of the coral reef fish species in the Indo–Pacific region, to disappear and put more pressure on coastal communities. In the past 40 years, over 40 percent of the coral reefs in the region have vanished. Research indicates that if current climate trends continue, the ability of reef systems to provide food for coastal populations will decline by 50 percent by 2050 and by as much as 80 percent by 2100, affecting more than 120 million people.[134]

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[124] Matthias Huss and Regine Hock, "Global-scale hydrological response to future glacier mass loss," *Nature Climate Change*, January 2018, Volume 8, Number 2.

[125] Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, 2019.

[126] Arun Bhakta Shrestha et al., eds., *The Himalayan climate and water atlas: Impact of climate change on water resources in five of Asia's major river basins*, CIMOD, GRID-Arendal, and CICERO, 2015.

[127] Insights, "17 countries, home to one-quarter of the world's population, face extremely high water stress," blog entry by Rutger Willem Hofste, Paul Reig, and Leah Schleifer, August 6, 2019.

[128] Ove Hoegh-Guldberg et al., "The ocean," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part B: Regional Aspects*, Intergovernmental Panel on Climate Change, New York, NY: Cambridge University Press, 2014.

[129] *Ocean acidification in the IPCC Special Report: Global warming of 1.5°C*, Ocean Acidification International Coordination Centre, October 2018.

[130] P. Ciais et al., "Carbon and other biogeochemical cycles," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2013.

[131] *Issues brief: The ocean and climate change*, International Union for Conservation of Nature, 2017; Ove Hoegh-Guldberg et al., "The ocean," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part B: Regional Aspects*, Intergovernmental Panel on Climate Change, New York, NY: Cambridge University Press, 2014.

[132] Christopher M. Free et al., "Impacts of historical warming on marine fisheries production," *Science*, March 2019, Volume 363, Number 6430.

[133] Scott F. Heron et al., *Impacts of Climate Change on World Heritage Coral Reefs : A First Global Scientific Assessment*, Paris, UNESCO World Heritage Centre, 2017.

[134] *Ecological footprint and investment in natural capital in Asia Pacific*, WWF and ADB, 2012.

20%

the decline in forests in Indonesia since 1990

Forests are being affected by climate change
Forests are a source of economic resources and ecosystems services. Like oceans, forests act as important carbon sinks; the biosphere currently absorbs approximately 30 percent of fossil fuel CO_2 emissions, with the majority stored in forests and mangroves. The value of primary forest products in Asia–Pacific was calculated at approximately $90 billion per year in 2016.[135] However, while 61 percent of the world's population lives in the region, it has only 17 percent of global forests. Deforestation rates remain especially high in Southeast Asia. Since 1990, the forest in Indonesia has decreased by 20 percent and in Myanmar by 19 percent. Although deforestation is mainly human-caused, climate hazards intensify it.[136] Research on the link between climate change and forest disturbances due to wind, snow and ice, fire, drought, insects, and pathogens shows that climate change most likely has a triggering or intensifying effect on disturbances. Fifty-seven percent of the observations in the studied literature were related to direct impacts of climate change on disturbance processes.[137] Disturbances can also feed back into climate change—wildfires emit large quantities of CO_2 and thus exacerbate the rate of change in the climate.

Because forests take a long time to grow but then live for decades or longer, they are likely to face risks from both changes in mean climate variables and extreme weather events.[138]

Protecting and adapting natural capital is complex because the systems and their interconnections can be difficult to understand and the effectiveness of solutions is assessable only over long periods. Potential measures for natural capital in general include sustaining important ecological functions by means of interventions, making ecosystems more adaptable, developing better mechanisms for monitoring, and investing in green infrastructure by integrating natural processes with spatial planning and territorial development. Where natural capital is already lost, economic diversification may help communities adapt.

It is critical to mobilize public and private finance to fund protection and adaptation measures. This requires collaboration; for example, the private sector could contribute capital resources and technical capabilities, and the public sector could create investment mechanisms and support risk mitigation.[139]

For the public sector, two key roles are worth considering. The primary one is to directly allocate parts of the budget to environment programs. For example, China's wastelands policy facilitates payments for conserving soil resources. Secondly, the public sector could also create incentive and market-based mechanisms to engage private capital. For example:

- Encourage trading of natural resources under regulation, allowing trading between private resource users under a regulatory cap or floor for the level of use or investment in natural capital. A conservation bank can sell credits to projects that will have an impact on the environment and use the income to protect natural capital.
- Create conditions for deals between the off-site beneficiaries of natural capital and the resource owners. The deals may take the form of payments by private water users to upstream farmers for their catchment protection efforts.
- Employ eco-labeling and certification of products and services, for which consumers are willing to pay a price premium. The global market for eco-labeling products will grow to $1.9 trillion in 2050, according to The Economics of Ecosystems and Biodiversity.[140]

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[135] *Forests and FSC in Asia Pacific*, Forest Stewardship Council Asia Pacific, 2016.
[136] *Ecological footprint and investment in natural capital in Asia Pacific*, WWF and ADB, 2012.
[137] Rupert Seidl et al., "Forest disturbances under climate change," *Nature Climate Change*, June 2017, Volume 7, Number 6.
[138] Marcus Lindner et al., "Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems," *Forest Ecology and Management*, February 2010, Volume 259, Number 4.
[139] *The Marine Socio-Economics Project (MSEP): Valuing the environment in economic terms*, New Economic Foundation, 2011.
[140] Ibid.

- Promote innovative financial products, for example environmental impact bonds for green initiative financing.[141] China is the second-largest green bond market. In 2018, internationally aligned green bond issuance from China totaled $31.2 billion.[142]
- Set up carbon offset programs and channel the revenue to decarbonization projects. The REDD+ program, negotiated by the United Nations Framework Convention on Climate Change in 2005, provides a mechanism for developed countries to purchase carbon offsets for the benefits derived from deforestation in developing countries, the proceeds of which can be invested in forest protection and restoration.[143] In 2017, Indonesia received the first part of a $1 billion payment pledged by the Norwegian government to prevent the emission of 4.8 million tons of carbon dioxide equivalent (CO_2e) through reduced deforestation.[144]

For natural capital projects that can generate positive commercial returns, the public sector can create incentives such as subsidies and tax benefits to support private-sector investment. Eco-tourism is a common format of this type of initiative, which helps protect ecosystems and provides income to local communities. One example is elephant rescue and rehabilitation parks in Thailand.

Another consideration is finding ways to better value natural capital. While putting a price on the environment may seem like an impossible task, not putting a price could mean that stakeholders perceive nature is an unlimited resource. Recognizing natural capital's value in monetary units can alert us to the cost of destruction, help communicate the importance of the system to stakeholders, and attract investment to finance protection, restoration, and adaptation. Research suggests there are multiple ways to estimate the value of natural capital. The New Economics Foundation, a British think tank that promotes social, economic, and environmental justice, introduced a framework for calculating the total environmental value of natural capital, where total value is the combination of use value, defined as aspects of nature that are directly useful for human production and consumption, and non-use value, defined as aspects of nature that have less tangible attributes—but might not link to economic production or consumption—and can influence human well-being.

An independent governing body is another approach to systematic management of natural capital. The body could address the root causes of deterioration, including a misaligned view of environmental value, a lack of significant penalties and enforcement for natural resource overuse, and insufficient incentives to prioritize the environment over the economy. It could also provide long-term and holistic natural capital stewardship. An example of this type of governing body is the US Environmental Protection Agency, which is an independent federal body and is authorized to write and enforce regulations according to environmental laws passed by Congress. It also owns, manages, and reports budgets and data for environment-related initiatives.

One example of a broad-based strategy to managing natural capital is New Zealand's approach, which provides a comprehensive framework that identifies the use and non-use value that people derive from natural capital (see Box 3, "Understanding New Zealand's natural capital management system").

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[141] *Atlanta: First publicly offered environmental impact bond*, Quantified Ventures, 2019.
[142] *China green bond market 2018*, Climate Bonds Initiative and China Central Depository & Clearing Company, 2019.
[143] *National REDD+ strategies in Asia and the Pacific: Progress and challenges*, ADB, 2010.
[144] *Indonesia, Values and priorities, Climate and forest cooperation*, Royal Norwegian Embassy in Jakarta, 2020.

Box 3

Understanding New Zealand's natural capital management system

New Zealand is ranked number one for natural capital per capita by the World Bank, excluding petroleum-exporting countries.[1] Some 20 percent of the country's GDP relies on natural capital, including agriculture, food manufacturing, tourism, and water services.[2] However, due to the combined impacts of climate change and human activities, New Zealand's land and water ecosystems are under threat. CO_2 equivalent emissions, mainly methane from agriculture, increased by 20 percent between 1990 and 2016, and some 13 percent of wetlands shrank between 2001 and 2016.[3]

Since 2017, the public and private sectors have implemented a series of measures to establish better guardianship of natural capital, including adopting a financial perspective to value and safeguard natural capital. The country has adopted the total economic value framework for natural capital valuation.[4] The total value of the country's natural capital is estimated at $300 billion, a partial measure that provides a useful benchmark against which to measure progress.[5]

The Aotearoa Circle, formed in 2019, is a voluntary initiative bringing together leaders from the public and private sectors to investigate the state of New Zealand's natural resources and to prioritize actions that will halt and reverse the decline. Its founding members include Air New Zealand, Auckland Airport, the Ministry for the Environment, and Westpac. One of its projects aims to establish a holistic financial system that integrates sustainability and environment for New Zealand by 2030. The organization is also developing plans for restoration of water systems and biodiversity.[6]

The Climate Change Commission, established in 2019, has been actively reviewing environmental and sustainability issues and providing feedback to the government. In the first six months of 2020, it reviewed and commented on New Zealand's first nationally determined contribution under the Paris Agreement.[7]

Taken together, these efforts are helping New Zealand develop a holistic approach to environmental sustainability that includes stewardship, mindset-focused initiatives, capabilities, data, and funding. The country's approach has the potential to serve as a blueprint for management of environmental issues across the region.

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[1] *About us*, The Aotearoa Circle, 2019.
[2] New Zealand Government Statistics, 2019.
[3] New Zealand's Environmental Reporting Series: Environment Aotearoa 2019, New Zealand Ministry for the Environment and Stats NZ, 2019.
[4] *Natural capital and the Living Standards Framework*, The Treasury of New Zealand, 2018.
[5] "Natural capital monetary estimates: 2007–16," Stats NZ, 2018.
[6] *Sustainable Finance Forum interim report*, The Aotearoa Circle, 2019.
[7] *Who we are*, Climate Change Commission, 2020.

Climate hazards create risks for socioeconomic systems, and Asia could see impacts across sectors and locations. The six case studies detailed in this chapter show that many of those impacts will manifest by 2030 and rise by 2050 without adaptation or mitigation. The greatest effects will be felt where risk exposures are closest to physical and biological thresholds. Our case studies show that China and India can expect significant changes to livability and workability from the effect of rising heat and humidity levels, and that Asian breadbaskets will see both negative and positive impacts. Wildfires in Australia and flooding in Japan will cause rising levels of damage to infrastructure, and resources of natural capital will come under increasing pressure. On a positive note, governments, business leaders, and other stakeholders are starting to respond, though more action is needed to manage rising risks. In the following chapter, we outline five key strategies that may help guide and support adaptation efforts.

Country dashboards

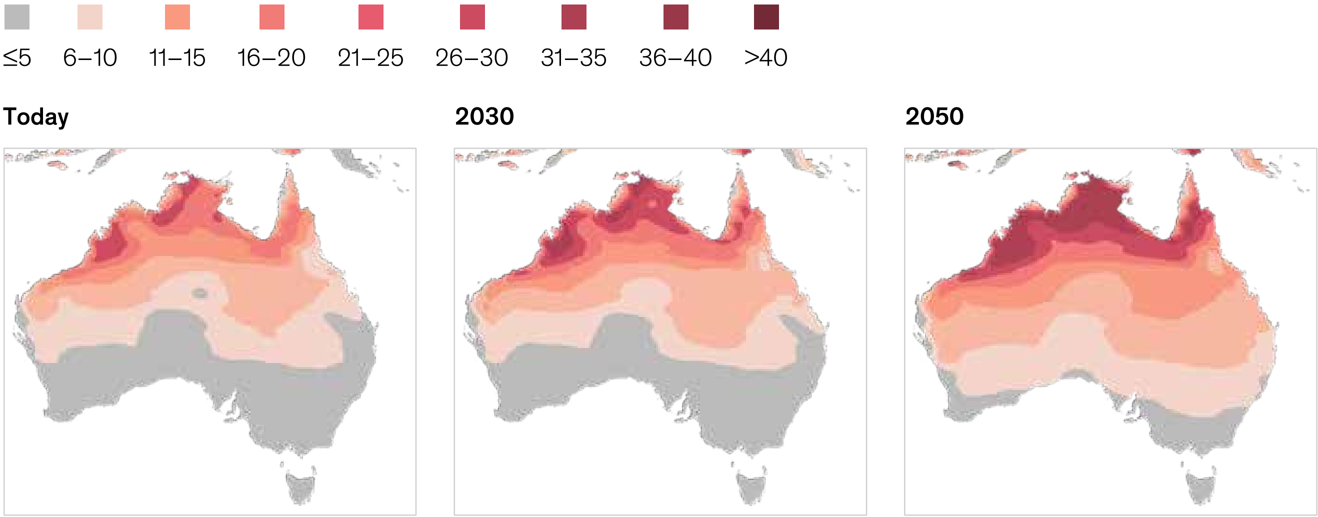
Country dashboard 1

In the absence of adaptation and mitigation, Australia will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly decreasing water supply and wildfires.

Based on RCP 8.5

Livability and workability

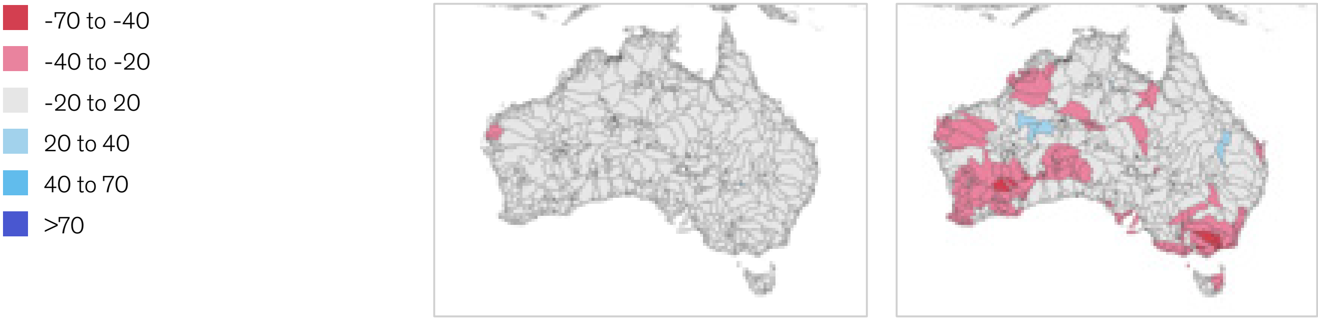
Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, %[1]



By 2030, **1.0%** of outdoor working hours could be lost (vs 0.7% today)

By 2050, share could grow to **3%** of working hours lost

Change in surface water compared with 2018 (map boundaries represent water basins), %



Food systems (Australia and New Zealand combined)

Yields vs today 🟥 Declining ⬛ Increasing

Yields vs today 🟥 Declining ⬛ Increasing

		Corn	Rice	Soy	Wheat
Probability of >10% grain yield decline, %[2]	Today	28	32	-	23
	2030	🟥 33	32	-	🟥 28
	2050	⬛ 22	⬛ 27	-	🟥 28
Probability of >10% grain yield improvement, %[2]	Today	29	30	-	22
	2030	⬛ 32	⬛ 33	-	⬛ 37
	2050	⬛ 47	⬛ 47	-	⬛ 44

For wheat, major crop in Australia, expected increase in probability of yield shocks (due to CO_2 fertilization, larger probability of yield increase is also expected)

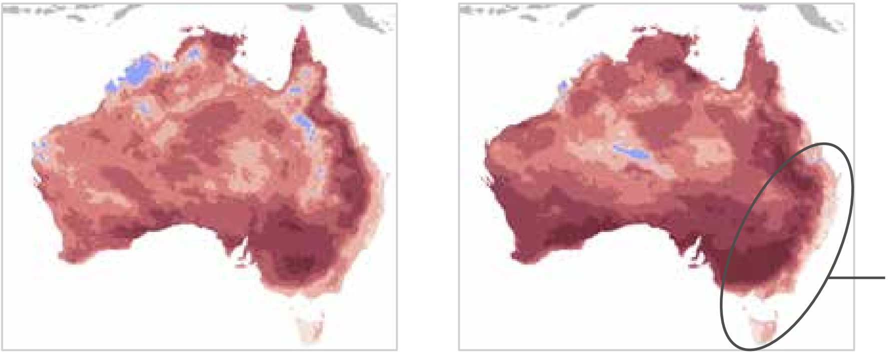
In the absence of adaptation and mitigation, Australia will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly decreasing water supply and wildfires (continued).

Based on RCP 8.5

Physical assets/infrastructure services,
number of high fire risk days per year[3]

Change from today …

To 2030 **To 2050**



Share of capital stock exposed to at least 5 high fire risk days grows to

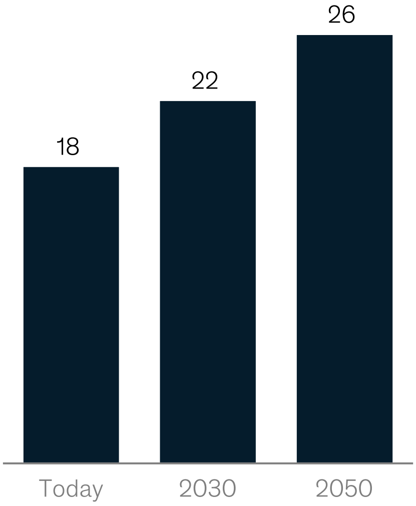
60% by 2050

from 44% today

Most populated and capital-dense areas in Australia

Natural capital

Share of land surface changing climate classification, %[4]



By 2050, up to **~90%** of coral will suffer severe degradation in Coral Triangle and Great Barrier Reef under climate change scenarios with 2°C global mean temperature increase

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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.
2. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits. Countries grouped for analyses to ensure modeling robustness. Yield changes are measured relative to the mean yield for the 1998–2017 period.
3. Defined as day where fire weather index is high enough to account for majority (79%) of observed historical fires. Fire weather index is general metric of fire danger used globally and is a function of precipitation, air temperature, wind speed, relative humidity, snow cover, latitude, and time of year.
4. Calculated using a biome shift measure. Biome refers to naturally occurring community of flora and fauna inhabiting a particular region. Changes in the Köppen Climate Classification System used as indicative proxy for shifts in biome.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

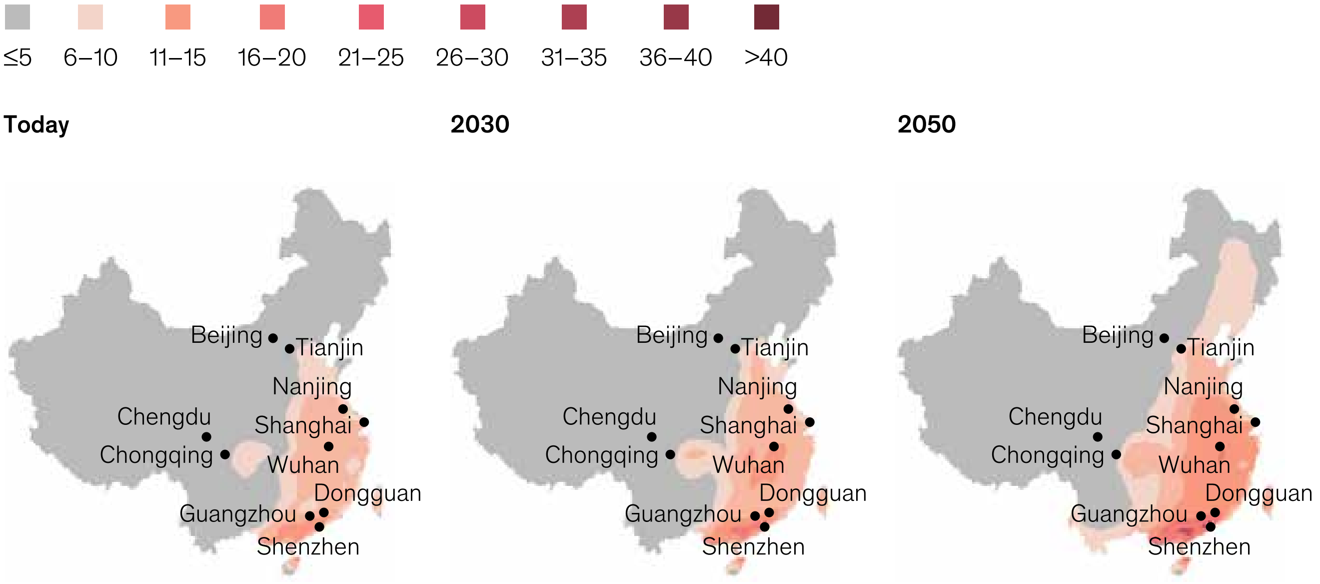
Source: FV model Risklayer, RCP 8.5 ensemble CC model with 50mm/hr drainage, CATDAT; IHS Markit Economics & Country Risk; Rubel and Kottek, 2010; Woodwell Climate Research Center; World Resources Institute Aqueduct Global Flood Analyzer, 2019; Australian Geography Teachers Association; Geoscience Australia; UN Office for the Coordination of Humanitarian Affairs; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Country dashboard 2

In the absence of adaptation and mitigation, China will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly from rising heat, humidity, and extreme precipitation.

Based on RCP 8.5

Livability and workability, annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, %[1]



By 2030, 6.5% of outdoor working hours could be lost (vs 4.0% today)

By 2050, share could grow to 9% of working hours lost

Food systems

Yields vs today 🟥 Declining ⬛ Increasing

		Corn	Rice	Soy	Wheat	
Probability of >10% grain yield decline, %[2]	Today	11	2	7	12	For corn, rice, and wheat, risk of yield shock increase by 2030 and decrease by 2050[3]
	2030	🟥 15	🟥 7	⬛ 1	🟥 20	
	2050	⬛ 8	🟥 6	⬛ 3	🟥 14	For soy, risk of yield shock decrease
Probability of >10% grain yield improvement, %[2]	Today	9	0	4	11	Across crops, increased probability of higher yields by 2050
	2030	🟥 4	0	⬛ 15	⬛ 12	
	2050	⬛ 14	⬛ 9	⬛ 36	⬛ 18	

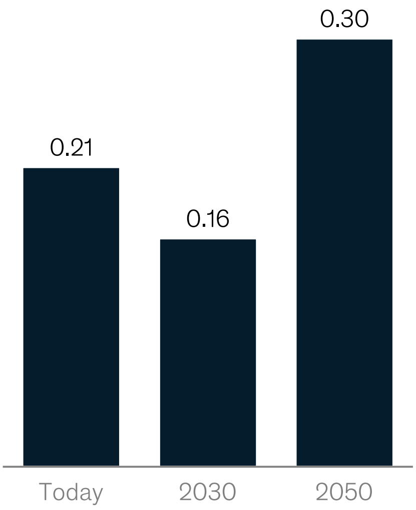
Country dashboard 2 (continued)

In the absence of adaptation and mitigation, China will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly heat, humidity, and extreme precipitation (continued).

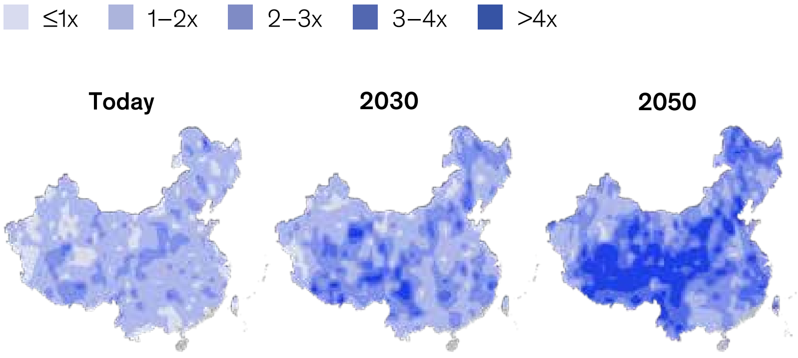
Based on RCP 8.5

Physical assets/infrastructure services

Annual share of capital stock at risk of riverine flood damage, %[4]



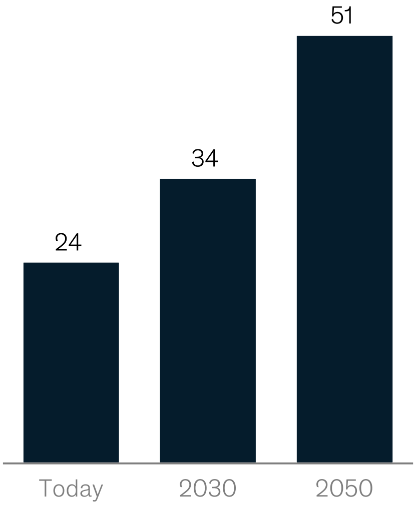
Extreme precipitation, change in likelihood of 50-year precipitation event compared to 1950–81



Overall 5-day rainfall average increases
25% by 2050

Natural capital

Share of land surface changing climate classification, %[5]



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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.
2. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits. Countries grouped for some analyses to ensure modeling robustness. Yield changes are measured relative to the mean yield for the 1998–2017 period.
3. Reasons for multidirectional effect by climate change can be larger increase in precipitation relative to additional warming by 2050 (vs 2030) or CO_2 fertilization acting as a buffer.
4. For estimation of capital stock at risk of riverine flooding we used a country level Urban Damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under business-as usual scenario (RCP 8.5, Shared Socioeconomic Pathways 2) and existing levels of flood protection. Risk values are calculated based on expected values, ie, probability-weighted value at risk.
5. Calculated using a biome shift measure. Biome refers to naturally occurring community of flora and fauna inhabiting a particular region. Changes in the Köppen Climate Classification System used as indicative proxy for shifts in biome.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

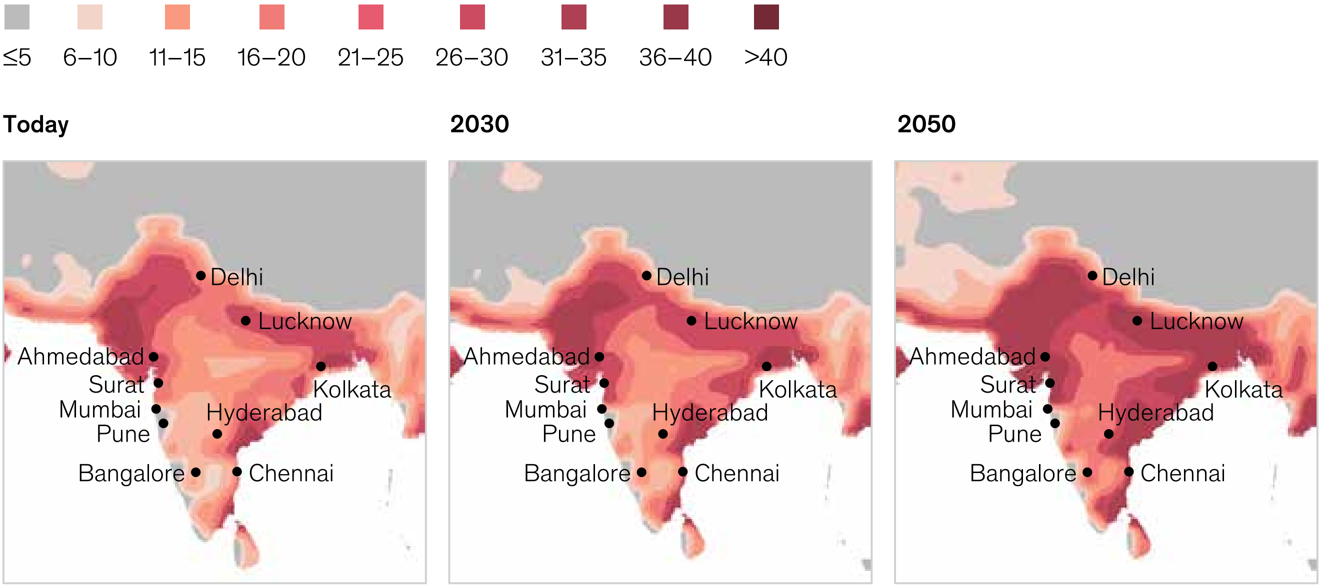
Source: FV model Risklayer, RCP 8.5 ensemble CC model with 50mm/hr drainage, CATDAT; IHS Markit Economics & Country Risk; Rubel and Kottek, 2010; Woodwell Climate Research Center; World Resources Institute Aqueduct Global Flood Analyzer, 2019; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Country dashboard 3

In the absence of adaptation and mitigation, India will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly heat and humidity.

Based on RCP 8.5

Livability and workability, annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, %[1]



By 2030, **24%** of outdoor working hours could be lost (vs 21% today)

By 2050, share could grow to **30%** of working hours lost

Food systems

Yields vs today 🟥 Declining ■ Increasing

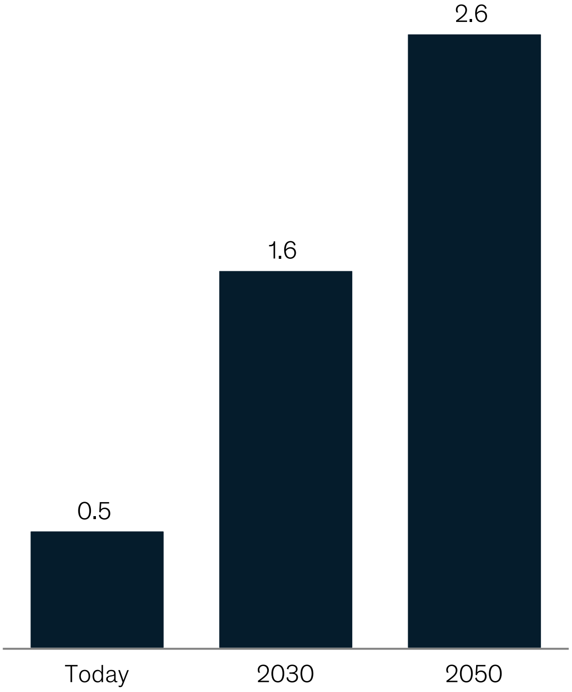
		Corn	Rice	Soy	Wheat	
Probability of >10% grain yield decline, %[2]	Today	28	9	27	34	Across crops, risk of yield shock increase by 2030/2050
	2030	29	11	29	50	
	2050	42	27	39	77	
Probability of >10% grain yield improvement, %[2]	Today	34	8	39	9	Across crops, yield distribution moves toward worse outcomes, probability of higher yields decreases
	2030	24	4	32	6	
	2050	20	4	26	4	

Country dashboard 3 (continued)

In the absence of adaptation and mitigation, India will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly heat and humidity (continued).

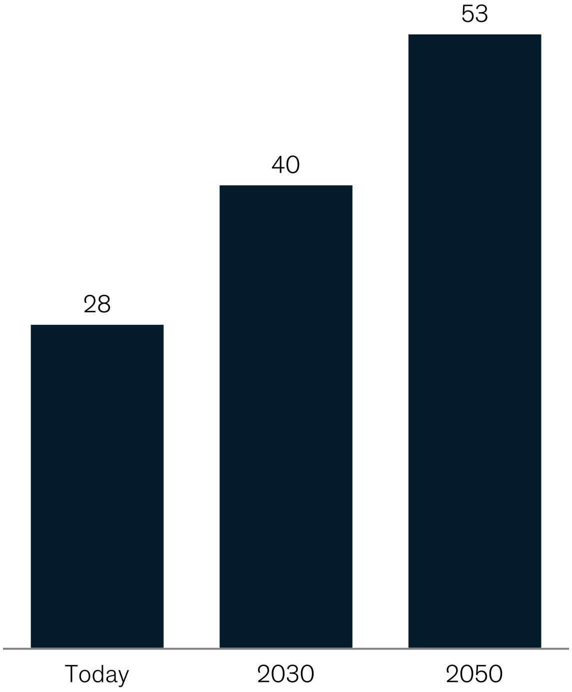
Based on RCP 8.5

Physical assets/infrastructure services,
annual share of capital stock at risk of riverine flood damage, %[3]



Major cities with more than **2% increase** of extreme precipitation event (once in 50 years) include Mumbai, Pune, Kochi, and Kozhikode

Natural capital,
share of land surface changing climate classification, %[4]



Glacial mass in Hindu Kush Himalayan region, providing water for **~750M people** including Indians, could drop by **20–40%** by 2050

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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.
2. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits. Yield changes are measured relative to the mean yield for the 1998–2017 period.
3. For estimation of capital stock at risk of riverine flooding we used a country level Urban Damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under business-as-usual scenario (RCP 8.5, Shared Socioeconomic Pathways 2) and existing levels of flood protection. Risk values are calculated based on expected values, ie, probability-weighted value at risk.
4. Calculated using a biome shift measure. Biome refers to naturally occurring community of flora and fauna inhabiting a particular region. Changes in the Köppen Climate Classification System used as indicative proxy for shifts in biome.

Note: See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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. The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

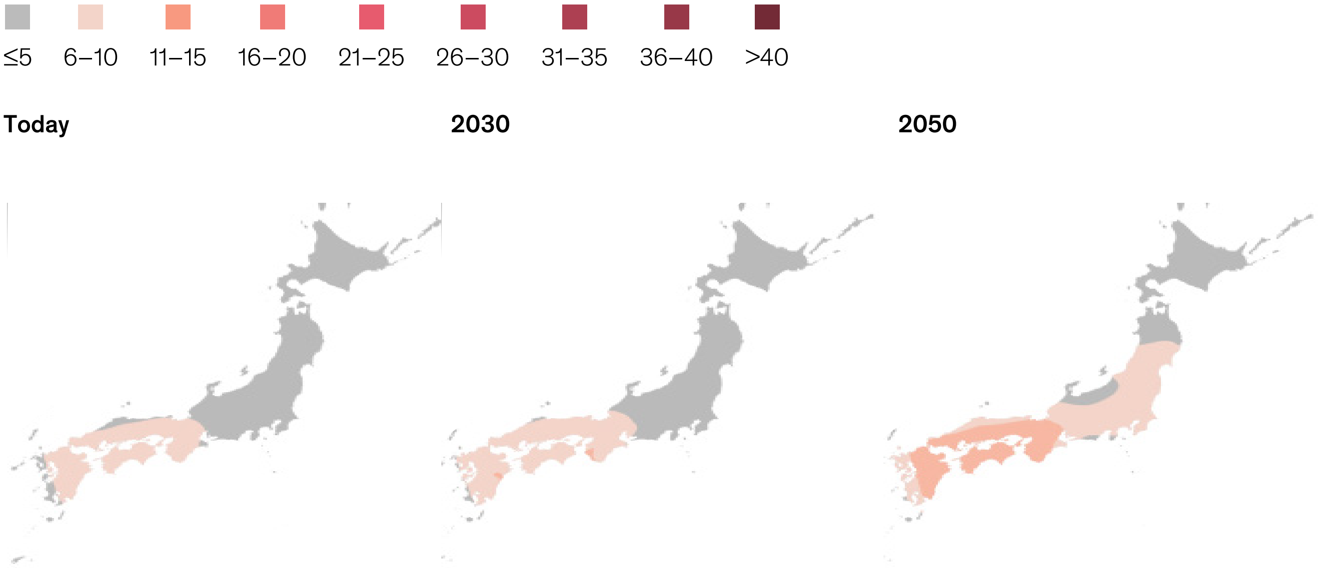
Source: FV model Risklayer, RCP 8.5 ensemble CC model with 50mm/hr drainage, CATDAT; IHS Markit Economics & Country Risk; Rubel and Kottek, 2010; Woodwell Climate Research Center; World Resources Institute Aqueduct Global Flood Analyzer, 2019; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Country dashboard 4

In the absence of adaptation and mitigation, Japan will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly floods and hurricane.

Based on RCP 8.5

Livability and workability, annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, %[1]



By 2030, **3.0%** of outdoor working hours could be lost (vs 2.0% today)

By 2050, share could grow to **4.0%** of working hours lost

Food systems

Yields vs today 🟥 Declining ⬛ Increasing

		Corn	Rice	Soy	Wheat	
Probability of >10% grain yield decline, %[2]	Today	13	4	4	6	For rice, main grain for Japan, significant increase in expected yields with decrease of yield decline probabilities
	2030	5	1	0	0	
	2050	5	0	0	0	
Probability of >10% grain yield improvement, %[2]	Today	7	2	11	2	
	2030	23	20	37	35	
	2050	38	52	72	86	

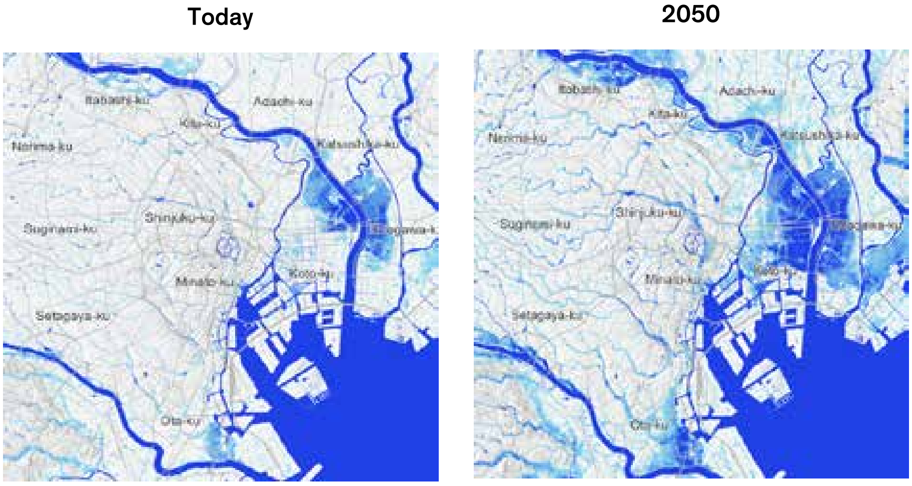
Country dashboard 4 (continued)

In the absence of adaptation and mitigation, Japan will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly floods and hurricane (continued).

Based on RCP 8.5

Physical assets/infrastructure services,
combined flood effects from 100-year rainfall, storm surge, and streamflow in Tokyo

Water level
15 cm 🟦 2+ meters



Direct real estate damage from the floods would grow to

$13.1 billion

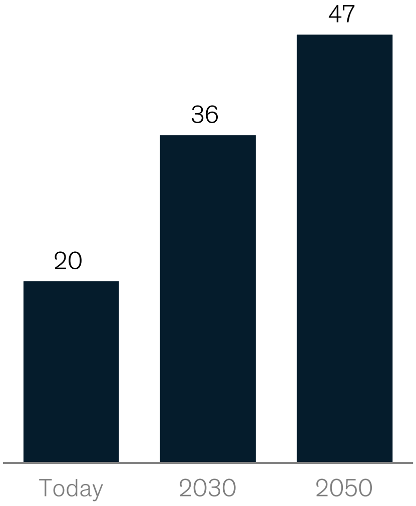
by 2050 from $5.9 billion today (infrastructure damage would grow to

$1.1 billion

from $0.4 billion today)

Natural capital

Share of land surface changing climate classification, %[3]



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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.
2. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits. Yield changes are measured relative to the mean yield for the 1998–2017 period.
3. Calculated using a biome shift measure. Biome refers to naturally occurring community of flora and fauna inhabiting a particular region. Changes in the Köppen Climate Classification System used as indicative proxy for shifts in biome.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

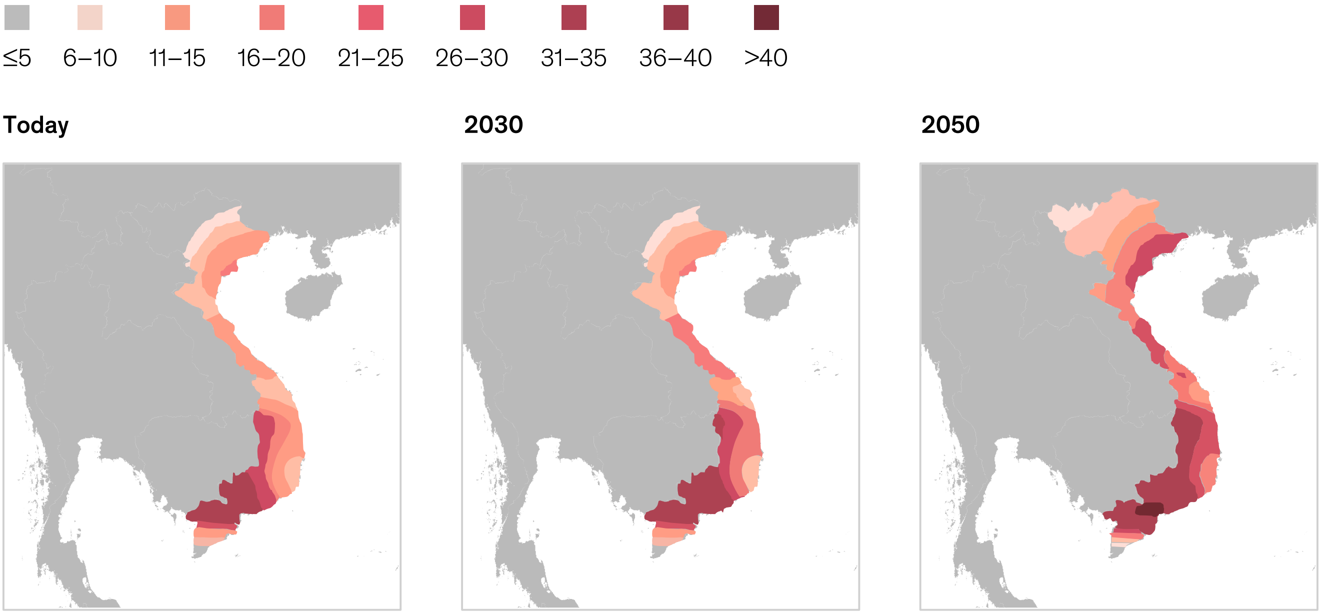
Source: FV model Risklayer, RCP 8.5 ensemble CC model with 50mm/hr drainage, CATDAT; IHS Markit Economics & Country Risk; Rubel and Kottek, 2010; Woodwell Climate Research Center; World Resources Institute Aqueduct Global Flood Analyzer, 2019; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis. See technical appendix for underlying data used to model Tokyo floods.

Country dashboard 5

In the absence of adaptation and mitigation, Vietnam will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly heat, humidity, and floods.

Based on RCP 8.5

Livability and workability, annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, %[1]



By 2030, 27% of outdoor working hours could be lost (vs 22% today)

By 2050, share could grow to 33% of working hours lost

Food systems (in 8 countries in Emerging Asia) [2]

Yields vs today 🟥 Declining ⬛ Increasing

		Corn	Rice	Soy	Wheat
Probability of >10% grain yield decline, %[3]	Today	10	3	10	-
	2030	⬛ 8	⬛ 2	⬛ 5	-
	2050	🟥 19	🟥 6	🟥 18	-
Probability of >10% grain yield improvement, %[3]	Today	2	3	11	-
	2030	🟥 1	⬛ 6	🟥 5	-
	2050	🟥 0	⬛ 6	🟥 10	-

For corn, marginal impact by 2030 and increased probability of yield decline by 2050

For rice, increased probability of both yield increase and decline by 2050 (tails of yield distribution flatten)

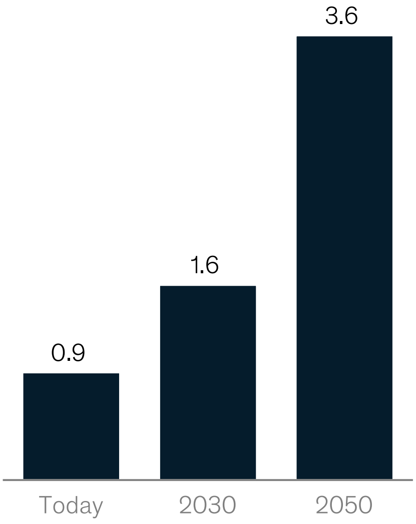
Country dashboard 5 (continued)

In the absence of adaptation and mitigation, Vietnam will be exposed to intensifying socioeconomic impacts from climate risk by 2030/2050, particularly heat, humidity, and floods (continued).

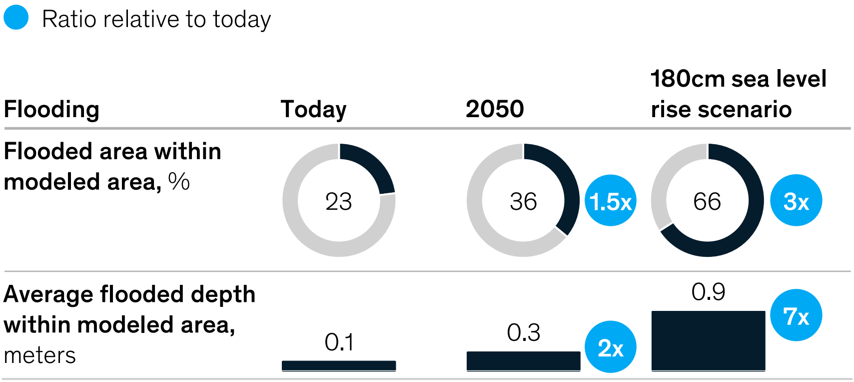
Based on RCP 8.5

Physical assets/infrastructure services

Annual share of capital stock at risk of riverine flood damage, %[4]



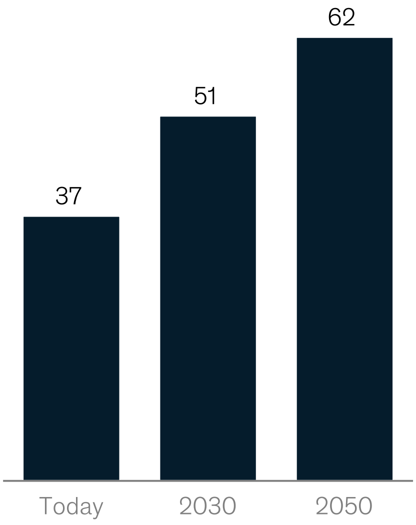
100-year flood effects in Ho Chi Minh City



Direct real estate damage from floods grows to **$8.4 billion** by 2050 from $1.5 billion today (infrastructure damage grows up to **$1 billion** from $0.3 billion today)

Natural capital

Share of land surface changing climate classification, %[5]



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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.
2. Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, and Vietnam.
3. Rice, corn, soy, and wheat; distribution of agricultural yields modeled by Woodwell using median of nitrogen-limited crop models from AgMIP ensemble. Note that this analysis focuses only on likelihood of yield declines (vs yield increases) since it focuses on risks from climate change. See text of report for discussion of potential benefits. Countries grouped for some analyses to ensure modeling robustness. Yield changes are measured relative to the mean yield for the 1998–2017 period.
4. For estimation of capital stock at risk of riverine flooding we used a country level Urban Damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under business-as-usual scenario (RCP 8.5, Shared Socioeconomic Pathways 2) and existing levels of flood protection. Risk values are calculated based on expected values, ie, probability-weighted value at risk.
5. Calculated using a biome shift measure. Biome refers to naturally occurring community of flora and fauna inhabiting a particular region. Changes in the Köppen Climate Classification System used as indicative proxy for shifts in biome.

Note: The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

Source: FV model Risklayer, RCP 8.5 ensemble CC model with 50mm/hr drainage, CATDAT; IHS Markit Economics & Country Risk; Rubel and Kottek, 2010; Woodwell Climate Research Center; World Resources Institute Aqueduct Global Flood Analyzer, 2019; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Storm shelter with mother and child, Manila, Philippines
© Rouelle Umali/Xinhua News Agency/Getty Images

3. An effective response, part 1: Adaptation

Climate science shows that warming over the next decade is already locked in.[145] Even if greenhouse gases never exceed their present level, temperatures and sea levels will continue to rise as the ocean slowly catches up with atmospheric warming. That means that increasing risk from a changing climate over the next decade is a virtual certainty, requiring governments and business leaders to develop adaptation strategies to offset the damage from more severe and / or frequent climate hazards. This is particularly critical for Asia, based on the rising risks our research identifies for Asia.

Despite the challenges, Asian countries are uniquely positioned to adapt to climate risks. Massive investment in infrastructure across the region represents a key opportunity to embed climate risk into future infrastructure design. To maintain its current growth trajectory, Asia must invest $1.7 trillion annually through 2030, according to the Asian Development Bank.[146] Factoring rising climate risk into these decisions can help make infrastructure more resilient and reduce potential damage. At the same time, many communities throughout Asia are already adapting to adverse events and to a changing climate, creating opportunities to build on their experience and replicate successful adaptation measures. For example, in 1991, Bangladesh suffered a devastating cyclone that killed over 100,000 people. Two decades later, the country was better prepared when a similarly powerful cyclone hit. Some two million people were evacuated to cyclone shelters that had been built along the coast, and while the death toll was 3,000, it was far lower than in the past.[147]

In this chapter, we highlight key adaptation measures for Asia, which include diagnosing risk and enabling a response, protecting people and assets, building resilience, reducing exposure, and ensuring that appropriate financing and insurance are in place. These accounts are not intended to be prescriptive but rather to provide a guide to what effective adaptation measures for the region may entail. Collaboration by stakeholders will also be critical for any effective adaptation strategy, including sharing of best practices and supporting intraregional funding mechanisms. Adaptation decisions may entail tough choices, for example what to protect now versus later, and where to invest versus where to retreat. It is also crucial that adaptation decisions factor in the regressive nature of climate risk highlighted previously. In this chapter, we discuss what we have learned from 50 adaptation case studies, and synthesize implications across the five adaptation measures described above.

Five adaptation measures are very relevant to Asia; in some cases, they are already in process and could be expanded

Our investigation of about 50 adaptation case studies across 14 major Asian economies, representing more than 90 percent of regional GDP and population, shows the that five key adaptation measures we developed in our global research are extremely relevant for Asia: diagnose risk and enable response, protect people and assets, build resilience, reduce exposure, and finance and insure (Exhibit 20).[148] In some cases, we find these adaptation measures are already under way but can be expanded or accelerated.

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[145] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1; David Archer, "Fate of fossil fuel CO_2 in geological time," *Journal of Geophysical Research*, March 2005, Volume 110; H. Damon Matthews and Susan Solomon, "Irreversible does not mean unavoidable," *Science*, April 2013, Volume 340, Issue 6131.

[146] Infrastructure investment is defined as fixed-asset investment in four sectors: transportation (road, rail, air, and ports), energy, telecommunications, and water and sanitation (including dams, irrigation, and flood control waterworks). *Meeting Asia's infrastructure needs*, ADB, 2017.

[147] Saleemul Haq, *Adapting to climate change: A challenge and an opportunity*, World Resources Institute, 2010.

[148] *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.

Exhibit 20

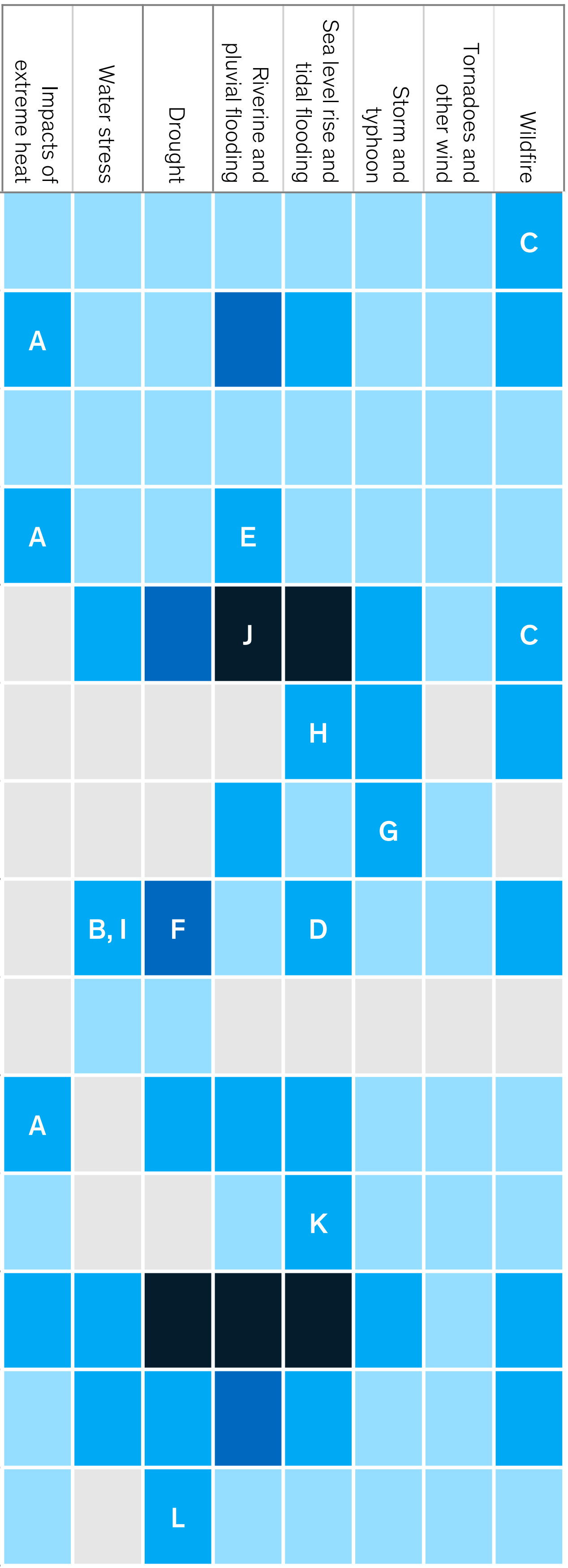
Adaptation measures for Asia vary according to specific climate hazards.

Number of use cases examined[1]

Low ■■■■ High

■ Measure not relevant to hazard

ABC Case deep dive follows



	Adaptation measures	Examples	Livability and workability: Impacts of extreme heat	Livability and workability: Water stress	Food system: Drought	Physical assets/ infrastructure services: Riverine and pluvial flooding	Physical assets/ infrastructure services: Sea level rise and tidal flooding	Physical assets/ infrastructure services: Storm and typhoon	Physical assets/ infrastructure services: Tornadoes and other wind	Physical assets/ infrastructure services: Wildfire
Diagnose risk and enable response	Build awareness	Ensure hazard maps reflect appropriate risk levels								C
	Incorporate risk	Mandate climate stress tests and disclosures	A							
	Enhance reporting	Increase transparency of risk in public reporting, asset valuations, and investment decisions								
	Plan and monitor	Institute early warning system on hazard and impact	A			E				
Protect people and assets	Harden assets	Reinforce and elevate physical assets and infrastructure				J				C
	Build green defenses	Build and restore natural defenses and ecosystems					H			
	Build gray defenses[2]	Build defenses that reduce severity or duration of climate events						G		
Build resilience	Increase backup	Identify alternate/backup sources for key inputs		B, I	F		D			
	Diversify	Utilize new maize varieties adapted for drought and pests								
Reduce exposure	Manage existing exposure	Manage retreat of physical assets in locations that cannot be sustained via asset hardening	A							
	Reduce future exposure	Carefully locate future infrastructure assets					K			
Finance and insure	Mobilize public and development finance	Use agricultural subsidies and improve access to financing to encourage climate-smart agriculture								
	Attract private capital	Create climate bonds to pay for critical infrastructure								
	Widen access to insurance	Provide climate insurance for farmers in affected areas			L					

Exhibit 20 (continued)

Adaptation measures for Asia vary according to specific climate hazards (continued).

Adaptation case studies

A. India. Ahmedabad is a city of ~7 million residents. A deadly heat wave in May 2010 that killed 300 people in a single day (and 1,344 people in total) prompted development of a heat action plan as a framework for the implementation, coordination, and evaluation of extreme heat responses in Ahmedabad (including heat alert system and cool roof strategies).

B. India. Due to climate change, natural glaciers are shrinking in the Ladakh region, which relies on melting glacier water for irrigation. Engineer Sonam Wangchuk came up with the idea to collect water from melting snow and ice in the cold months, which would normally go to waste, and store it in the form of "ice stupa" until spring, when farmers need irrigation water the most.

C. Australia. The Victoria Department of Education and Training initiated a substantial and wide-ranging review of bushfire and emergency management arrangements. One significant project was the School Bushfire Protection Project, which aimed to improve bushfire protection for students and staff at schools in a practical and timely manner. The consortium included experts in fire risk modeling, threatened species assessments, and engineering solutions for bushfire-prone locations.

D. Bangladesh. Climate change has intensified riverine and tidal flooding. Each year, when the fields flood, farmers in Charbhangura, a village of 2,500 people in the Pabna district, cannot work. The strategy is to build a floating garden using aquatic weeds as a base on which vegetables can be grown. This garden consists of a duck coop, fish enclosures, and a vegetable garden moored by rope to the riverbank.

E. Japan. As climate change increases the possibility of flooding, the Tokyo Metro is working to minimize the disruption of subway operations, preventing water ingress and minimizing damage caused by floods in the Tokyo subways using precipitation data acquired from space, as well as enhancing station facilities and emergency response for passenger safety.

F. China. In the past 10 years, increasing water shortages and frequent drought in agricultural ecosystems have caused tremendous problems with crop yield in Yunnan and Guangxi provinces. With support from scientists, farmers are using participatory plant breeding to conserve, improve, and develop new maize varieties with satisfactory yields, agronomic traits, and palatability, which are better adapted to drought and pests than modern hybrids.

G. Philippines. In 2015, the International Organization for Migration and UNICEF launched a program to enhance the network of evacuation centers in Eastern Samar, one of the provinces hardest hit by Super Typhoon Haiyan. The program will construct 2 fit-for-purpose evacuation centers that will act as protective shelters from natural hazards such as floods, typhoons, and earthquakes, and, when not in use as evacuation centers, as multipurpose centers for community-based activities.

H. Vietnam. Over the past 30 years, Vietnam has lost half of its mangrove forests, notably to make way for shrimp ponds. Mangroves act as a natural barrier against storms, sea level rise, and erosion. To reduce the pressure on mangrove forests, SNV and the International Union for Conservation of Nature jointly developed the MAM project, which restores and protects mangrove forests while enhancing smallholder livelihoods and resilience.

I. South Korea. As global warming intensifies, increasing soil erosion and water shortages are leading to declining yields in crops. NextOn, an indoor vertical farm startup, rents a deserted tunnel (closed in 2002 due to the sharp curve deemed dangerous) in North Chungcheong to build a 2,000-foot-long vertical farm, growing salads, leafy greens, and strawberries.

J. Malaysia. Kuala Lumpur has experienced an increase in flash flooding, which now occurs almost annually. Malaysia's government controls flooding through increasing river channel capacity, by building a highway tunnel, and by channeling water to holding ponds. The whole project provides storage for 3 million cubic meters of water, sufficient to prevent most of the flooding.

K. Indonesia. The country is in a race against sea level rise, which threatens to submerge swaths of its capital city, Jakarta, by 2050. The plan, announced in 2019, is to move the capital from the island of Java to the island of Borneo. The new capital is to act as the center of government, while Jakarta would remain the country's business and economic center.

L. Thailand. Farmers in northeast Thailand were suffering significant revenue losses as a result of extreme weather events and other climate impacts. Sompo Japan Nipponkoa Insurance launched a new weather index insurance product that provides compensation and/or insurance payments to farmers when temperatures and rainfall breach certain thresholds or when other extreme weather events occur.

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1. Total 50 cases researched; some cases have more than 1 measure.
2. Gray defense refers to technological and engineering solutions to improve adaptation of territory, infrastructure, and people.

Source: McKinsey Global Institute analysis

$500M–$1B

the amount of direct damage from a 1-in-100-year flood in Ho Chi Minh City by 2050

Diagnose risk and enable response

Climate risks are spatial (manifested locally), systemic, and nonstationary, and can lead to nonlinear impacts that are regressive. Given these dynamics, an appropriate analysis of exposure and vulnerability to climate risk is critical. In Ho Chi Minh City, for example, direct infrastructure damage from a 100-year flood would be very different today from what it might be in the future, because flooding of the same probability will likely be more severe. As a result, direct damage could rise from about $200 million to $300 million today to between $500 million and $1 billion by 2050 under RCP 8.5.[149] This rising and nonstationary impact indicates that investment decisions should be routinely indexed to potential future climate hazards, and planning should reflect advanced modeling of probabilities. For cities, a climate focus should be seen as an essential component of urban planning. The same applies to companies facing decisions about where to locate supply chains and how to allocate capital. Moreover, while this report focuses on physical risk, a comprehensive strategy should include an assessment of climate transition and liability risks, which will have significant impacts on some industries.

In Asia, many companies and public-sector organizations are beginning to assess their exposure. For example, the Tokyo Metro is working to minimize the disruption of its subway operations by flooding, preventing water ingress and minimizing damage caused by floods through precipitation data acquired from space, as well as enhancing station facilities and emergency response for passenger safety.[150] Another example is the heat action plan introduced by India's Ahmedabad City Corporation in response to the 2010 heat wave that killed 300 people in a single day.[151] This plan, the first of its kind in India, included building the population's awareness of the dangers of extreme heat. The city now has a seven-day probabilistic heat-wave early warning system, a citywide cool-roofs albedo management program, and teams to distribute cool water and rehydration tablets during heat waves.[152]

Yet more could be done. Much as thinking about information systems and cybersecurity has become integrated into corporate and public-sector decision making, climate change will also need to feature as a major factor in decisions. Organizations must take decisive steps to adopt new mindsets that incorporate climate risk, build the necessary tools and capabilities to be able to diagnose risks, and integrate an understanding of climate risk into all decision making.

Developing a robust quantitative understanding is complex, for the many reasons outlined in this report. Companies and communities are beginning to assess their exposure to climate risk, but much more needs to be done. Lack of understanding significantly increases risks and potential impacts across financial markets and socioeconomic systems, for example, by driving capital flows to risky assets in risky geographies or increasing the likelihood of stakeholders being caught unprepared. At the same time, opportunities from a changing climate will emerge and require consideration. These could arise from a change in the physical environment, such as new places for agricultural production, or for sectors like tourism, as well as through the use of new technologies and approaches to manage risk in a changing climate.

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[149] Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Peter Cooper, *Can coastal cities turn the tide on rising flood risk?*, McKinsey & Company, April 2020.

[150] "Using radar to scan rainclouds in 3D to protect subways from flooding," The Government of Japan.

[151] 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*, April 2014, Volume 11, Issue 4.

[152] Albedo refers to the reflectivity of a surface. Increasing the albedo of a city—through, for example, painting dark surfaces white—reduces temperature by reducing the amount of sunlight absorbed. Thomas R. Knutson, Fanrong Zeng, and Andrew T. Wittenberg, "Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth century simulations," *Journal of Climate*, November 2013, Volume 26, Number 22; Markus Huber and Reto Knutti, "Anthropogenic and natural warming inferred from changes in Earth's energy balance," *Nature Geoscience*, January 2012, Volume 5, Number 1; Ron L. Miller et al., "CMIP5 historical simulations (1850–2012) with GISS ModelE2," *Journal of Advances in Modeling Earth Systems*, June 2014, Volume 6, Number 2.

One of the biggest challenges could stem from using the wrong models to quantify risk. These range from financial models used to make capital allocation decisions to engineering models used to design structures. As we have discussed, there is uncertainty associated with global and regional climate models, underlying assumptions on emissions paths, and, most importantly, in translating climate hazards to potential physical and financial damages. While these uncertainties are non-negligible, continued reliance on current models based on stable historical climate and economic data presents an even higher "model risk."

Protect people and assets

Our analysis in chapter 1 showed that 600 million to 1 billion people in Asia could be living in areas with nonzero annual probability of lethal heat waves by 2050, and about 75 percent of global capital stock that could be damaged by riverine flooding in a given year is in Asia. That means protecting people and assets is critical.

Measures to protect people and assets typically fall into several categories: hardening assets, such as reinforcing or elevating physical assets and infrastructure; building green defenses, such as restoring natural defenses and ecosystems; and building gray defenses that reduce the severity or duration of climate events, such as disaster relief community shelters.

In 2015, the International Organization for Migration and UNICEF launched a program to enhance the network of evacuation centers in Eastern Samar, one of the Philippine provinces hardest hit by Super Typhoon Haiyan two years previously. The program facilitated the construction of disaster-resilient community buildings. The design combined international best practices with local construction technology and materials, enabling sustainable replication across the Philippines.[153]

In another example, Japanese manufacturer DISCO Corporation offers staff disaster training and has deployed tide embankments around its factories, installed backup power generators, redesigned logistics, and even secured food resources. These measures proved invaluable in 2018, when the company's Hiroshima facility was severely flooded. Despite the difficulties, operations resumed in one day.[154] In Kuala Lumpur, which typically experiences flash flooding, the Malaysian government introduced flood controls, increasing river channel capacity, building a highway tunnel, and channeling water to holding ponds. The entire project provides storage for three million cubic meters of water, sufficient to offset most flooding in a typical year.[155]

Measures to protect existing infrastructure and assets may also include the development of natural capital or green infrastructure. Mangroves, for example, act as a natural barrier to storms, sea level rise, and erosion, and can store and sequester carbon. In addition, mangrove ecosystems form a natural habitat for many aquatic and terrestrial species, and provide a source of livelihood for coastal communities. A challenge for policy makers, therefore, is to reverse established trends of mangrove destruction. Vietnam has lost half of its mangrove forests over the past 30 years, notably to make way for shrimp ponds.[156]

In some cases, initiatives are helping. SNV and the International Union for Conservation of Nature, along with other stakeholders, established the Mangroves and Markets (MAM) project, aimed at creating a sustainable shrimp aquaculture value chain that protects and increases mangrove coverage while improving yields through the use of ecological farming practices. By August 2019, the project had protected some 12,600 hectares and replanted 80 hectares in the Mekong Delta.[157]

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[153] *Building safe spaces for the community*, UNICEF Philippines and International Organization for Migration, 2018.

[154] *Corporate report 2018*, DISCO Corporation, 2018.

[155] *Special Unit for South-South Cooperation*, Kuala Lumpur, Malaysia, UNDP.

[156] Nguyen Thi Bich Thuy, *Case study: Reduced climate change resilience—the need for a new model*, SNV Netherlands Development Organisation, August 2019.

[157] *MAM-II: Scaling up ecosystem-based adaptation in the Mekong Delta*, SNV Netherlands Development Organisation.

Build resilience

Building greater resilience to climate change can result from creating alternate or backup sources to help communities, companies, and governments minimize disruption during extreme weather events. For producers, diversification of inputs, product lines, and field of operations as well as technological innovations may be necessary.

An example of creating alternatives as a tool for building greater resilience is the case of Yunnan and Guangxi provinces in Southwest China. Over the past ten years, pressure on water systems and frequent droughts have led to significant crop losses. One project to foster resilience helped farmers develop new maize varieties better adapted to drought and pests. In the case of Maharashtra, in western India, the city has suffered severe drought conditions for decades, leading to the degradation of its canal system. As a result, many districts have seen much lower agricultural yields. Tata Trusts has provided financial support to Bharatiya Jain Sanghatana, a not-for-profit organization that works to desilt and restore bodies of water. This has led to improved soil quality, higher groundwater levels, and increased crop yields.[158]

Other examples illustrate the use of technological innovation to build resiliency. The Ladakh region in India traditionally relies on melting snow and ice from the Himalayas to irrigate its fields. However, as glaciers have shrunk, water supplies have declined. The solution, developed by educator and engineer Sonam Wangchuk, is ice stupas, which are manufactured glaciers that provide irrigation throughout the year.[159] Farmers in Bangladesh have the opposite problem—too much water during the summer monsoon. The solution has been to build so-called floating gardens that rise and fall with water levels, helping local people produce food no matter the weather conditions.[160]

Reduce exposure

In the 50 case studies we investigated, this adaptation response was not commonly considered, but it could be an important measure to manage risk. As the impact of climate change grows, adapting by using some of the measures described above may become more difficult, and decision makers will need to consider reducing the exposure of communities to climate hazards. For example, as rising sea levels and regular tidal flooding manifest in wider areas, more human settlements will be affected, and the economics of adaptation could worsen over time. In addition, barriers and similar adaptation measures may face technical or other limits, such as inadequate suitable geological conditions for building the structures. Some tough decisions may be required, and preferred solutions may be impractical. In such conditions, the relocation of people and assets may be a suitable adaptation response. Another example of reducing exposure is thoughtful planning of infrastructure and assets to ensure they are located out of harm's way. This latter opportunity is particularly relevant for Asia, given the vast amount of infrastructure investment anticipated in the coming years. For example, sea defenses are particularly costly for low-lying islands.[161]

Decisions about when to protect and when to relocate will require balancing which regions and assets to spend on, how much to spend, and what to do now versus in the future. The impact on individual home owners and communities must be weighed against the rising burden of repair costs and possible post-disaster aid. Asian countries are home to some of the world's largest populations of economically disadvantaged people, many of whom are highly vulnerable to the impacts of climate change. Therefore, it is crucial for Asian countries to ensure that the most vulnerable communities are protected and that their voices are included in decision making. Asset owners could leverage cost-benefit analyses to decide whether physical resilience measures make sense. If not, in some cases, preferable adaptation strategies may include relocating and redesigning asset footprints.

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[158] *Defeating drought*, Tata Trusts, 2019.

[159] *Ice stupas: Water conservation in the land of the Buddha*, India Water Portal, 2015.

[160] *Floating gardens in Bangladesh: Technical brief,* Practical Action, The Schumacher Centre for Technology and Development, 2006.

[161] Nicholas Stern, *The Economics of Climate Change: The Stern Review*, Cambridge, UK: Cambridge University Press, 2007.

One example of large-scale exposure reduction is the Indonesian government's 2019 decision to relocate its capital from Jakarta, parts of which may be submerged by 2050, to Kalimantan in Borneo.[162]

Finance and insure

The financial aspect of the adaptation equation is particularly important because of Asia's significant infrastructure needs. Some $1.7 trillion needs to be invested in infrastructure every year if the region is to maintain its growth momentum, eradicate poverty, and respond to climate change. The Asian Development Bank calculates that about 2 percent of this total ($40 billion per year) must be applied to climate risk adaptation to meet the region's rising needs.[163]

The UN Environment Programme and the Global Commission on Adaptation have sought to estimate global adaptation spending in the next few decades. In 2016, the UN program identified adaptation costs of $140 billion to $300 billion per year for all developing countries, rising to $280 billion to $500 billion annually by 2050.[164] In 2019, the commission calculated necessary adaptation investment between 2020 and 2030 of $1.8 trillion, equivalent to less than 1 percent of projected total gross fixed capital formation in the period.[165] The anticipated investment includes many of the measures described above, ranging from strengthening early warning systems to making new infrastructure resilient, improving dryland agriculture crop production, protecting mangroves, and making water resources management more resilient.

While these are global estimates, it is important to note that adaptation costs are ultimately incurred at a local level, by individual countries, communities, and companies, and that financing of adaptation may be challenging depending on specific economic conditions.

$1.7T

amount per year estimated for infrastructure investment needs in Asia

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[162] Paige Van de Vuurst and Luis E. Escobar, "Perspective: Climate change and the relocation of Indonesia's capital to Borneo," *Frontiers in Earth Science*, January 2020.

[163] *Meeting Asia's infrastructure needs*, ADB, 2017.

[164] Anne Olhoff et al., *The adaptation finance gap report*, UNEP DTU Partnership, 2016.

[165] Manish Bapna et al., *Adapt now: A global call for leadership on climate resilience*, Global Commission on Adaptation, September 2019.

All stakeholders will need to play a role, including via public-private partnerships and participation by multilateral institutions. The private sector owns significant assets in climate-sensitive sectors, such as water, agriculture, energy, and transportation, and beyond its capital resources, the private sector is critical for its technical capabilities and capacity to innovate.[166] Conversely, as the World Resources Institute suggests, the public sector can help unlock private capital, including through reducing risk (for example, by getting involved in risky early-stage investment), directing investment, and maximizing private and public benefit (for example, helping ensure that the greatest economic and environmental benefits are generated at the lowest possible cost).[167]

Governments can leverage direct or indirect instruments to play a role. Direct instruments apply public funds, for example through loans or guarantees, to drive private-sector investment. Indirect instruments include enacting legislation that encourages private-sector involvement, creating a bond market to raise financing for projects, and facilitating the creation of multilateral funds dedicated to climate change actions.[168]

A number of innovative financial instruments have recently aimed at helping organizations adapt to climate change. Companies and governments have issued climate bonds to raise funds for projects including building Nile delta flood defenses and helping the Great Barrier Reef adapt to warming waters. Some innovative techniques are used to provide additional incentive for investors—for example, wrapping a municipal bond into a catastrophe bond, which allows investors to hold standard municipal debt without worrying about difficult-to-assess climate risk.

The Asian Development Bank Climate Investment Funds, launched in 2008, are the largest source of financing for the bank's climate change program and of concessional climate finance for the Asia–Pacific region. The funds have built a strong private-sector portfolio and at the time of writing had about $1.6 billion under management. Financing sourced from the government, multilateral development banks, and the private sector augments and leverages the financial resources donors have pledged to the funds.[169] One of its investments is the Rainwater Harvesting and Drip Irrigation for High-Value Crop Production Project in Cambodia. The project enables farmers to irrigate their farms throughout the year without having to extract water from irrigation canals, lakes, rivers, or groundwater reserves.[170]

Insurance is another important measure for adapting to climate change. Researchers estimate that just 50 percent of losses today are insured, and underinsurance is common in Asia. Insurance models suggest that if extreme events with a probability of more than 1 percent come to pass, underinsurance could be as high as 60 percent; for 0.4 percent probability events, the figure is 70 percent.[171]

The Organisation for Economic Co-operation and Development (OECD) in 2018 said that the average insurance penetration rate in OECD countries was 8.9 percent. However, three of four Asia–Pacific OECD countries did not achieve that rate, with South Korea being the exception. Similarly, most non-OECD Asia–Pacific countries did not achieve the OECD average.[172]

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[166] *Developing a private sector portfolio*, ADB and the Climate Investment Funds, 2016.

[167] *A once in a generation opportunity*, World Resources Institute, 2012.

[168] *Climate change adaptation and the role of the private sector*, Climate Action Network Europe, 2013.

[169] ADB Climate Change and Disaster Risk Management Division, *Country fact sheets*, second edition, ADB and the Climate Investment Funds, 2016.

[170] ADB and the Climate Investment Funds, *Developing a private sector portfolio*, 2016.

[171] Lucia Bevere et al., "Natural catastrophes and man-made disasters in 2018: 'Secondary' perils on the frontline," Swiss Re Institute, *Sigma*, 2019, Number 2; Global modeled catastrophe losses, *AIR Worldwide*, November 2018.

[172] "Insurance indicators: Penetration," OECD.

Without insurance as a shock absorber, recovery after disaster becomes harder and knock-on effects more likely.[173] Underinsurance, or the absence of insurance, reduces resilience. Appropriate insurance can also encourage behavioral changes by sending risk signals, for example discouraging development in certain locations. Instruments such as parametric insurance and catastrophe bonds can provide protection against climate events, minimizing financial damage, and fostering speedy recovery after disasters.

Among Asia–Pacific initiatives, Sompo Japan Nipponkoa Insurance in 2015 launched a weather index insurance product in Thailand.[174] It may, for example, pay farmers when temperatures and rainfall breach certain thresholds or when extreme weather events occur.

One challenge of insurance is the cost of premiums, which may rise as climate risks increase. Without risk reduction, risk transfer, or premium financing or subsidies, some risk classes in certain areas may become harder to insure, widening the insurance gap. Innovative approaches such as public subsidies (already in place in some circumstances) will likely be required, based on a reasonable assessment of risk and reward. The provision of insurance in particularly risky areas will require careful consideration. One approach could be to set up voucher programs to help ensure affordability for vulnerable populations, while maintaining premiums at a level that reflects the appropriate risk.

The insurance industry may also need to overcome policy duration mismatches; for example, homeowners may expect long-term stability in their insurance premiums, whereas insurers may look to reprice annually in the event of growing hazards and damages. This could also apply to physical supply chains, with the cost of insurance rising over time. Trade-offs between private and public insurance, and, for individuals, between when to self-insure or buy insurance, will need to be carefully evaluated. In addition, underwriting may need to shift to drive greater risk reduction in particularly vulnerable areas (for example, new building codes or rules regarding hours of working outside). This is analogous to fire codes that have emerged in cities in order to make buildings insurable; to be insured, parties must meet certain underwriting requirements.

Climate science tells us that some amount of warming is already “locked in.” Policy makers and business leaders will have to implement adaptation measures. In this chapter, we outlined the critical measures that decision makers could consider. However, adaptation alone will not be enough. Climate science tells us that mitigation is essential to prevent increasing climate risk. The more the world implements effective mitigation measures, the less adaptation may be necessary. In the final chapter of this report, we examine mitigation case studies, identify potential measures for Asian countries to consider, and highlight some implementation challenges and risks that will need to be overcome.

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[173] Goetz von Peter, Sebastian von Dahlen, and Sweta C. Saxena, “Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes,” *BIS Working Papers*, number 394, December 2012.

[174] *Climate Resilience and the Role of the Private Sector in Thailand: Case Studies on Building Resilience and Adaptive Capacity*, BSR, September 2015.

Boy charging electric car.
© Michael H/DigitalVision/Getty Images

4. An effective response, part 2: Mitigation

Adaptation is critical in the face of climate change that is already locked in, but it is not sufficient to prevent the buildup of climate risk. Climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions.[175] Asia has a key role to play in global mitigation efforts. Its share of global greenhouse gas emissions has grown to 45 percent in the past 30 years, from about 25 percent.[176] The Paris Agreement, the landmark global agreement on emissions reduction, aims to limit global temperature rise in this century to well below two degrees Celsius above preindustrial levels and, if possible, keep the increase to 1.5 degrees.[177] The goal of 1.5 degrees requires staying within a global carbon budget of 570 gigatons (Gt) of CO_2 from 2018.[178] One way to stay within the carbon budget requires the world to achieve 50 to 55 percent net emissions reduction by 2030 (versus 2010 levels) and net-zero emissions by 2050.[179] Given the substantial share of emissions from Asia as well as its expected economic and corresponding emissions growth, decisions made in the region today will be a critical determinant of the global emissions pathway.

Major economies in Asia, including Australia, China, India, Indonesia, Japan, and South Korea, have already set emissions targets for 2030 and beyond. Together, the six countries account for about 90 percent of Asia's emissions. One Australian goal is a 26 to 28 percent reduction in absolute GHG emissions from 2005 by 2030.[180] China aims to reach peak emissions before 2030 and to achieve carbon neutrality before 2060, according to a government announcement in September 2020. Other countries like Japan and South Korea have also recently made similar commitments.[181]

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[175] Net-zero emissions refers to a state in which total addition of greenhouse gases to the atmosphere, on an annual basis, is zero, because all emitting activities have ceased, all emitting technologies have been replaced with zero emissions technology, or remaining emissions are balanced by an equal quantity of negative emissions (for example, removing greenhouse gases from the atmosphere). For an overview of the amount of locked-in warming (called the Zero Emissions Commitment, or ZEC), the mechanics of climate stabilization, net-zero emissions, and carbon budgets, see H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1; H. Damon Matthews and Ken Caldeira, "Stabilizing climate requires near zero emissions," *Geophysical Research Letters*, February 2008, Volume 35, Issue 3; and Myles R. Allen et al., "Warming caused by cumulative carbon emissions towards the trillionth tonne," *Nature*, April 2009, Volume 458, Issue 7242.

[176] Based on AR5GWP20.

[177] *Paris Agreement*, United Nations Framework Convention on Climate Change, 2015.

[178] Our analysis draws on the work of the IPCC by using a remaining carbon budget of 570 metric gigatons (Gt) CO_2 as of January 1, 2018. Remaining within this budget would equate to a 66 percent chance of limiting warming to 1.5° Celsius. For more about the IPCC methodology and how it differs from other carbon-budget estimates (for example, 420 $GtCO_2$ for a 66 percent chance, and 580 $GtCO_2$ for a 50 percent chance), see Myles R. Allen et al., *Special report: Global warming of 1.5°C*, IPCC, 2018 and "Climate math: what a 1.5 degree pathway would take," *McKinsey Quarterly*, April 2020.

[179] "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020.

[180] Based on AR5GWP100.

[181] "South Korea joins Japan in making 2050 carbon neutral pledge," *Nikkei Asia*, October 28, 2020.

Our analysis of Asia's mitigation opportunities and challenges was built on four country- and sector-level decarbonization case studies: coal in India, steel in China, agriculture and forestry in Indonesia, and transportation in Japan. These case studies were not meant to be exhaustive; rather, the purpose was to understand current decarbonization trends, to identify potential opportunities for decarbonization, including availability and applicability of new technology, and to understand the extent and costs of transition risks associated with decarbonization. In some instances, decarbonizing a sector might require continuing to invest in new technologies that can be deployed at scale, for example the use of hydrogen for steel decarbonization. In other cases, technologies may be viable and scalable; however, other challenges and risks should be managed.

Looking at the decarbonization potential across sectors, we find that technologies can be operationally feasible and sometimes already profitable today, but their accelerated deployment is challenging given large initial capital investment requirements, particularly in cases where existing assets may be years away from depreciation. For example, in India, solar generation already has comparable operating expenditures per MWh to coal power plants, and by 2030 its operating expenditures are expected to be 20 percent lower than coal's.[182] However, purely from a financial perspective, this cost advantage is insufficient to justify replacement of coal power plants with renewable energy before the end of their life. Additionally, decarbonization efforts may result in significant disruptions to existing production and supply chains, requiring OEMs to build new capabilities and transform operations. Many Japanese automakers, for example, are already making efforts to secure access to battery cells, often in the form of joint ventures with battery suppliers. Furthermore, the livelihood of vulnerable communities could also be affected by decarbonization efforts. For example, farmers may be affected by the agricultural transition and may need support and capability building to adopt new farming practices. Given the risks associated with decarbonization, it would require action to enable the transition, for example through incentives or subsidies to drive adoption, and to minimize the impacts of transition risks, for example through capability building and financial support for affected vulnerable communities.

The good news is that, in many ways, Asia is well placed to lead mitigation efforts. Significant opportunity lies in infrastructure development, especially in power. As they build out their economies, policy makers across Asia can exploit synergies between infrastructure needs and opportunities for emissions reduction. At the same time, Asia is home to some of the world's largest and most innovative companies, and almost half of R&D investment globally takes place in Asia. Over the past decade, the region accounted for the highest share of global growth in key technology metrics—namely, technology company revenue, venture capital funding, spending on research and development, and number of patents filed.[183] Asia could build on this momentum to advance technological solutions for mitigation.

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[182] McKinsey Global Energy Perspective 2020: Reference case.

[183] See Oliver Tonby, Jonathan Woetzel, Noshir Kaka, Wonsik Choi, Jeongmin Seong, Brant Carson, and Lily Ma, *How technology is safeguarding health and livelihoods in Asia*, McKinsey & Company, May 2020.

We find four key ways to promote decarbonization in Asia based on major sources of emissions and key carbon abatement measures over the period to 2030 and to 2050 (Exhibit 21). In many respects, these actions apply to countries across the world but are particularly relevant for Asia. Major decarbonization actions for Asia to consider include the following:

- **Shifting from coal to renewable energy.** Asia is uniquely positioned to accelerate coal decarbonization given its critical mass of regional production capacity. And the impact may be large. About half of global investment in power is expected to occur in Asia by 2040, and the scale of power demand could also help drive down the cost of renewables.
- **Decarbonizing industrial operations and advancing carbon capture, utilization, and storage (CCUS).** Asia has the biggest industrial sector worldwide. The industrial sector is the largest greenhouse gas emitter in Asia, accounting for over 35 percent of the region's annual CO_2 emissions.[184] In particular, Asia generates about 80 percent of global CO_2 emissions in the steel and cement industries.[185] Consequently, structural shifts within these two industries in Asia are critical to success in decarbonizing the world's industrial sector.
- **Transforming agriculture and forestry.** Decarbonizing agriculture in Asia and preventing deforestation are a significant mitigation opportunity; agriculture and deforestation combined account for 10 percent of CO_2 emissions in Asia and over 40 percent of CH_4 emissions. Given that Asia is the world's biggest breadbasket, producing about 90 percent of rice and at least 30 percent of corn and wheat, and has massive reforestation potential, the decarbonization efforts in agriculture and forestry could have a big impact on emissions.
- **Electrifying our lives and decarbonizing road transportation and buildings.** More than 30 percent of global GHG emissions from transportation and buildings comes from Asia.[186] At the same time, Asia is a leader in technology to decarbonize the sector, such as electric vehicles and fuel cell vehicles (FCVs).

But the challenges are very real, and Asia faces some unique challenges. For example, in the case of coal, the transition to renewables must take into account recent large-scale investment in newly built coal plants. In this chapter, we highlight each action and case study in more detail. At the end, we bring these insights together with a focus on Japan, to illustrate what a mitigation strategy, including required emissions reductions by carbon-emitting sectors, may be like for an individual country.

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[184] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019; EDGAR 2015; FAOSTAT, FAO, 2015.

[185] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019.

[186] Based on AR5 GWP20.

Exhibit 21

Asia has unique decarbonization opportunities across key carbon-heavy sectors.

Total Asia GHG emissions, 2016, $MtCO_2e$[1]

Low ░ ▒ ▓ █ High

	By sector							Total emissions		
Country[2]	Power	Industry	Agri-culture	Defores-station	Trans-portation	Buildings	Waste	CO_2	Non-CO_2	GHG
China	4,023	7,732	1,689	4	970	628	1,017	10,338	5,726	16,064
India	1,060	1,327	1,912	34	288	141	758	2,249	3,271	5,520
Indonesia	181	742	456	1,115	147	26	237	1,630	1,274	2,904
Japan	484	422	64	0	244	118	31	1,214	148	1,363
Australia	188	512	290	10	111	15	88	441	773	1,215
Pakistan	43	183	470	0	50	19	90	192	662	854
South Korea	279	233	37	0	153	53	46	675	127	803
Thailand	93	220	186	15	92	7	59	320	352	672
Myanmar	7	44	226	321	5	4	28	345	289	635
Vietnam	78	209	193	3	42	12	60	233	364	597
Malaysia	106	199	24	52	73	5	46	288	218	506
Philippines	54	77	176	1	38	6	81	130	304	435
Bangladesh	34	76	226	5	12	9	71	86	348	434
New Zealand	3	19	111	1	18	2	18	37	134	171
Total	**6,634**	**11,995**	**6,061**	**1,561**	**2,242**	**1,046**	**2,631**	**18,178**	**13,992**	**32,170**

Key statistics	Power emits **~20%+** of GHGs. **~90%** of power emissions in Asia are from coal (vs ~70% globally).	Industrial GHGs per unit of GDP in Asia are **~60%** higher than global. Asia emits **~80%** of global CO_2 emissions in steel and cement.	Asia agriculture and deforestation emit **20%+** of GHGs. Agriculture emits **~20%** of global methane emissions.	**1/3** of global transportation and buildings' GHGs come from Asia.
Key dicarbon-ization areas	**Shift from coal to renewable energy in power mix.** Critical mass of regional production capacity and scale to drive down costs of renewables (eg, ~50% of global power investment by 2040 expected in Asia).	**Decarbonize industrial operations and advance CCUS.**[3] Biggest industrial sector worldwide (eg, China alone accounts for ~50% of global steel production). Rapid investment and large carbon storage potential for CCUS.	**Transform agriculture and forestry.** Major breadbaskets for global crop production (eg, ~90% of rice, 30%+ of corn/wheat from Asia). Significant reforestation potential (~45GtCO_2 could be absorbed).	**Electrify daily life to decarbonize road transportation and buildings.** Technology leadership especially in EVs/FCVs (eg, dominant global share of EVs/batteries, governmental initiatives to accelerate FCV adoption).[4]
Example challenges for Asia	**Large share of newly built plants.** Decarbonization heavily depends on age profile of country's power plants; significant capital expenditures required to retire newly built plants in Asia and decarbonize.	**Dominant global share in steel and cement.** Scaling new solutions (eg, CCUS, hydrogen, bioenergy) is required to accelerate decarbonization and still meet global production demand.	**People's high dependency on agriculture.** Securing livelihoods of people dependent on agriculture while decarbonizing the sector is required.	**Massive infrastructure investment.** A challenge exists to scale significant infrastructure required to shift from ICEs to BEV/FCVs.

1. Greenhouse gases. Non-CO_2 emissions converted into CO_2e using AR5GWP20 values.
2. The objective of this heat map is to show the largest emitting country-sectors in the region, so Cambodia and Laos are not included. The 14 countries included here account for >95% of total GHGs in the region.
3. Carbon capture, utilization, and storage.
4. Electric vehicles, fuel cell vehicles.

Note: Figures may not sum to 100% because of rounding.

Source: EDGAR 2008, 2015; FAOSTAT, 2015; McKinsey Global Energy Perspective 2019: Reference case, McKinsey Energy Insights, 2 019; McKinsey 1.5C Scenario analysis; McKinsey Global Institute analysis

Shifting from coal-powered energy to renewables

The Asian power sector accounts for more than 35 percent of the region's CO_2 emissions (compared to about 30 percent globally), and about 90 percent of Asian power emissions come from coal (compared to 70 percent globally).[187] Still, about half of global power investment by 2040 will be in Asia, putting the region in a unique position to lead mitigation efforts in the energy sector.[188] Energy demand in Asia is expected to rise, with increasing levels of development, growing population, and potentially greater need for air-conditioning as the climate changes. The good news is that a shift to renewables is already under way. China is already the largest renewable market worldwide (more than 750GW of a total 2,500GW global capacity), and its investment in renewable power and fuel in 2018 accounted for 47 percent of global total investment.[189]

To understand the opportunities and challenges surrounding a shift from coal to renewables, we look more closely at India's power sector. Coal accounts for about 75 percent of India's electricity generation, but is responsible for more than 90 percent of CO_2 emissions in the power sector. India's demand for energy is only expected to grow, surpassing China's by 2050.[190] India's challenge over the next few decades is to reduce its reliance on coal while continuing to meet its growing energy needs in a manner which is affordable to the broadest section of population.

By 2030, in our reference case based on McKinsey Energy Insights, we expect coal in India to account for 60 percent of power generation, declining to one-fifth by 2050 as solar and wind grow rapidly.[191] Even after that, coal would still be the third-largest source of energy.

Here we consider two alternative scenarios for accelerated decommissioning of subcritical coal power plants by 2030 and by 2050. We estimate the potential impact of these scenarios on CO_2 emissions and the investment required.

Half

of global power investments will be in Asia by 2040

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[187] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019; EDGAR, 2015; FAOSTAT, FAO, 2015; "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020.

[188] Based on the Current Policies Scenario from the World Energy Outlook, which provides a baseline for the analysis by considering only the consequences of existing laws and regulation. It excludes the effects of stated ambitions and targets that have not yet been translated into operational laws and regulations. *World Energy Outlook 2019*, International Energy Agency, 2019.

[189] International Renewable Energy Agency, *Renewable capacity statistics 2020*, March 2020; BloombergNEF; BP, *BP statistical review of world energy 2019*, 2019.

[190] The Global Energy Perspective reference case describes major transitions in the global energy landscape, such as the rise of renewables, a move towards electrification, and shifts in the thinking on climate change and decarbonization. This outlook is based on contributions from hundreds of McKinsey experts from around the world, from fields including oil and gas, automotive, renewable energy, and basic materials. Through this global network, McKinsey's Energy Insights team is able to incorporate a diverse set of views into one consensus reference case; *World Electricity Statistics*, Enerdata, 2020.

[191] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019.

Total capacity for subcritical coal plants is 150GW; about 50GW, roughly one-third of total capacity, is more than 20 years old, or halfway through their useful life. Of the 50GW, we assume a little over one-half (~30GW) will remain until 2030 (for the other ~20GW, after the natural retirement of power plants reach their end of life by 2030). On that basis, we consider the following scenarios:

- **Scenario 1.** Thirty gigawatts of additional subcritical coal capacity to be decommissioned by 2030 (90GW decommissioned by 2050). Here we assume the decommissioning by 2030 of remaining plants over 20 years old today (and 60GW of additional decommissioning by 2050, as the period from 2030 to 2050 is twice as long as from today to 2030).
- **Scenario 2.** Sixty gigawatts of additional subcritical coal capacity to be decommissioned by 2030 (112GW decommissioned by 2050). We assume the decommissioning of 60GW plants over ten years as of today by 2030 and of all the remaining capacity (assumed to be approximately 50GW) by 2050.

We calculate that by 2030, about 170 $MtCO_2$ could be abated in scenario 1, and in scenario 2, about 340 $MtCO_2$ compared to 2030 emissions in our reference case (Exhibit 22).[192] In addition, compared to CO_2 emissions from the India power sector in 2017 (over 1,000 $MtCO_2$), both scenarios would significantly minimize the net increase in CO_2 emissions by 2030. By 2050, even in the reference case, CO_2 emissions would decrease compared to 2030, but both scenarios would lead to a major reduction above and beyond that. In particular, scenario 2 would result in about a 50 percent reduction in CO_2 emissions compared to 2017 levels.

India has already taken initial steps toward deployment of renewable hybrid systems, combining solar and wind with additional resources such as battery storage or pumped hydro storage. Our McKinsey Energy Insights model indicates that the levelized cost of energy (LCOE) of renewable hybrid systems could be competitive compared to opex of coal fired plants by 2030. According to our calculations, both scenarios would further improve the average operating expenditures perGWh, with the scale benefits from more renewable deployment.

However, there are many challenges. While there are manifest climate benefits in accelerating the switch to renewables, significant costs and socioeconomic impacts would need to be managed to enable a successful transition.

First, consider investment needs. We calculate that the two scenarios would require a high level of up-front investment, including for renewables (solar and wind), battery storage, and decommissioning of coal fired plants.[193] By 2030, incremental cumulative initial investment relative to our reference case could amount to $110 billion to $220 billion, depending on the scenario. Between today and 2050, the scenarios would require an additional $210 billion to $310 billion compared to the reference case. This number includes not only the capital expenditures to deploy renewables and energy storage, but also the financial cost that would need to be paid to coal asset owners for decommissioning their plants before the end of their asset lifetime (assumed to be 15 to 20 percent of the entire cost). Although the total incremental cost would decline as the cost of renewables and energy battery storage falls, accelerating coal retirement and renewables deployment would still require financial incentives or government aid to compensate for financial costs associated with early retirement of coal assets.

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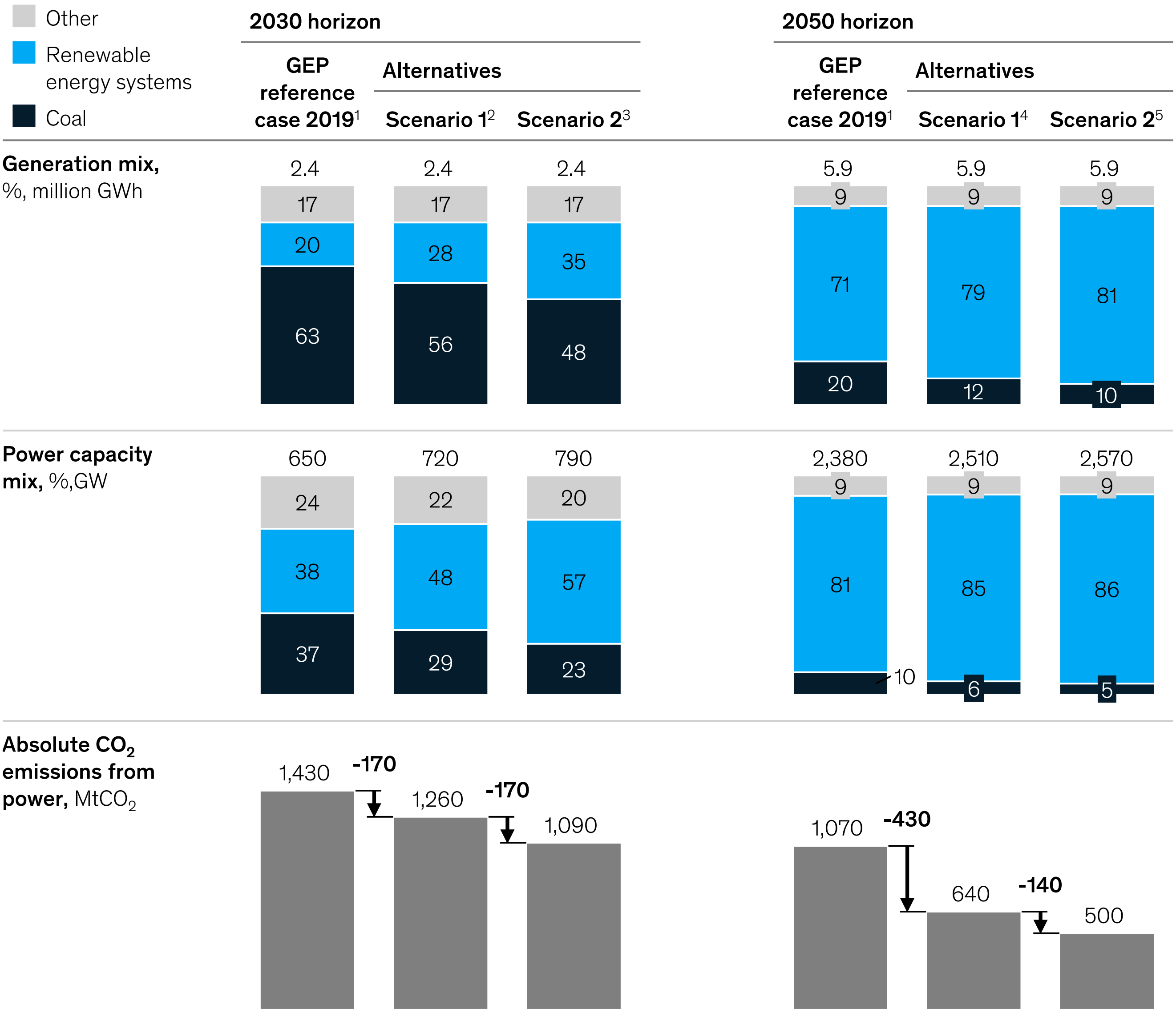
[192] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019.

[193] Based on projected capital expenditures for renewables in 2025 and in 2040 as an average year of plant construction commencement for 2030 and for 2050 scenario. Assume 138MW of storage is required to replace 100MW of coal with renewable energy sources. Physical costs of coal decommission (assuming approximately $115 million/GW) are determined by a variety of factors such as the extent of environmental remediation required to meet the desired end state, the physical location of the plant, and the potential salvage value of equipment and scrap. Financial costs of coal decommission (assumed to be roughly $355 million/GW) include our estimation of the present value of the coal power plants to be decommissioned for the period that has to be unserved and needs to be paid in compensation.

Exhibit 22

Alternative scenarios for decarbonizing the coal industry in India lead to significant reductions of emissions but require substantial up-front capital expenditures.



	2030 horizon: GEP reference case 2019[1]	Scenario 1[2]	Scenario 2[3]	2050 horizon: GEP reference case 2019[1]	Scenario 1[4]	Scenario 2[5]
Required initial investment, $ billion[6]	–	+110	+220	–	+210	+310
Average operating expenditures, $ per GWh[7]	8,540	8,450	8,360	6,000	5,570	5,480

1. *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019; describes major transitions expected in the global energy landscape (eg, renewables, electrification, and shifts in thinking on climate change and decarbonization).
2. Assumes 30GW of additional subcritical coal capacity to be decommissioned by 2030.
3. Assumes 60GW of additional subcritical coal capacity to be decommissioned by 2030.
4. Assumes 90GW of additional subcritical coal capacities to be decommissioned by 2050.
5. Assumes 112GW of additional subcritical coal capacities to be decommissioned by 2050.
6. Incremental initial investment to baseline case (GEP reference case 2020); includes capital expenditures for renewables, physical, and financial costs of coal decommissioning. In scenario 1, 30GW of additional subcritical coal capacity to be decommissioned by 2030 (90GW decommissioned by 2050). In scenario 2, 60GW of additional subcritical coal capacities to be decommissioned by 2030 (112GW decommissioned by 2050).
7. Weighted average operating expenditures per GWh of coal, solar, and wind power generation.

Note: For both scenario 1 and 2, a combination of solar/wind power and battery storage would be installed to balance the reduction of coal capacities. Figures may not sum to 100% because of rounding.

Source: *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019; McKinsey Global Institute analysis

On top of massive investment required for the two scenarios, accelerated shifts from coal may precipitate transition risks such as a potential increase in electricity prices and labor shifts.

Consider energy prices. While accelerated deployment of renewable energy is operationally profitable and comes with reduced operating expenditures perGWh, the massive initial investment required to replace coal with renewables could drive electricity prices up. Therefore, the operational benefits of our alternative scenarios would not be enough to cover the initial investment. As a result, without government support, electricity prices could well rise.

Job impacts could also be substantial. There were half a million coal miners in India in 2019, together with many jobs connected with the industry indirectly. Although investment in renewables implies job creation, reemployment of coal-dependent workers in the renewables sector would be challenging. For example, most coal mining areas in India are not suitable for wind-power generation. Still, by 2030 and by 2050 the impact could be mitigated, for example by reducing coal imports (India imports approximately 20 percent of the overall coal it uses) or providing education and training to help workers shift industries.[194]

Finally, challenges from a technical standpoint would also need to be overcome. It will be important to design the overall grid system for performance and stability (for example, addressing challenges related to the daily and seasonal presence of sunshine or wind). Investment would be required to integrate renewables with existing networks and develop ancillary services to maintain load (including generation balance or frequency control), voltage, and transmission reserves. Beyond switching to renewables, another technological solution would be to retrofit coal plants with either biomass or carbon capture and storage. However, doing so at scale may be challenging because of the high capital costs involved and the limited availability of biomass globally. Overcoming the challenges and risks described would require private-sector and government action and support.

18%

the amount of China's CO_2 emissions coming from the steel industry

Decarbonizing industrial operations and advancing carbon capture, utilization, and storage

The single largest source of greenhouse gas emissions in Asia is the industrial sector, accounting for over 35 percent of the region's annual CO_2 emissions.[195] Furthermore, industrial GHG emissions per unit of GDP in Asia are about 60 percent higher than the global average.[196] Steel and cement are the top two sectors in emissions, accounting for about 70 percent of total industrial emissions in 2016 in Asia. We focus here on the decarbonization of China's steel industry.

The Chinese steel industry produces 50 percent of the world's steel.[197] It accounts for about 18 percent of China's CO_2 emissions. However, demand is declining. Construction industry demand in China is expected to drop by 2030 due to a slowdown in urbanization and a saturated real estate market.[198]

China's steelmakers are gradually shifting away from the traditional heavy-coal-burning basic oxygen furnace, which accounted for 89 percent of steel produced in 2019, to much greener electric arc furnace (EAF) production. As of 2020, average EAF CO_2 emissions in China were 0.6 to 0.7 ton of CO_2 per ton of steel, compared to 2.0 tons of CO_2 in the basic oxygen furnace. However, due to cheap coal prices, the transition to EAF in China is progressing at a slower pace than in the European Union or the United States, where it accounts for 66 percent and 75 percent of production, respectively.[199] Nonetheless, the EAF share of steel production in

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[194] Worldometer, 2016.

[195] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019: EDGAR, 2015; FAOSTAT, FAO, 2015.

[196] Based on AR5GWP20.

[197] Steel Institute VDEh, 2017; McKinsey Basic Materials Institute.

[198] China Iron and Steel Association; World Steel Association; McKinsey BMI China Steel Demand Model.

[199] Shaohui Zhang et al., "Integrated assessment of resource-energy-environment nexus in China's iron and steel industry," *Journal of Cleaner Production*, September 2019, Volume 232, pp. 235–49.

China is set to increase from less than 10 percent in 2017 to about 18 percent by 2030 and 50 percent by 2050, under a current-trajectory scenario.[200]

Along with adoption of EAF and renewable energy, a shift to cleaner iron, such as scrap instead of pig iron, is critical to reducing emissions from iron ore use and achieving decarbonization. Global analysis shows 72 percent of direct fossil fuel combustion in the steel industry is from pig iron production, but scrap usage is increasing. China's steel scrap supply is expected to rise from 163 Mt in 2015 to 355 Mt by 2030 as the country's products and infrastructure enter the replacement phase.[201] Moreover, the government is considering lifting an import ban on scraps.[202]

Looking forward, other technologies could also play a role in decarbonizing the steel industry. They include green hydrogen, biomass metallurgy, and carbon capture, use, and storage. They are not yet available at scale but offer potential, particularly after 2030.

Hydrogen metallurgy refers to using hydrogen, instead of coal, to produce direct reduced iron, which can replace emissions-intensive pig iron. There are two main methods of producing hydrogen, gray and green. Gray implies production of hydrogen from hydrocarbons, mainly natural gas. This method is mature and available at the industrial level elsewhere, but not in China, which does not have large reserves of natural gas. Green hydrogen is obtained from water electrolysis powered by renewable energy, and currently can be produced only on a small scale.

Biomass metallurgy uses biomass as a fuel, thus reducing the consumption of coal. There are two main types of biomass feedstock: wood and agricultural residues, and dedicated crops such as sugar, energy cane, and pyrolyzed eucalyptus. Biomass harvesting that does not involve deforestation can reduce total carbon emissions. However, biomass resources are regionally dependent and not pervasive in China.

Carbon capture, use, and storage has significant decarbonization potential, but the technology is also among the least mature measures available. Geographically, China has huge potential for CCUS. Its onshore and offshore basins have a total estimated theoretical CO_2 geological storage capacity of 3,088 gigatons, including a storage capacity of 3,066 gigatons for deep saline formations.[203] Still, long-term storage presents challenges (for example, safely transferring carbon emissions to designated locations and side effects such as leaving carbon waste for future generations and the danger of leakage) and the technology has not yet rolled out at scale.

An assessment of decarbonization costs and emissions reduction potential suggests that by 2030, ongoing structural shifts (based on McKinsey's BMI China Steel Demand Model)—namely reductions in demand, improved energy efficiency, and increased usage of scrap EAF production—will be key decarbonization measures (Exhibit 23).[204] On the current trajectory, this could lead to annual reduction of 370 $MtCO_2$ from current levels of about 1,720 $MtCO_2$ by 2030. A scenario based on accelerated deployment of EAF would create a 440 $MtCO_2$ reduction. But looking forward, advancements in green hydrogen technology, CCUS, and lower HDRI–EAF costs will also be critical for the decarbonization of the steel industry by 2050.[205]

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[200] McKinsey BMI China Steel Demand Model.

[201] Ibid.

[202] "China urged to end steel scrap import ban," *Argus Media*, November 5, 2019.

[203] Xiaochun Li et al., "CO_2 point emission and geological storage capacity in China," *Energy Procedia*, February 2009, Volume 1, Issue 1.

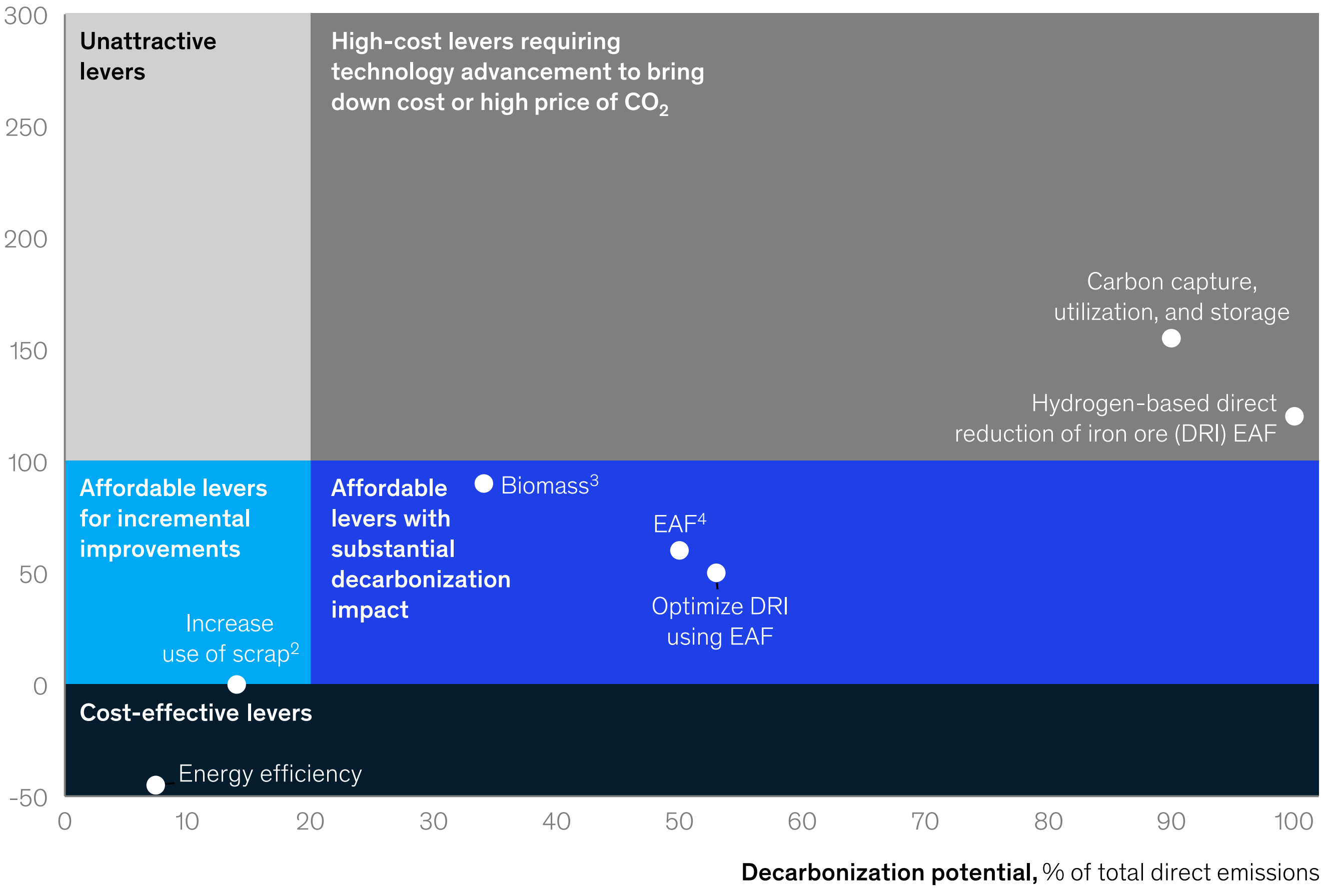
[204] Include both capital expenditures and operating expenditures for each decarbonization lever.

[205] Hydrogen-based direct reduction of iron ore (HDRI)-EAF for steel production.

Exhibit 23

While China's steel industry has decarbonization opportunities, some levers are also high-cost and need further technology advancement.

Decarbonization cost, \$ per tCO_2[1]



1. Abatement cost vs blast furnace-basic oxygen furnace route.
2. Decarbonization cost of increased use of scrap depends on price differences between iron ore and scrap.
3. Potential without upgrade of coal power plants; 35% decarbonization potential is defined by maximum share of biomass in coal power plant fuel. Biofuel power plants that operate on biomass exclusively have decarbonization potential of 100%.
4. Depending on availability of scrap; unlikely that industry-wide potential is 50%.

Note: These numbers are global and not Asia-specific.

Source: Decarbonization Pathway Optimizer; McKinsey Global Institute analysis

Each new technology has its own challenges to scale and become operationally viable in China. The decarbonization of the steel industry requires overcoming those challenges while maintaining production volumes. Shifting production to using EAF or biomass comes with significant decarbonization potential, but still at a cost, as shown in Exhibit 23. Moreover, the next wave of decarbonization technologies in the industry, for example CCUS and hydrogen, have even higher costs. Implementing these technologies will require near-term capital investment by steel manufacturers, which, in an industry with low margins, could prove challenging. For China, securing at-scale hydrogen supply could also prove challenging. Without a direct tax stimulus policy or other support, CCUS projects will have difficulty becoming economically viable. Most policies concentrate on the storage component of CCUS and neglect capture and transportation, which are also critical to scale the technology at an economically feasible level.

Looking more closely at hydrogen, hydrogen-based steel production using EAF is most technically feasible and already considered to be part of a potential long-term solution for decarbonizing the steel industry at scale. However, implementation carries a variety of challenges and risks. We identify a number of external factors that will shape future development and time to adoption of green hydrogen–based steel.[206] These include: the need for a significant capacity increase in electricity from renewables; the availability of green hydrogen on an industrial scale; changes in raw materials; new production technology; demand for hydrogen-based steel; and financing and access to capital.

Transforming agriculture and forestry

40%

the share of Asia's CH_4 emissions from agriculture and deforestation

Agriculture and deforestation through burning and clearing account for over 10 percent of CO_2 emissions in Asia and 40 percent of CH_4 emissions. India and China account for more than half of Asia's methane emissions. Furthermore, methane emissions from agriculture alone in Asia account for almost 20 percent of global total methane emissions.

Several critical measures would reduce emissions in agriculture, including a dietary shift (reducing the share of ruminant animal protein in the protein-consumption mix, which would lower the number of animals raised, in turn cutting methane emissions) and new farming practices such as dry direct seeding for rice and improved rice paddy water management.[207]

Meat production from beef and lamb is the most GHG-intensive food production, with production-related emissions more than ten times those of poultry or fish. This is due to enteric fermentation inherent in the digestion of animals such as cows and sheep.[208] Reducing consumption of beef and lamb and replacing them with less carbon-intensive protein sources (mostly legumes, poultry, and fish) are the most significant measures by far to achieve desired emissions reduction targets.[209]

Sustainable forestry, which may be defined as maintaining current levels of tree cover by replacing felled trees, is vital to enable absorption of CO_2 from the atmosphere and stop climate change. According to one estimate, annual tree cover loss in Asia amounted to about 63,000 square kilometers in 2016, equivalent to the size of Sri Lanka. Conversely, the total area of reforestation potential is approximately 90 million hectares, which could potentially absorb up to about 45 Gt of CO_2 emissions.[210] Promoting sustainable forestry will require thoughtful land use decisions about urban land, agriculture, forests, and other uses. At the same time, agriculture and forestry are a critical source of employment in the region, meaning mitigation efforts in the industry need to be carefully managed to minimize impacts. According to the International Labour Organization, agriculture and forestry account for 25 percent of China's total employment, 40 percent of India's, and 30 percent of Indonesia's. Here we look more closely at food supply chains and forest management in Indonesia.

Agriculture and forestry play a significant role in Indonesia's economic growth and development. The agricultural and forestry sector contributes 13 percent to national GDP and represents one-third of overall jobs.[211] Agriculture alone accounted for about 15 percent of national GHG emissions in 2016 and deforestation 39 percent.[212] Emissions from agriculture mainly came from rice cultivation, manure management, and enteric fermentation, which

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[206] Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, *Decarbonization challenge for steel*, McKinsey & Company, 2020.

[207] Most rice cultivation systems involve growing seedlings in a separate nursery and transplanting them into flooded paddies. By contrast, dry direct seeding entails sowing seeds directly into dry rice paddies. This method reduces by a month the time a field needs to be flooded, limiting the activity of methane-producing microorganisms and cutting emissions. Several practices could reduce methane emissions in rice paddies relative to what is observed in the continuous flooding systems used most widely across the world. Alternate wetting and drying, single-season drainage, and other methods can increase nitrous oxide emissions.

[208] Enteric fermentation is a digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

[209] Justin Ahmed, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, *Agriculture and climate change: Reducing emissions through improved farming practices*, McKinsey & Company, April 2020.

[210] Jean-Francois Bastin et al., "The global tree restoration potential," *Science*, July 2019, Volume 365, Issue 6448.

[211] "Indonesia: Share of economic sectors in the gross domestic product (GDP) from 2008 to 2018," Statista, 2020; "Employment in agriculture (% of total employment) (modeled ILO estimate)," World Bank, 2019.

[212] *McKinsey Global Energy Perspective 2019: Reference case*, McKinsey Energy Insights, 2019; Emissions Database for Global Atmospheric Research (EDGAR), 2008, 2015; FAOSTAT, FAO, 2015. Based on AR5GWP20.

were responsible for 65 percent of total agricultural GHG emissions.[213] And agriculture and deforestation are connected. Many deforestation activities involve setting illegal forest fires to clear land, especially for palm oil. From 2001 to 2018, Indonesia lost 25.6 million hectares of tree cover in primary forests, equivalent to a 16 percent decrease in tree cover.[214] Notably, Indonesian agriculture is also at risk from a changing climate, as previously discussed.

The Indonesian government in 2015 joined countries that submitted their post-2020 climate pledges, known as Intended Nationally Determined Contributions, to the United Nations Framework Convention on Climate Change. Indonesia is targeting a 29 percent reduction in emissions by 2030, or 41 percent with international support.[215] However, achieving these major changes may be difficult for agriculture, which lacks clean technology that can significantly reduce emissions. Agriculture is also significantly less consolidated than other sectors—the average size of 93 percent of farms is 0.6 hectare. This fragmentation means that driving change can be challenging, as it requires action on the part of multiple stakeholders.[216] Finally, the agriculture sector has a complicated set of priorities in addition to climate goals, including biodiversity, nutritional need, food security, and the livelihood of farmers and farming communities.

Based on the top three contributors to Indonesia's agriculture GHG emissions—rice cultivation, manure management, and enteric fermentation—we find six cost-efficient measures with high $MtCO_2e$ mitigation potential (these are measures related to agricultural production, vs. other measures like diet shifts, that entail shifts in consumer behavior).[217] Three are in cultivation of rice, which has a significant socioeconomic impact in Indonesia, and three in meat production (Exhibit 24).[218] Evaluated according to global abatement costs, four of the six measures result in cost savings.[219] Abatement measures that come at significant cost (such as zero-emissions farm equipment) are not considered. While our discussion focuses on agriculture, it is also important to note that for Indonesia to achieve its decarbonization targets, efforts would need to expand to other sectors, including waste management and restoration of carbon sinks (see Box 4, "Decarbonization beyond the Indonesian farm").

Rice production is the largest contributor to Indonesia's agricultural emissions. The three most effective decarbonization measures in rice cultivation are improved fertilization, improved rice paddy management, and dry direct seeding.

One of the most promising decarbonization measures may be to improve fertilization practices. That is because the warm, waterlogged soil of flooded rice paddies provides ideal conditions for bacterial processes that produce methane, most of which is released into the atmosphere.[220] Farmers who adopt improved fertilization practices can reduce methane emissions from rice cultivation by about 40 percent.[221] Sulfate-containing fertilizers (such as ammonia sulfate) and sulfate amendments (such as gypsum) can inhibit methane-producing bacteria in fields, thus reducing the amount of methane released.

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[213] FAOSTAT, FAO, 2019.

[214] *Global Forest Watch*, World Resources Institute, 2020.

[215] *National Action Plan for greenhouse gas emissions reduction (RAN-GRK)*, Republic of Indonesia, Presidential Decree number 61/2011, 2011. The plan considers potential global warming on a 100-year timescale. Based on AR5GWP100.

[216] Prashant Gandhi, Somesh Khanna, and Sree Ramaswamy, "Which industries are the most digital (and why)?," *Harvard Business Review*, April 1, 2016, hbr.org.

[217] These costs are based on a global cost curve. While the exact cost for Indonesia may vary, the global cost curve provides an indication of mitigation strategies Indonesia may pursue.

[218] Although abatement costs are generalized from our analysis and not specific to Indonesia, we believe they provide a useful guide for each measure.

[219] *Agriculture and climate change: Reducing emissions through improved farming practices*, McKinsey and Company, April 2020.

[220] Ronald L. Sass, "CH_4 emissions from rice agriculture," in *IPCC good practice guidance and uncertainty management in national greenhouse gas inventories*, IPCC, 2003.

[221] Bruce A. Linquist et al., "Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis," *Field Crops Research*, August 2012, Volume 135.

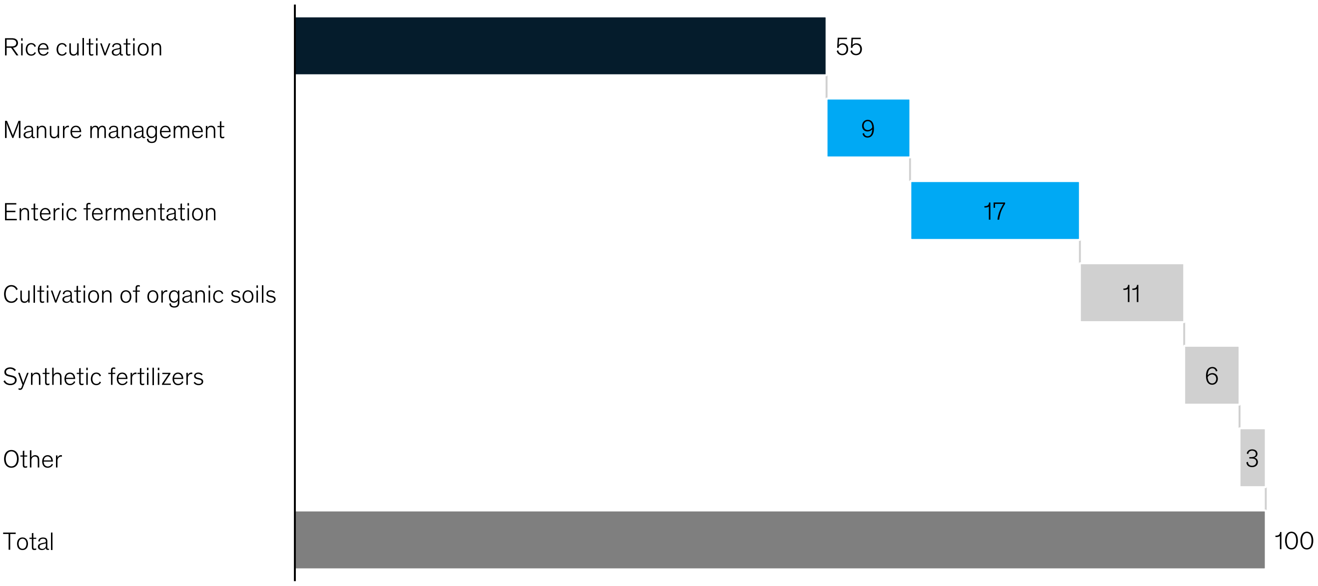
Exhibit 24

GHG-efficient farming practices could help Indonesia not only to decarbonize but also to achieve considerable cost savings.

Case: Indonesia agriculture and deforestation

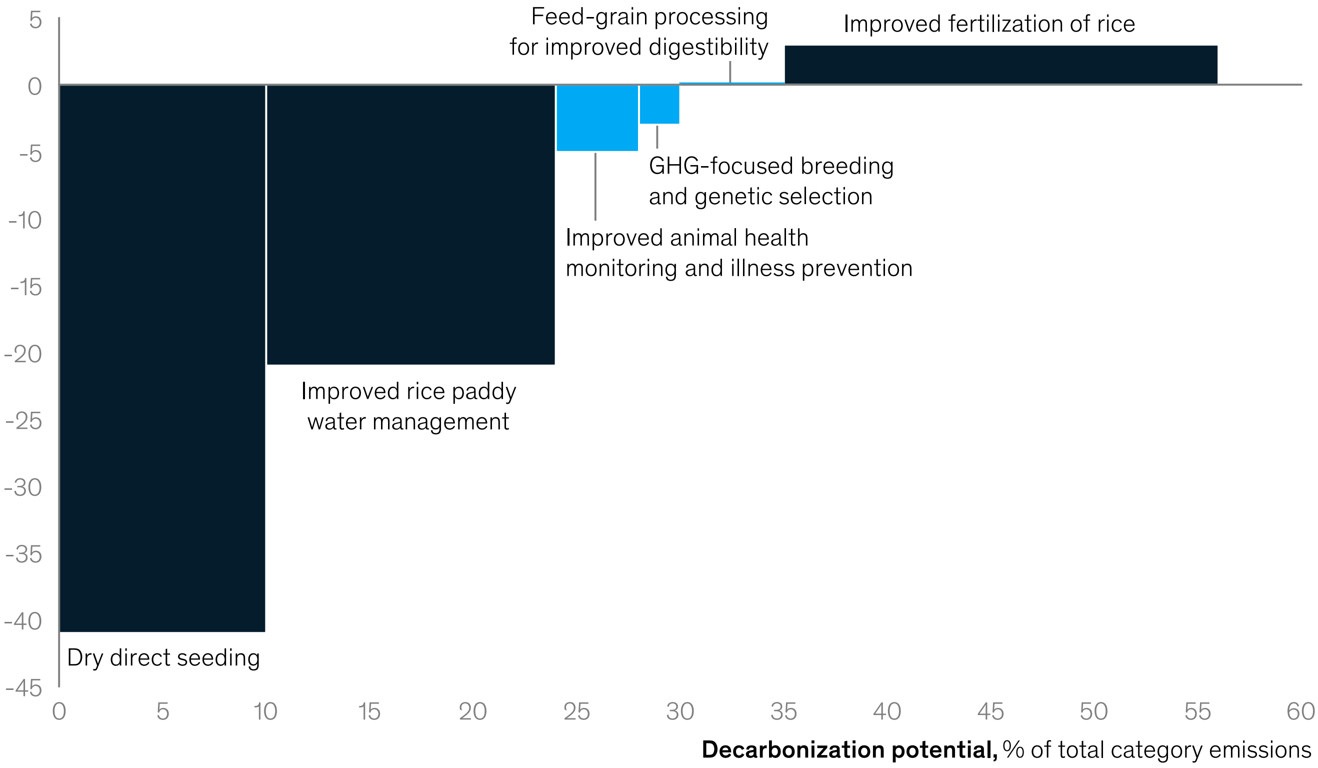
■ Rice
■ Animal protein

Structure of Indonesia's GHG emissions from agriculture (excl energy), 2016, %[1]



We focus on 6 cost-efficient farming practices with significant GHG mitigation potential for top contributors of agricultural emissions in Indonesia

Global GHG abatement cost, 20-year IPCC Fifth Assessment Report (AR5) global warming potential values, $/tCO$_2$e



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1. 20-year AR5 global warming potential values. For further details see *Agriculture and climate change: Reducing emissions through improved farming practices,* McKinsey & Company, April 2020.

Note: Figures may not sum to 100% because of rounding.

Source: FAOSTAT, 2019; McKinsey Global Institute analysis

Several practices could reduce methane emissions in rice paddies, relative to what is observed in the continuous flooding systems used most widely across the world. Alternate wetting and drying, single-season drainage, and other methods can increase nitrous oxide emissions. This adverse impact is significantly offset by direct methane-emissions reduction. Challenges include payment and financing schemes (typically flat rates paid to irrigation agencies that are not tied to water use volume and therefore carry little financial incentive to reduce water consumption), regional rainfall patterns (too much rain inhibiting ability of fields to dry), and field characteristics (land must be level to control water flow). Expansion of laser land leveling technology can be a game changer because in a level field, water is distributed evenly, reducing the amount of time and volume of water needed for irrigation. In the northern Indian state of Uttar Pradesh, laser land leveling allowed farmers to reduce irrigation water use by 25 percent and save on energy use.[222] Water pricing policies could further shift the economics in favor of improved water management.

Finally, expanding adoption of dry direct seeding could reduce the time for which a field needs to be flooded, limiting the activity of methane-producing microorganisms and cutting emissions by approximately 45 percent per hectare.[223]

Meat production is the second largest GHG contributor in Indonesia's agriculture sector. The three most effective decarbonization measures in animal production are employing greenhouse gas–focused genetic selection and breeding, improving animal health, and improving the digestibility of grains.

The most effective measure to decarbonize in this area is to employ GHG-focused genetic selection and breeding. Genetic selection and breeding programs focused on ruminant animals' enteric fermentation could significantly reduce overall emissions by 2050.[224] Research shows that about 20 percent of a ruminant's methane emissions rate stems from genetics alone.[225] In single herds, intentional breeding for methane efficiency has achieved variation in methane production of about 20 percent.

By improving the health of livestock, farmers could increase productivity and reduce animal mortality due to disease. The ability to meet the world's projected animal protein demand with fewer, healthier animals could reduce emissions from enteric fermentation, manure left on pasture, and manure management.

Finally, improved digestibility of feed grains could cut emissions. Mechanical processing, such as steam flaking, improves the starch digestibility of grain for large ruminants.

Ensuring that agriculture, forestry, and land-use change in Indonesia, as elsewhere, meet emissions targets aligned with a 1.5 degree Celsius pathway will require substantial changes—specifically, what is eaten, how much food is wasted, how food is produced, and how forests and natural carbon sinks are managed. Changes in diet and reduction in food waste in Indonesia and beyond would go a long way toward reducing emissions and can be implemented by individuals. Improvements in land use and carbon-sink management will also be crucial to reversing the impact of land conversion due to agriculture and urbanization.

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[222] Travis J. Lybbert et al., "Targeting technology to increase smallholder profits and conserve resources: Experimental provision of laser land-leveling services to Indian farmers," *Economic Development and Cultural Change*, January 2018, Volume 66, Number 2; M. L. Jat et al., *Laser land leveling: A precursor technology for resource conservation*, Rice-Wheat Consortium technical bulletin series 7, Rice-Wheat Consortium for the Indo-Gangetic Plains, 2006.

[223] Debashis Chakraborty et al., "A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production," *Scientific Reports*, August 2017, Volume 7. Based on AR5GWP20.

[224] Enteric fermentation is a natural part of the digestive process in ruminant animals such as cattle, sheep, goats, and buffalo. Microbes in the digestive tract, or rumen, decompose and ferment food, producing methane as a by-product.

[225] Jan Hartger Mathijs Harmsen, *Non-CO_2 greenhouse gas mitigation in the 21st century*, Utrecht University, 2019; M. J. Bell et al., "Effect of breeding for milk yield, diet and management on enteric methane emissions from dairy cows," *Animal Production Science*, August 2010, Volume 50, Number 8; *Lower methane production through breeding*, Viking Genetics.

The biggest challenge, however, would be the transition to low-carbon farming practices from current carbon-intensive and unsustainable farming practices, which have increased deforestation and waste but at the same time supported the livelihoods of billions of people in the region. About 90 percent of Indonesia's farmers work on small family farms, whose livelihood largely depends on agriculture, with about 50 percent of annual household income coming from farm activities.[226] Therefore, it is important to ensure that any decarbonization measures do not affect those whose livelihoods depend on agricultural activities as well as the overall affordability of food. This could involve providing training and incentives to adopt new farming practices as well as support for any new capital investment needed. Enabling diet shifts and reduction in food waste will also require measures to alter consumer behaviors.

Box 4

Decarbonization beyond the Indonesian farm

Waste contributes to emissions, accounting for 8 percent of Indonesia's total GHG emissions in 2016.[1] Some 75 percent of total waste is organic, of which about one-third is food waste.[2] On average, 30 percent of solid waste is not collected and managed. Collected waste mainly ends up in landfills, nearly half of which are uncontrolled open dumps. The government is stepping up efforts to address these challenges. The National Solid Waste Management Policy and Strategy aims to cut waste by 30 percent by 2025 and introduce management frameworks for the remainder.[3] To further improve waste management, public funding could be used to accelerate the scaling of circular business solutions, such as including relevant criteria in public procurement tenders. Cities should ensure that relevant infrastructure—like waste collection systems, treatment and recycling facilities, and material banks—is in place to ensure effective recirculation of materials.[4]

Indonesia is home to the third-largest rainforest in the world. From 2001 to 2018, the country lost 25.6 million hectares of tree cover, equivalent to a 16 percent reduction since 2000 and 10.5 Gt of CO_2 emissions. The main drivers are forest clearing for palm oil and for timber harvesting, which account for about two-fifths of deforestation.[5] In response, in 2019, Indonesian President Joko Widodo issued a permanent moratorium on deforestation from activities such as palm plantations and logging. The moratorium stops new permits for forest conversion within the moratorium area, which covers about 66 million hectares of primary forest and peatland.[6] A combination of actions (including regulation, enforcement, and incentives such as opportunity-cost payments to farmers) are required to stop deforestation.

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[1] Based on AR5GWP20.

[2] Budi Triyono et al., *Study on utilization of Indonesian non-recycled municipal solid waste as renewable solid fuel*, 2017.

[3] *OECD Green Growth Policy Review of Indonesia 2019*, OECD, 2019.

[4] Ellen MacArthur Foundation, *Completing the picture: How the circular economy tackles climate change*, September 2019; *Agriculture and climate change: Reducing emissions through improved farming practices*, McKinsey and Company, April 2020.

[5] *Global Forest Watch*, World Resources Institute, 2019.

[6] Tabita Diela, "Indonesia has just made its moratorium on forest clearance permanent," World Economic Forum, August 14, 2019.

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[226] Average farms size is 0.6 hectare; "Indonesia: Share of economic sectors in the gross domestic product (GDP) from 2008 to 2018," Statistica, 2020; "Employment in agriculture (% of total employment) (modeled ILO estimate)," World Bank, 2019.

75%

the share of emissions from transport in Asia that comes from road transportation

Electrifying our lives and decarbonizing road transportation and buildings

Asia accounts for more than 30 percent of global GHG emissions from transportation and buildings, and electrification is the most critical measure to decarbonize them.[227] In the transportation sector, road transportation emits about 75 percent of CO_2 in the region. Asia has the technological resources to decarbonize the sector, especially in electric vehicles (EV) and fuel cell vehicles (FCVs). It has a dominant global share of EV and battery production and many government initiatives to accelerate FCV adoption. Primary measures to decarbonize road transportation include improving internal combustion engine (ICE) fuel efficiency, increasing EV and FCV penetration across vehicle types, and cutting road travel.

China already has the largest EV market for passenger cars, with nearly half of global plug-in hybrid electric vehicle and battery electric vehicle sales today.[228] Among government initiatives, Japan's Basic Hydrogen Strategy calls for replacing 1,200 ICE buses and 800,000 ICE vehicles with FCVs by 2030.

Electrifying buildings is another important lever to reduce emissions in Asia. Space and water heating, which typically rely on fossil fuels, are the primary emission contributors, and electrifying these two processes would be a primary decarbonization driver. In addition, expanding the use of district heating and blending hydrogen or biogas into gas grids for cooking and heating could further reduce emissions. Electric technologies are already available at scale, and their economics are often positive. However, the combination of higher up-front costs, long payback times, and market inefficiencies often prevents consumers and companies from taking action.[229] Moreover, the average life span of currently installed (but often less efficient) equipment can span decades, making inertia tempting for many asset owners, and a broad-based shift to electric heating more challenging.

We look more closely at the decarbonization of Japan's transportation sector. Japan faces a significant challenge to meet its emissions-reduction targets for 2030 and 2050. It has committed to reduce GHG emissions by 26 percent by 2030 and by 80 percent by 2050, but 33 percent of Japan's emissions come from hard-to-abate industrial sectors in which decarbonization technology remains immature or not cost-effective (this is compared with the 2013 baseline of 1,407 $MtCO_2e$). Transportation accounted for 16 percent (209 $MtCO_2e$) of Japan's total GHG in 2016, third after the power and industry sector, with road transportation representing 80 percent of that proportion.[230] The following key transportation decarbonization measures stand out:

- **Improving ICE fuel efficiency.** The primary lever to cut internal combustion engines' fuel consumption without drastically changing the transportation mix is to increase fuel efficiency. Average new gasoline-powered car fleet fuel efficiency increased 3.4 percent annually between 2000 and 2017, leading to a decrease in total fuel consumption. Japan has issued new fuel economy standards for passenger vehicles starting in 2030. The standards require an average fleet gasoline-equivalent fuel economy of 25.4 kilometers per liter for passenger vehicles, which is a 2.8 kilometer per liter improvement from 2017.[231]

- **Increasing EV and FCV penetration across vehicle types.** Accelerating adoption is likely to be the most powerful lever to cut road transportation emissions. The share of next-generation vehicles (including hybrid, clean diesel, electric, fuel cell, and natural gas) grew to 10.9 million units in 2018 from 1.5 million units in 2010.[232] However, among the new generation of vehicles, full hybrids are currently the preferred choice, with low shares of EVs (300,000 units in 2018) and FCVs (2,000 to 3,000 units in 2018). To increase the penetration of EVs in Japan, cost reduction is likely to be necessary, which

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[227] Based on AR5 GWP20.

[228] China Association of Automobile Manufacturers (CAAM); The Electric Vehicle World Sales Database, EV Volumes.

[229] For more on improving energy efficiency in buildings, see *Resource revolution: Meeting the world's energy, materials, food, and water needs*, McKinsey Global Institute, November 2011, McKinsey.com, and view the interactive.

[230] Non-CO_2 emissions converted into CO_2e using the Global Warming Potentials of a 100-year time horizon.

[231] *Japan 2030 fuel economy standards*, The Government of Japan, 2019.

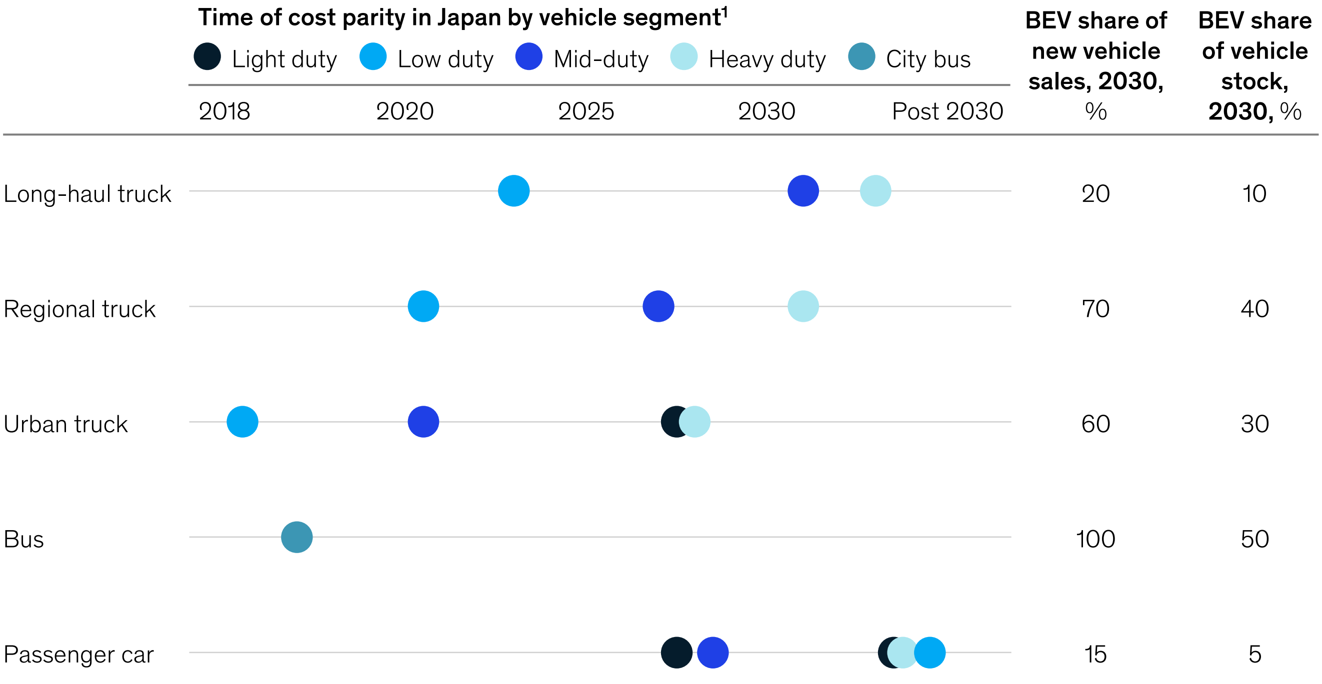
[232] Japan Automobile Manufacturers Association.

is expected first in commercial segments and later in passenger vehicles. In 2030, approximately 2.6 million passenger battery electric vehicles (BEVs) could be on the road, and about 15 percent of new passenger vehicle sales could be BEVs (Exhibit 25).[233] For BEV passenger vehicles, we expect total cost of ownership (TCO) parity in the late 2020s for low- and medium-duty segments like small and medium cars and after 2030 for other segments like SUVs. This is later than expected in European countries because average annual miles driven is lower in Japan, which reduces the fuel-saving impact of BEVs.[234] We expect TCO parity before 2030 for most truck segments. This scale of electrification is in line with commitments being made globally. FCVs are expected to become increasingly competitive, particularly for long-distance and heavy-duty vehicle segments. The TCO of fuel cell trucks has the potential to be the same as for e-trucks by 2040.[235]

- **Reducing the number of miles driven.** In 2018, the distance driven by gasoline-powered vehicles increased by 1.2 percent compared with the previous year. By 2030, however, research suggests a 3 percent reduction, due to a combination of factors including a declining population, better public transit, and more car sharing.

Exhibit 25

By 2030, battery electric vehicles (BEV) are expected to reach cost parity in most commercial vehicle segments in Japan, and later for some passenger car segments.



	BEV share of new vehicle sales, 2030, %	BEV share of vehicle stock, 2030, %
Long-haul truck	20	10
Regional truck	70	40
Urban truck	60	30
Bus	100	50
Passenger car	15	5

1. Based on a maximum gross vehicle weight of motor vehicle.

Source: Decarbonization Pathway Optimizer by McKinsey Sustainability Insights; McKinsey Global Institute analysis

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[233] For details, see *Meeting Japan's Paris Agreement targets—more opportunity than cost*, McKinsey & Company, March 2020.

[234] Nathaniel Bullard, "Electric car price tag shrinks along with battery cost," Bloomberg, April 12, 2019.

[235] Steven Loveday, "Why electric cars don't like cold temperatures, and how to fix it," *InsideEVs*, February 6, 2019.

We calculate that these three primary decarbonization measures in road transportation could contribute 70 $MtCO_2e$ (23 percent) of Japan's total 300 $MtCO_2e$ required abatement by 2030.[236] Improvement in the fuel efficiency of internal combustion engines could create 34 $MtCO_2e$ of abatement, assuming that new non-BEV fuel use per kilometer falls by approximately 2 percent per year until 2025 before BEV cost parity is reached. EV penetration across vehicle types could lead to 30 $MtCO_2e$ of abatement.[237] This assumes 2.6 million passenger BEVs, 2.7 million BEV trucks, and 48,000 electric buses. Reduced driver miles would lead to 6 $MtCO_2e$ of abatement.

While cost-efficient, many decarbonization technologies require higher up-front capital investment than conventional technologies. We estimate that this means about $120 billion incremental capital investment in 2016–30, including the cost of transportation electrification and charging infrastructure.

Although the measures we identify would contribute significantly to the decarbonization of Japan's transportation sector by 2030, the country's 2050 Paris Agreement target of an 80 percent reduction in GHG emissions (against the 2013 baseline) will require more drastic measures and structural change. Given the pace of technology advances we have seen in the past decade, it would be premature to predict the precise measures to support this level of emissions reduction. However, the following two major technologies will be critical:

- **Electrification of medium-duty and heavy-duty transportation.** By 2030, EVs in these segments could still be relatively expensive. Success for post-2030 deployment will depend on progress in the next decade to improve battery density and reduce battery prices, as well as establishing a strong supply chain for both batteries and EVs.

- **Hydrogen-fueled technologies.** Economic viability for FCVs is initially likely in specific use cases such as long-haul segments, but the long-term evolution of competitiveness versus BEVs is still unclear.[238] Cost-competitive hydrogen supply is a potential challenge for Japan. However, the country is one of only a few that has a strong hydrogen strategy.

The structural shifts discussed here also pose some challenges for key stakeholders in the transportation sector such as automobile manufacturers, suppliers, and industrial players. The biggest issue would be a rapid increase in demand for batteries, challenging OEMs and suppliers to scale supply chains and production. To catch up with demand, many automakers are striving to secure access to battery cells. Many Japanese automakers are constantly increasing the value chain coverage, often in the form of joint ventures with battery suppliers. For example, Toyota has built a joint-venture partnership with Panasonic, which has a large share of the global lithium-ion battery market. In addition, electrification of road transportation would require car owners to switch their purchasing behavior and decision-making criteria. The higher up-front cost of BEVs could still pose an adoption barrier even if TCO parity is reached, requiring government and automotive manufacturers to introduce incentives (such as subsidies, tax credits, and preferential number-plate policies) and innovative financing programs to help consumers overcome this barrier. Scaling charging stations is also vital to enhance consumers' EV adoption. In addition to the required investment we describe, key challenges such as availability of real estate for charging stations, ease of charging, and availability of different EV model types still need to be addressed. Traditional industrial players such as fuel retailers will also be required to adapt to this disruption given that consumption of gasoline is expected to drop as the share of EVs increases.

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[236] As projected demand growth in commercial transportation (trucks) is expected to lead to a 12 $MtCO_2e$ emissions increase by 2030, overall sector emissions in 2030 are estimated to be 151 $MtCO_2e$—a decrease of 28 percent (58 $MtCO_2e$) compared with 2016.

[237] This shift will be enabled by drastically decreasing battery prices.

[238] Steven Loveday, "Why electric cars don't like cold temperatures, and how to fix it," *Inside EVs*, February 6, 2019.

Finally, in addition to our country-sector decarbonization case studies, we outline an example of how one country as a whole could overcome the unique local challenges of decarbonization and meet the Paris Agreement goals. In this case, we look more closely at Japan (see Box 5, “Decarbonization in the case of Japan”).

While Asia faces many risks from climate change, it also has opportunities to accelerate adaptation and mitigation efforts that are already occurring across the region. Whether it be through modernization of India’s energy sector, new production methods in China’s steel industry, innovation in Indonesia’s farming communities, or electrification of transportation in Japan, Asia has the resources and capabilities to cut emissions, prepare for climate change that is already locked in, and help put the world on the road to a more sustainable future.

Box 5

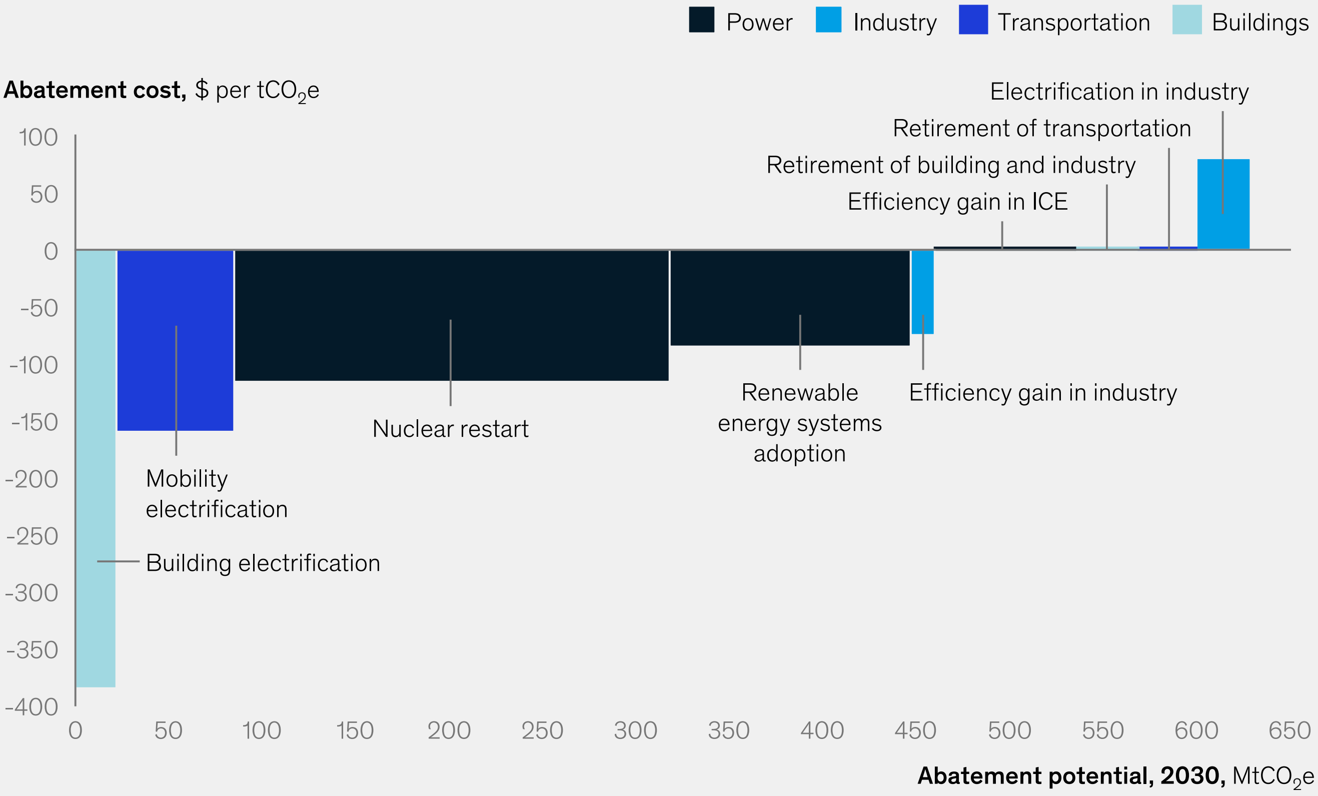
Decarbonization in the case of Japan

Decision making for decarbonization is complex. With this in mind, we assessed more than 350 emissions-reduction measures on a year-by-year basis and optimized the total cost of ownership (TCO) across all sectors each year to determine the most cost-effective measures to meet Paris Agreement targets. TCO considers the cost of the stand-alone technology and does not include the costs of enabling infrastructure, which are separately assessed. This analysis is not a forecast of what Japan would look like in 2030 if the current technology and policy trajectory continues. Rather, it is an analysis of one path for Japan to meet its Paris Agreement targets and the potential technology mix that could be achieved when various challenges are properly addressed. In this report, we use this analysis as an illustration of the type of transformation a country might need to undertake and the scale of the challenge to be met. While this analysis focuses on economic cost optimization, both the Japanese government and its citizens should consider factors other than economic cost in choosing the best possible path for Japan's decarbonization.

Japan has committed to reduce GHG emissions by 26 percent by 2030, and by 80 percent by 2050 (compared with the 2013 baseline of 1,407 $MtCO_2e$) to meet Paris Agreement targets.[1] However, 33 percent of the country's emissions come from hard-to-abate industrial sectors in which technology for deep decarbonization is still not mature or cost-effective. Its energy production CO_2 emissions are among the highest in the OECD. Still, we find that 95 percent of all abatement required to meet Japan's 2030 targets can be achieved through measures that are either cost neutral or result in lifetime cost savings (Exhibit 26). In other words, these measures would result in TCO savings, which includes the initial investment costs and the operation costs for the full lifetime of the measure. These measures are made possible by the remarkable global trends driving a rapid decline in the cost of major decarbonization technologies, including battery electric vehicles, heat pumps, and renewable power generation.

Exhibit 26

Japan's 2030 emissions reduction target can be achieved with a variety of measures, many with cost benefits.



Source: Decarbonization Pathway Optimizer by McKinsey Sustainability Insights; McKinsey Global Institute analysis

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[1] Analysis from *Meeting Japan's Paris Agreement targets—more opportunity than cost*, McKinsey & Company, March 2020. Based on AR5GWP100.

Our analysis identifies the most cost-effective measures to deliver 300 $MtCO_2e$ of abatement required from 2016 to 2030 across four key sectors: power, industry, transportation, and buildings. The Marginal Abatement Cost Curve shows the most cost-effective measures; this curve describes the abatement potential of a technology relative to cost as measured by the difference in TCO of emission-reduction technology versus current technology per ton of CO_2e reduction. We find the following three critical themes that can support decarbonization:

- Decarbonizing the power sector (174 $MtCO_2e$ abatement) makes the largest contribution to achieving the 2030 emission-reduction target. While the future of nuclear power in Japan is still unclear and under discussion, nuclear restart (112 $MtCO_2e$) is the single most effective and cost-effective measure from a decarbonization perspective. Large-scale adoption of renewable energy, such as solar photovoltaic cells and onshore wind (62 $MtCO_2e$), will also have a bigger impact than other measures.
- Electrification in the buildings (11 $MtCO_2e$), transportation (30 $MtCO_2e$), and industrial sectors (15 $MtCO_2e$), as well as efficiency gains in transportation (34 $MtCO_2e$) and industry (6 $MtCO_2e$), is also crucial.
- Reducing energy demand through the retirement of fossil-fuel-based technologies in buildings, industries, and transportation would also make an important contribution to decarbonization.

Infrastructure investment costs are considered separately here and are not incorporated into abatement costs. However, the scale of this investment does not reverse the business case for switching to EVs, increasing electrification, or increasing solar and wind generation.

The most important enabling infrastructure investment consists of:

- Charging infrastructure for BEVs: A $9 billion investment would be required to deploy approximately 3.3 million chargers to support 5.4 million BEVs by 2030. This is only 4 percent of the $225 billion total investment required for the full deployment of 5.4 million BEVs.
- Grid reinforcement to accommodate growing electricity demand: Approximately $7 billion would be required, primarily on the distribution grid, to accommodate peak load growth due to end-use sector electrification.
- Grid reinforcement to accommodate increase in variable generation: Our analysis finds that approximately $27 billion to $69 billion in additional investment would be required through the 2016–30 period for grid reinforcement in the full nuclear-restart scenario, while $64 billion would be required for the nuclear-phaseout scenario.
- Accumulation of storage to balance electricity supply with demand: Approximately $4 billion to $8 billion would be needed for 15 to 25 gigawatts of battery storage capacity.

Including the infrastructure investment and depending on the nuclear scenario, we estimate that deploying these measures would require an incremental up-front capital investment of approximately $270 billion to $329 billion between 2016 and 2030, compared with the investment required to maintain the 2016 technology mix. This translates to an average annual increase in investment of $19 billion to $24 billion, or 0.5 percent of Japan's annual GDP.

Beyond 2030, Japan's 2050 Paris Agreement target of an 80 percent reduction in emissions (against the 2013 baseline) will require more drastic measures and structural changes. Outside transportation, we identify six technologies that will be crucial: electrification of medium-duty and heavy-duty transportation; offshore wind; long-duration storage; hydrogen-fueled technologies; carbon capture, utilization, and storage; and electrification of high-temperature heat.

Forestation to protect the environment, China.
© Loonger/iStock/Getty Images

Technical appendix

This report seeks to provide an understanding of how climate hazards can create risk. In this technical appendix, we outline our key assumptions and approach (Exhibit A1).

Woodwell Climate Research Center (Woodwell) performed most of the climatological analysis for this report, and senior scientists at the University of Oxford's Environmental Change Institute independently reviewed the methodological design. All final design choices and interpretations of climate hazard results were made by Woodwell.

From the outset, it is important to understand the distinction between weather and climate. Weather is defined as the behavior of the atmosphere with respect to temperature, wind speed, cloudiness, and precipitation for a given location over a short period such as a day or a week. Climate is defined as the statistical or probabilistic summary of weather patterns over time and space. As a result, climate is possible to predict with reasonably high reliability, whereas weather is not predictable more than two weeks in advance, due to the theoretical constraints of modeling chaotic systems.[239] Throughout this report, we consider only expected changes in climate. We generally do this over two periods: the present to 2030, and the present to 2050. (In some instances, we also consider other periods in our case studies, and highlight where we do so.) Following standard practice, we define future states as the average climatic behavior over multiple-decade periods. The climate state today is typically defined as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 as the average between 2041 and 2060.[240]

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[239] Klaus Hasselmann, "Is climate predictable?," in *The Science of Disasters: Climate Disruptions, Heart Attacks, and Market Crashes*, Armin Bunde, Jürgen Kropp, and Hans Joachim Schellnhuber, eds., Berlin, Germany: Springer, 2002; Jaana Sillmann et al., "Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities," *Weather and Climate Extremes*, December 2017, Volume 18.

[240] See Gerald A. Meehl et al., "Decadal prediction: Can it be skillful?," *Bulletin of the American Meteorological Society*, October 2009, Volume 90, Number 10.

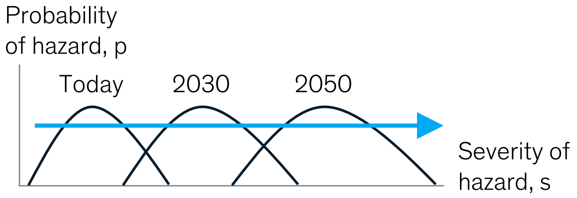
Exhibit A1

We used this methodology for translating climate hazard to climate risk.

Evaluate climate hazard
h = probability (s)

Description

Changes in the physical environment caused by higher temperatures, measured as probability (p) of severity of hazard (s)



Types

Acute (storms and hurricanes, wind, flooding, forest fires) and chronic (heat stress, drought, sea level rise)

Example

Hurricane hits coastal real estate

Evaluate exposure to hazard
E (s)

Description

People, assets, or economic activity exposed to hazard

Types

People, assets, economic activity

Examples

Properties close to the coast are exposed to storm surge

People working in outdoor activities are exposed to heat stress

Evaluate vulnerability to hazard
v(s)

Description

Impact/damage per exposed unit for a given unit of climate hazard.

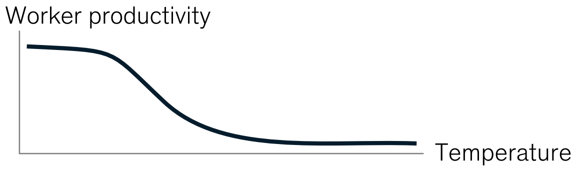
Types

Physiological, eg, % impact on labor productivity at different temperatures

Ecological, eg, % impact on crop yields at different temperatures

Physical, eg, % capital stock damaged at X feet of flooding

Example



Evaluate direct impacts in absence of adaptation

Description

Immediate impact of climate change on socioeconomic systems

Assumes exposure increases in line with historical trends, vulnerability remains as today

Calculated as
$\Sigma p(s) \times E(s) \times v(s)$

Types of socioeconomic systems affected

Livability and workability

Food systems

Physical assets

Infrastructure services

Natural capital

Example

Properties are damaged by flooding

GDP is lost due to reduced worker productivity from heat stress

Evaluate adaptation measures

Description

Assessment of adaptation needs to reduce vulnerability and exposure to climate risk

Types

Identify five types of adaptation responses including diagnosing risk and enabling a response, protecting assets and people, building resilience, reducing exposure, and finance and insurance

Examples

Hardening infrastructure, protecting coastal zones, installing backup power supply, building cooling shelters, etc

Source: McKinsey Global Institute analysis

How climate hazard is estimated

The specific projections in this report were derived from climate models. Climate models are complex computational models based on physics that simulate the atmosphere, ocean, land, biosphere, and cryosphere down to resolutions of roughly 100 km by 100 km. The climate models used in this report are drawn from an ensemble of 60 climate models known as general circulation models (GCMs) or earth system models; they are developed, owned, and operated independently by 28 leading scientific research institutions across the world.[241] The World Climate Research Programme brought these models together to run standardized experiments to determine the likely outcome of various rates of carbon emissions in an undertaking known as CMIP5: Coupled Model Intercomparison Project 5.[242] The results of the CMIP5 ensemble are the most widely used source of climate projections in climate research today and have been evaluated in more than 1,500 papers.[243]

We also drew on projections from an ensemble of regional climate models, which are dynamic models that take GCM input and refine it to simulate specific regions of the globe at a finer resolution. This allows scientists to more accurately investigate future climates in regions with complex terrain.

When modeling the response of agricultural systems to climate change, we drew from the Agricultural Model Intercomparison and Improvement Project (AgMIP), an ensemble of coupled climate and agricultural models coordinated by the Columbia University Earth Institute in partnership with multiple other organizations including NASA, the USDA, the Potsdam Institute for Climate Impact Studies, and others.[244] Finally, we also sometimes rely on projections from external sources (for example, the World Resources Institute on water stress). The details of the modeling for the change in high fire risk days in Australia and floods in Tokyo due to climate change can be found at the end of this appendix.

When making climate projections, we used the multimodel ensemble mean or median projection (depending on the requirements of the specific analysis)—in other words, the average projection across all selected models—because it has been proven both theoretically and empirically that using the average result across the full ensemble of models gives the most accurate projection.[245]

Emissions pathways and pace of warming

Climate impact research has inherent uncertainties and as a result makes extensive use of scenarios. One particular input around which scenarios are frequently constructed is atmospheric greenhouse gas levels. Climate projections must be based upon an assumed trajectory for future atmospheric greenhouse gas concentrations. Because future human emissions of greenhouse gases are inherently unpredictable, the climate community has developed a set of four standardized scenarios for future atmospheric greenhouse gas concentrations, known as Representative Concentration Pathways (RCPs).[246] They outline atmospheric greenhouse gas concentration trajectories between 2005 and 2100 that roughly range from lower (RCP 2.6) to higher (RCP 8.5) CO_2 concentrations. During their inception, RCPs were designed to collectively sample the range of then-probable future emission pathways. Each RCP was created by an independent modeling team. and there is

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[241] CMIP Phase 5 (CMIP5), World Climate Research Programme, wcrp-climate.org/wgcm-cmip/wgcm-cmip5. The specific models used in this report are: ACCESS1-0, ACCESS1-3, CNRM-CM5, CSIRO-Mk3-6-0, CanESM2, GFDL-CM3, GFDLESM2G, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5B-LR, IPSL-CM5A-MR, MIROC-ESMCHEM, MIROC-ESM, MIROC5, MRI-CGCM3, MRI-ESM1, and NorESM1-M.

[242] Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl, "An overview of CMIP5 and the experiment design," *Bulletin of the American Meteorological Society*, April 2012, Volume 93, Number 4.

[243] Gregory Flato et al., "Evaluation of climate models," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[244] Cynthia Rosenzweig et al., "The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies," *Papers in Natural Resources*, 2013; Cynthia Rosenzweig et al., "Coordinating AgMIP data and models across global and regional scales for 1.5C and 2C assessments, *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Issue 2113.

[245] Every model in the ensemble performs best at representing some aspect of the climate system, and no model performs best across all aspects, and therefore all models add some measure of skill to the multimodel projection. Furthermore, combining multiple models leads to cancellations of nonsystematic errors.

[246] Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An overview," *Climatic Change*, November 2011, Volume 109, Issue 1–2.

no consistent design of the socioeconomic parameter assumptions used in the derivation of the RCPs.

Uncertainty in future greenhouse gas emissions is a key contributor to long-term (for example, end-of-century) uncertainty in future temperatures but is less important on the shorter time horizons (to 2030 and to 2050) considered in this report. As we discuss in detail in the report, warming during the next decade is determined largely by past emissions and by physical inertia in the climate system. Beyond the next decade, warming is primarily a function of cumulative emissions of carbon dioxide. Because decarbonization takes time, even a scenario of targeted decarbonization action will result in significant cumulative emissions over the next three decades. Climate simulations driven by the four RCP scenarios show a small divergence in warming over the next two decades, and a moderate divergence by 2050. It is important to note that RCP 2.6 is no longer possible without carbon capture, and a small divergence in one aspect of climate models does not mean all aspects will show a similar small divergence.

We rely on RCP 8.5 for the analyses in this report. RCP 8.5 was created to model a case of no further climate action and relatively higher rates of baseline greenhouse gas emissions.[247] 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.

While RCP 8.5 has been criticized for assuming unrealistically high use of coal and thus projecting too-high emissions in the second half of the century, we consider a time frame only to 2050, and we adopted RCP 8.5 as a best available description for an “inherent risk” scenario over the next two to three decades.[248]

There are three points to note about this choice.

— Since the starting point of the RCPs in 2005, RCP 8.5 has most closely tracked actual greenhouse gas emissions (and going forward, RCP 8.5 is broadly consistent with a continuation of the emissions trend of the past decade).[249] As a result, it best matches current CO_2 concentrations, whereas the other RCPs assume lower CO_2 concentrations than observed.

— Changes in the relative cost of renewable and fossil fuel energy sources are forecast to lead to a moderate downward divergence from the historic trend line of energy-related CO_2 emissions over the coming decades, even in the absence of further decarbonization policies.[250] In contrast, emissions from biotic feedbacks, such as permafrost thaw and increasing wildfires, are expected to increase. These feedbacks are not considered in the current generation of CMIP5 models and need to be accounted for exogenously. According to a recent review of the literature on biotic feedbacks, in the near term these feedbacks are estimated to reduce the 1.5 degree Celsius carbon budget by 100 $GtCO_2$, and the 2.0 degree Celsius carbon budget by 150 $GtCO_2$.[251]

— Early results from the next generation of climate models, CMIP6, suggest that the climate system may be more sensitive to CO_2 than the current generation of models (CMIP5), suggesting that the CMIP5 models may tend to underestimate future warming.[252]

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[247] Christopher R. Schwalm, Spencer Glendon, and Philip B. Duffy, “RCP8.5 tracks cumulative CO_2 emissions,” *Proceedings of the National Academy of Sciences*, August 2020.

[248] Justin Ritchie and Hadi Dowlatabadi, “The 1000 GtC coal question: Are cases of vastly expanded future coal combustion still plausible?” *Energy Economics*, June 2017, Volume 65; Justin Ritchie and Hadi Dowlatabadi, “Why do climate change scenarios return to coal?” *Energy*, December 2017, Volume 140, Part 1; Keywan Riahi et al., “The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview,” *Global Environmental Change*, January 2017, Volume 42; Keywan Riahi, Arnulf Grubler, and Nebojsa Nakicenovic, “Scenarios of long-term socio-economic and environmental development under climate stabilization,” *Technological Forecasting and Social Change*, September 2007, Volume 74, Issue 7; Detlef P. van Vuuren et al., “The Representative Concentration Pathways: An overview,” *Climatic Change*, November 2011, Volume 109, Issue 1–2.

[249] K. J. Hayhoe et al., “Climate models, scenarios, and projections,” in *Climate Science Special Report: Fourth National Climate Assessment*, Volume I, D. J. Wuebbles et al., eds., Washington, DC: US Global Change Research Program, 2017.

[250] World Energy Outlook 2019, International Energy Agency, 2019.

[251] Jason A. Lowe and Daniel Bernie, “The impact of Earth system feedbacks on carbon budgets and climate response,” *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Number 2119.

[252] Stephen Belcher, Olivier Boucher, and Rowan Sutton, *Why results from the next generation of climate models matter*, Carbon Brief, March 2019.

Based upon these considerations, we chose to employ RCP 8.5 as a base case for considering 2030 to 2050. Were this study investigating the risk outlook for 2100, we would consider multiple emissions pathways, but for the next three decades, we consider RCP 8.5 to be the best guide for understanding inherent risk.

Restricting warming to less than two degrees Celsius, the goal of the 2015 Paris Agreement, would mean reaching net-zero emissions in the next 40 to 50 years. If this were achieved, the impact estimates presented in this report would likely not manifest to their full extent. Alternatively, a decarbonization approach somewhere between business-as-usual and a two-degree-compliant pathway would mean that temperatures in 2050 would be below the roughly two degrees Celsius increase reflected in the RCP 8.5 scenario, but that such temperature increases would be reached at some point post-2050. This means that the impact assessments presented in this report would manifest, but only after 2050; it would push the 2050 impacts further back into the second half of the century but would not prevent them.

Another way to frame this would be that if we were to limit warming to 2.0 degrees Celsius, our 2050 impact estimates would be the most severe impacts we would be expected to see (but at some point after 2050), and if we were to limit warming to 1.5 degrees Celsius, correspondingly, our 2030 impact estimates would be the most severe impacts we would be expected to see (but at some point after 2030). For example, RCP 8.5 predicts global average warming of 2.3 degrees Celsius by 2050, compared with 1.8 degrees for RCP 4.5. Under RCP 4.5, 2.3 degrees Celsius warming would be reached in the year 2080.[253]

How climate hazard in a region of interest is estimated

Throughout this report, we seek to answer specific questions about future climate variables for a particular region. Since GCMs tend to apply at continental or global scale, we needed a tool for regional or subregional climate projections.[254] At times, a statistical process known as bias correction and spatial disaggregation was performed. Both methodologies have been proven to increase the skillful resolution of GCM projections to facilitate regional climate study.[255] Some questions required additional methodology. For example, “What is the probability of a heat wave of severity X occurring in a given year in region Y?” To quantify the probability, the scientists with whom we collaborated used a process known as bootstrapping to generate probability distributions drawn from the full ensemble of bias-corrected models.[256]

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[253] Michael Prather et al., “Climate system scenario tables,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[254] Stanley L. Grotch and Michael C. MacCracken, “The use of general circulation models to predict regional climatic change,” *Journal of Climate*, March 1991, Volume 4, Number 3, pp. 286–303.

[255] Nurul Nadrah Aqilah Tukimat, “Assessing the implementation of bias correction in the climate prediction,” *IOP Conference Series: Materials Science and Engineering*, April 2018, Volume 342; Jie Chen et al., “Bias correcting climate model multi-member ensembles to assess climate change impacts on hydrology,” *Climatic Change*, April 2019, Volume 153, Issue 3; Martin Aleksandrov Ivanov, Jurg Luterbacher, and Sven Kotlarski, “Climate model biases and modification of the climate change signal by intensity-dependent bias correction,” *Journal of Climate*, August 2018, Volume 31, Number 16; Gerhard Krinner and Mark G. Flanner, “Striking stationarity of large-scale climate model bias patterns under strong climate change,” *Proceedings of the National Academy of Sciences*, September 2018, Volume 115, Number 38; Patricio Velasquez, Martina Messmer, and Christoph C. Raible, “A new bias-correction method for precipitation over complex terrain suitable for different climate states,” *Geoscientific Model Development* preprint, July 2019.

[256] Beran Efron, “Bootstrap methods: Another look at the jackknife,” *The Annals of Statistics*, January 1979, Volume 7, Number 1, pp. 1–26; Manfred Mudelsee, “The bootstrap in climate risk analysis,” in *In Extremis: Disruptive Events and Trends in Climate and Hydrology*, Jurgen P. Kropp and Hans Joachim Schellnhuber, eds., Heidelberg, Germany: Springer, 2011; Barbara Hennemuth et al., *Statistical methods for the analysis of simulated and observed climate data: Applied in projects and institutions dealing with climate change impact and adaptation*, Climate Service Center, CSC report number 13, 2013; Andrew C. Parnell, “Climate time series analysis: Classical statistical and bootstrap methods,” *Journal of Time Series Analysis*, March 2013, Volume 34, Issue 2.

How we determine physical climate risk from climate hazard

Our approach to determine physical climate risk assesses direct impacts from climate change and knock-on effects, and describes adaptation measures to avoid impacts (see Exhibit A1). The magnitude of risk from physical climate change depends on the following:

- **Direct impact.** The magnitude of the direct impact of climate change depends on three factors: the magnitude of the climate hazard and the probability of its occurrence; how much assets, population, and economic activity are exposed to the hazard; and to what degree they are vulnerable to the hazard when exposed (direct impact = hazard x exposure x vulnerability). To assess impacts, we typically look at hazards of different severity. For each of our cases, and for our country risk assessment, we identify how hazard and exposure to that hazard could evolve. For case studies, exposure was typically assumed to grow in line with expected trends (for example, for India, including continued sectoral shift of the economy and increasing penetration of air-conditioning). For our geospatial assessment, similarly, we assumed increases in population or GDP trends. However, for this analysis, we assumed that geospatial distribution of these variables stays constant over time because of data limitations with geospatial time series data. We also assess the vulnerability of each system to a hazard through identifying appropriate "damage functions"—for example, how damage to capital stock varies based on floods of different depths. Damage functions are obtained from published academic literature or external data sources. We consider three broad types of damage functions: physiological (for example, impact on human productivity from heat stress), ecological (for example, impact on agricultural productivity from drought), and physical (for example, vulnerability of buildings to floods). We identify five types of systems directly affected by climate hazards: livability and workability, food systems, physical assets, infrastructure services, and natural capital. Collectively, this points to how climate change could affect economic output, capital stock, and lives.

  Impacts of climate change can be large, and potentially nonlinear, when climate hazards breach certain system thresholds. For example, the human body functions normally at a stable core temperature of about 37.0 degrees Celsius. The core temperature needs to rise by only 0.06 degree to compromise task performance, 3.0 degrees to induce dangerous heatstroke, and 5.0 degrees to cause death. As part of our analysis, we examine operational thresholds for physical, social, and economic systems in our case studies to determine potential impact.

- **Adaptation costs.** We define adaptation broadly to include protecting people and assets, building resilience, reducing exposure to hazard, and insurance and finance. We first examine inherent risk, assuming that there is no significant increase in adaptation efforts, that exposure continues to increase at historical rates, and that vulnerability to risk remains the same as today. Then we explore adaptation measures and, where feasible, costs needed to adapt to climate risk, including exposure reduction where appropriate.

How we selected our case studies and performed the regional geospatial risk analysis

To link physical climate risk to socioeconomic impact, we investigate six specific cases that illustrate exposure to climate change extremes and proximity to physical thresholds. To select our case studies, we built a long list of 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 find that these hazards affect five key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital. We ultimately chose six cases to reflect these systems based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds. These cases represent leading-edge examples of climate change risk. For each case, we used the approach described above to quantify the inherent direct impact as well as outline a possible adaptation response.

For the regional geospatial risk assessment, we analyzed 16 countries, representing more than 95 percent of regional GDP and population, against six indicators that cover the five systems affected by climate change.[257] We did this using geospatial data on climate hazards (including a probabilistic assessment of the severity of the hazard and the likelihood of occurrence of events of different severity), exposure, and resilience. We conducted these at a grid-cell level, overlaying data on a hazard, with exposure to that hazard and a damage function. We then combined these grid-cell values to country and regional numbers. We attempt to quantify changes in climate only and do not try to predict weather.

Note that this analysis provides an estimate only of the direct impact of physical climate risk and not the knock-on effects. These country-level analyses were then added up, where possible, to derive insights about the evolution and distribution of various forms of climate risk in Asia.

A detailed discussion of the indicators used in the assessment is provided in chapter 1 of the report. Here we primarily discuss the details of the hazard data and climate models used in the analysis. We examined a subset of possible climate hazards, defining and measuring them as follows.

Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature could exceed the survivability threshold for a healthy human being resting in the shade. (Wet-bulb temperature is the lowest temperature to which air can be cooled by the evaporation of water into the air at a constant pressure.) We took the average wet-bulb temperature of the hottest six-hour period in each rolling three-day period as the relevant threshold. This was calculated according to the methodology in Stull (2011).[258] The threshold maximum temperature chosen for this analysis was 34 degrees Celsius wet-bulb because the commonly defined heat threshold for human survivability is 35 degrees wet-bulb. At this temperature, a healthy human being resting in the shade can survive outdoors for four to five hours. Large cities with significant urban heat island effects could push 34 degrees Celsius wet-bulb heat waves over the 35-degree threshold. This could lead to widespread mortality in the absence of targeted adaptation.[259]

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[257] The indicators include: share of annual GDP at risk due to extreme heat and share of people at mortality risk due to lethal heat waves (measures of decrease in workability and livability), expected value of cereal production at risk of agricultural failure (measure of disruption of food systems), capital stock at risk of damage from floods, and annual probability of a yield decline of greater than 15 percent for four major crops (i.e., rice, wheat, soy, and corn) and land area experiencing biome shift (measures of destruction of natural capital).

[258] Roland Stull, "Wet-bulb temperature from relative humidity and air temperature," *Journal of Applied Meteorology and Climatology*, November 2011, Volume 50, Issue 11, pp. 2267–69.

[259] A healthy human being can survive exposure to 35°C wet-bulb temperatures for roughly four to five hours, assuming they are well hydrated and resting in the shade. For more details, please see 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, pp. 9552–5.

The lethal heat-wave projections were derived from the CMIP5 multimodel ensemble, where each model was independently bias corrected using the ERA-Interim data set.[260] Specifically, the projected incidence of lethal heat waves in the 2021–40 period were counted across 20 GCMs drawn from the CMIP5 ensemble and independently bias corrected. Because 20 single-year observations from 20 models provide a sample size of only 400 years of data, the sample size was bootstrapped out to 1,000 years. Once a robust statistical sample size was established, the projected annual probability of a lethal heat wave was identified for each specific location by treating each year as independent. To account for a bug in the arid land-atmosphere feedbacks in the MIROC family of models, the analysis was performed both with and without the MIROC models. The results were insensitive to their exclusion.[261] We eventually excluded all grid cells where the annual likelihood of lethal heat waves was less than 1 percent. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. High levels of atmospheric aerosols provide a cooling effect that masks the risk. Atmospheric aerosols, or air pollution, reflect a proportion of incoming sunlight and therefore artificially cool regions, reducing air temperatures.[262]

Today, the regions that are subject to nonzero risk of lethal heat waves all have high prevalence of atmospheric aerosols (see the India case study for further details). However, the CMIP5 models have poor representation of observed atmospheric aerosols in those regions. As a result, if the CMIP5 results showed a nonzero probability of lethal heat waves in certain regions today, this was set to zero. The other form of uncertainty relates to the urban heat island effect. A global analysis of 419 major cities showed that the average daytime temperature difference between urban areas and their immediate surroundings is +1.5 degrees Celsius ± 1.2 degrees, with some outliers up to 7.0 degrees Celsius warmer.[263]

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 to 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 under way, these cities are at risk of having 34-degree heat waves amplified to 35-degree heat waves.[264]

The annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions is calculated using the average percentage of a given 12-hour workday lost in regions exposed to these hazards. Labor capacity is lost due to heat and humidity through two mechanisms, the first because workers must take breaks to avoid heatstroke, and the second because the body will naturally limit physiological output in hot conditions by fatiguing itself in a process known as self-limiting. Temperature projections were likewise taken from the CMIP5 multimodel ensemble mean projection, again bias corrected using the ERA-Interim data set. Conversion to lost working hours was done following the methodology of Dunne et al. (2013), using combined ISO heat-exposure standards corrected with empirical data from Foster et al. (2019).[265] When deriving global

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[260] Bias corrected using the LOCI method, according to Jurg Schmidli et al., "Downscaling from GCM precipitation: A benchmark for dynamical and statistical downscaling methods," *International Journal of Climatology*, April 2006, Volume 26, Number 5, pp. 679–89.

[261] Geert Jan van Oldenborgh et al., "Extreme heat in India and anthropogenic climate change," *Natural Hazards and Earth System Sciences*, January 2018, Volume 18, Number 1, pp. 365–81.

[262] Ibid.

[263] Shushi Peng et al., "Surface urban heat island across 419 global big cities," *Environmental Science & Technology*, January 2012, Volume 46, Issue 2.

[264] Hiteshri Shastri et al., "Flip flop of day-night and summer-winter surface urban heat island intensity in India," *Scientific Reports*, January 2017, Volume 7.

[265] John P. Dunne et al., "Reductions in labour capacity from heat stress under climate warming," *Nature Climate Change*, February 2013, Volume 3, pp. 563–66; Josh Foster et al., "A new paradigm to quantify reduction of physical work capacity in the heat," *Medicine and Science in Sports and Exercise*, 2019, Volume 51, Number 6, p. 15.

GDP at risk, we applied lost working hours to GDP generated in sectors that we were confident are exposed to heat and humidity risk globally: agriculture, mining and quarrying, and construction. Lost working hours were applied one-to-one to sector GDP: that is, a projected X percent reduction in working hours is assumed to lead to an X percent reduction in sector GDP. These estimates are, as a result, likely an underestimate, because other sectors (particularly hospitality and tourism) are also exposed to heat. We considered a range based on the pace of sectoral transitions, from keeping sector mix at today's level to varying it going forward based on projections from IHS Markit Economics & Country Risk. To investigate the potential range of uncertainty around these findings, we explored the range of variability around the mean projection as captured by the ensemble model spread: we performed the same analysis using the 75th and 25th percentile ensemble projections. This was done to capture the potential impacts in an "average" year, compared with a "hotter than average" or "colder than average" year. Countries that include no change in share of effective outdoor working hours affected as a possible outcome within the range of model uncertainty by 2030 were noted as likely not robust. All countries show robust trends by 2050.

For our agricultural investigation, we used projections from the AgMIP ensemble. Changes in yield were quantified relative to the mean yield for the 1998–2017 period. Because projections from the AgMIP ensemble scale in skillfulness as a function of both physical spatial resolution and intensity of crop production, we were not able to perform a country-by-country analysis. (In other words, we were not able to obtain robust projections for small countries and large countries with marginal agricultural output.) Instead, we identified the largest grain breadbaskets in each region and quantified changes to output there. Agricultural projections were done using the mean projection from the full range of available GCMs, as well as the full range of non-potential-yield crop models. Nitrogen limitation and CO_2 fertilization were kept "ON" for all projections. We did not account for reductions in nutritional content of crops. Therefore, these results may be underestimates, as future behavior of CO_2 fertilization is not well constrained.

Water stress and change in water supply are calculated using the increase or decrease in the average annual supply of renewable freshwater available in a given water basin. The amount of available renewable freshwater is a function of annual precipitation over that basin, as well as influx and outflux of water to and from that basin via riverine systems. Water supply data were taken from the World Resources Institute, which combines output from the CMIP5 ensemble with the GLDAS-2 NOAH v. 3.3 hydrological model. Data were taken from the World Resources Institute Water Risk Atlas (2018), which relies on six underlying CMIP5 models. Time periods of this raw data set are the 20-year periods centered on 2020, 2030, and 2040. The 1998–2017 and 2041–60 data were linearly extrapolated from the 60-year trend provided in the base data set. For our geospatial assessment of water stress across countries, we assumed water demand stayed constant at today's levels, to allow us to isolate and investigate the impact of climate change alone.

For our flooding analysis, we used updated Aqueduct Global Maps 3.0 data from the World Resources Institute. We considered only riverine flooding for this analysis due to data availability. Riverine flooding represents flooding from river overflow and occurs in river basins with an area of at least 10,000 square kilometers. Also due to data availability, only urban assets were considered for this analysis, and the exposure was measured using a land use map showing which cells were built up and not built up. A detailed approach can be found in the World Resources Institute Aqueduct Floods Methodology. Here we highlight the following key points:

To calculate the river hazard layers for the individual return periods, we used the GLOFRIS model.[266] GLOFRIS applies a global hydrological model, PCRaster Global Water Balance (PCR-GLOBWB), with a river and floodplain routing scheme to make long-term simulations of discharges and flood levels for several climate conditions. The meteorological data sets of the European Union Water and Global Change (EUWATCH) program and the Inter-sectoral Impact Model Intercomparing Project (ISI-MIP) were used to force PCR-GLOBWB over various time periods between 1950 and 2099. Based on PCR-GLOBWB output, we then applied extreme value statistics to derive the floodplain water volumes per grid cell for several flooding return periods (two, five, ten, 25, 50, 100, 250, 500, and 1,000 years) for the current time (based on 1960–99 simulation) and future climate (2010–49, 2030–69, and 2060–99). These are then used as inputs to a volume spreading flood model to convert the 5' × 5' flood volumes into maps of high-resolution inundation depth at a resolution of 30" × 30".

Each impact indicator is calculated for the return periods of two, five, ten, 25, 50, 100, 250, 500, and 1,000 years for floods using hazard (riverine), exposure (urban assets), and vulnerability data. Impacts are translated into the expected annual damage (EAD)—or risk—using the exceedance probability-impact curve. The curve is created by plotting the flood probabilities (1/return periods) on the x axis and the impacts on the y axis. The area under the curve represents EAD; however, flood protection must be incorporated into the calculation before the integral of the area under the curve is taken. The flood protection is added to the risk curve as a vertical line.[267] All impacts to the right of the flood protection line (damage from smaller floods) are assumed to be protected against and are set to 0. EAD is calculated by integrating the area of the curve to the left of the flood protection line.

The level of flood protection used in the default analysis was modeled by using FLOPROS. Flood protection level represents the strongest magnitude flood that flood infrastructure can protect against (given the return period). For example, a ten-year flood protection level will prevent ten-year floods (or smaller) from damaging assets. FLOPROS provides flood protection estimates at the state level. For larger locations, like countries and river basins, the average protection was estimated by first summing all EAD from the state level within the location (for river basins, only the portion of the state within the basin was used). Next, the location's loss-probability curve was run through several trials using a range of flood protection values to estimate EAD. Once a trial matched the actual EAD, the corresponding flood protection was set as that location's default.

Our measure of natural capital risk is defined as the percentage of land surface that changes category under the Köppen Climate Classification System, which evaluates a particular area based on average annual climate statistics, like precipitation and temperature. While not a perfect analog, ecosystem type correlates very closely with Köppen climate classification, and therefore shifts are a good directional indicator of ecosystem stress or change.[268]

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[266] *Aqueduct Floods Methodology*, World Resources Institute, 2020.

[267] The flood protection, in return years, is first converted into a probability before being added to the calculation (1/flood protection).

[268] Our biome shift data were taken from Franz Rubel and Markus Kottek, "Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification," *Meteorologische Zeitschrift (Contributions to Atmospheric Sciences)*, April 2010, Volume 19, Number 2.

Methodologies for climate modeling: Tokyo flooding

Present and future flood risk in Tokyo are estimated using the LISFLOOD-FP flood model version 5.9.[269] LISFLOOD-FP has been tested extensively and produces comparable results to several localized and detailed flood studies conducted by the United States Geological Survey (USGS).[270] Wing et al. (2017) compared the output of a continental United States LISFLOOD-FP model run at a 30-meter resolution to USGS flood risk estimates that utilized elevation data with resolutions between one and ten meters. The LISFLOOD-FP model was able to achieve a consistent hit rate of at least 80 percent across nine USGS flood studies that estimated the one-in-100-year flood event. The critical success index was between 60 and 90 percent for all but one USGS flood benchmark study.[271] Therefore, LISFLOOD-FP was chosen to model flood risk for Tokyo because of its computational efficiency when run at a 30-meter resolution and its ability to accurately estimate flood risk at large spatial scales.

Tokyo is vulnerable to all three sources of flooding: fluvial, pluvial, and coastal. To simulate the worst-case scenario, all three flood sources were used as inputs to model a 24-hour compound flood event (Exhibit A2). In this context, the compound flood event is defined as the flood extent caused by the one-in-100-year rainfall, streamflow, and storm surge events occurring simultaneously. As discussed below, the one-in-100-year rainfall, streamflow, and storm surge values were calculated independently using various data sources. However, this does not mean that the rainfall, streamflow, and storm surge events are probabilistically independent. The probability of an extreme storm surge event can be higher when conditioned on the occurrence of extreme precipitation compared to the probability of extreme storm surge estimated when assuming the two events are independent.[272]

Therefore, to avoid underestimating flood risk, all three flood sources were modeled together to provide a realistic estimate of the one-in-100-year flood event. However, since the rainfall, streamflow, and storm surge values were not calculated using a joint probability distribution, three additional flood model runs were completed for 2050 where each flood source (fluvial, pluvial, and coastal) was individually simulated. This additional analysis was completed to identify the major driver of flooding for different areas of Tokyo.

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[269] P. D. Bates and A. P. J. De Roo, “A simple raster-based model for flood inundation simulation,” *Journal of Hydrology*, September 2000, Volume 236, Issues 1–2, pp. 54–77.

[270] Jeffrey Neal et al., “How much physical complexity is needed to model flood inundation?,” *Hydrological Processes*, July 2012, Volume 26, Issue 15; Tom J. Coulthard et al., “Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: Implications for modelling landscape evolution,” *Earth Surface Processes and Landforms*, December 2013, Volume 38, Issue 15; Oliver E. J. Wing, “Validation of a 30 m resolution flood hazard model of the conterminous United States,” *Water Resources Research*, September 2017, Volume 53, Issue 9.

[271] The hit rate measures how well the model predicted the number of wet cells in the benchmark data. Essentially, the hit rate gives an indication of how much the model underpredicted the validation data. The lower the hit rate, the greater the underprediction. The critical success index accounts for both underprediction and overprediction and so will usually be lower than the hit rate.

[272] S. F. Kew et al., “The simultaneous occurrence of surge and discharge extremes for the Rhine delta,” *Natural Hazards and Earth System Sciences*, August 2013, Volume 13, Issue 8.

Exhibit A2

Rainfall, storm surge, and streamflow patterns vary for a 1-in-100-year flood in Tokyo in 2050.

Based on RCP 8.5

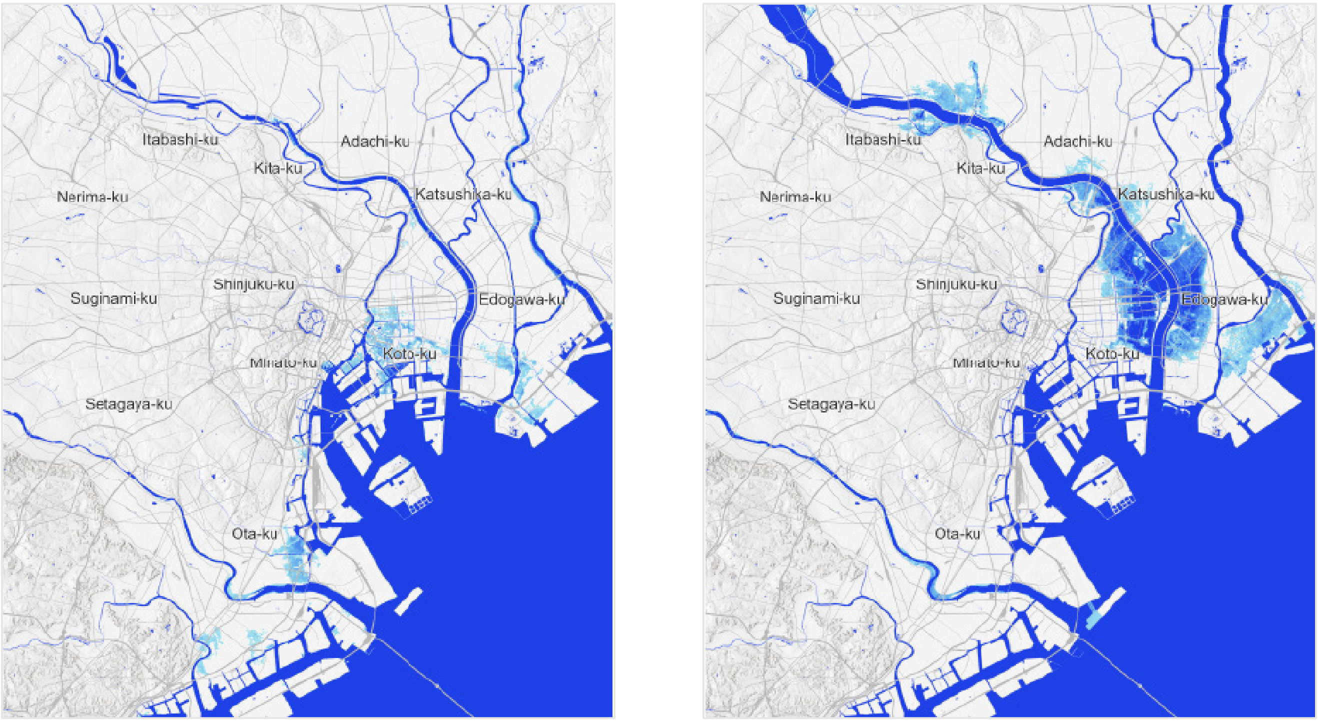
Illustrative examples, 1-in-100-year events in 2050

Water level 15 cm 2+ meters

Rainfall

Storm surge

Streamflow



Note: See the technical appendix of the global report, *Climate risk and response*, McKinsey Global Institute, January 2020, for why we chose RCP 8.5. Following standard practice, 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. The boundaries and names shown on these maps do not imply official endorsement or acceptance by McKinsey & Company.

Source: Woodwell Climate Research Center; McKinsey/United Nations (disputed boundaries); McKinsey Global Institute analysis

Several inputs are required to run the model are described in detail below.

- Elevation data. The final elevation raster is mainly composed of the five-meter raster from the Japanese Geographical Survey Institute.[273] The ten-meter raster from the institute was used to fill in any missing areas in the five-meter raster. The merged raster was then rescaled to a 25-meter resolution raster.

- Flood defenses. An effort was made to ensure that all flooding occurring was a product of the flood model simulation and not an artifact of the elevation data preprocessing. All coastal flood defense elevations identified by the Japanese Ministry of Land, Infrastructure, Transport, and Tourism's Coastal Conservation Facility Dataset were burned into the elevation raster.[274] For the defenses that had no height attributes, a height value was applied using data from Hoshino et al. (2016).[275] River levees were also burned into the elevation data by first tracing the levees using the five-meter elevation raster. Then the elevations of those levees were extracted from the five-meter data and burned into the final 25-meter raster. The levee extraction method may not always capture the highest point of the levee, so areas with errors were corrected through an iterative process of running the model and checking whether the elevations at locations where levees were overtopped matched the five-meter data. Additionally, all floodgates were assumed to be closed and therefore were burned into the elevation raster using nearby levee elevations. Floodgates were identified through the iterative elevation correction process described above.

- Infiltration and stormwater drainage system. Soil infiltration values were calculated using the USDA Soil Conservation Service Curve Number method and the global curve number data set from Jaafar et al. (2019).[276] According to the Japanese National Institute for Land and Infrastructure Management, Tokyo's stormwater drainage system is designed to handle 50 millimeters per hour, so this infiltration rate was applied for all areas where the land cover was classified as urban.

- Rainfall. The 24-hour 100-year rainfall amount was applied using a frequency-based storm rainfall distribution. This distribution consists of nested precipitation depths for different storm durations with the same return period. This storm distribution was selected because of its usefulness within design and engineering frameworks.[277] The precipitation depths for various storm durations were taken from an analysis completed by a Nakagawa River Survey Committee of the Tokyo Metropolitan Construction Bureau.[278] The 2050 100-year rainfall amount was calculated by first estimating the change in probability of the historical (1971–2000) 100-year precipitation event in the 2035–64 period under the RCP 8.5 scenario using output from a regional 0.22° resolution climate model, REMO2015, which was forced by three GCMs. A regional frequency analysis method was used to fit a generalized extreme value distribution by the method of L-moments to the model output.[279] The future median percentile value for the three model runs of the historical 100-year precipitation event was then assigned a precipitation amount based on the observed rainfall record, not model output. From this analysis, the 1971–2000 one-in-100-year rainfall event becomes a one-in-28-year event in 2035–64. While precipitation biases may exist in the raw model output, assessing the extreme rainfall probability change through a percentile-based method reduces the impact of

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[273] "5-meter and 10-meter elevation mesh," *Geographical Survey Institute of Japan*, 2020.

[274] "Coastal conservation facility data," National Land Information Division, National Spatial Planning and Regional Policy Bureau, Ministry of Land, Infrastructure, Transport, and Tourism of Japan, 2012.

[275] Sayaka Hoshino, "Estimation of increase in storm surge damage due to climate change and sea level rise in the Greater Tokyo area," *Natural Hazards*, January 2016, Volume 80, Issue 1.

[276] V. Mockus and A. Hjelmfelt, "Estimation of direct runoff from storm rainfall," in *SCS National Engineering Handbook*, Washington, DC: US Department of Agriculture, Soil Conservation Service, 1972; Hadi H. Jaafar, Farah A. Ahmad, and Naji El Beyrouthy, "GCN250, new global gridded curve numbers for hydrologic modeling and design," *Scientific Data*, 2019, Volume 6.

[277] *Hydrologic modeling system HEC-HMS: Technical reference manual*, US Army Corps of Engineers, 2000.

[278] *How to prepare for the future of the Nakagawa River in Tokyo*, Survey Committee on How to Prepare for the Future of the Nakagawa River in Tokyo, Tokyo Metropolitan Construction Bureau, 2012.

[279] Armelle Reca Remedio et al., "Evaluation of new CORDEX simulations using an updated Köppen–Trewartha Climate Classification," *Atmosphere*, November 2019, Volume 10, Issue 11; J. R. M. Hosking and J. R. Wallis, *Regional Frequency Analysis: An Approach Based on L-Moments*, Cambridge, UK: Cambridge University Press, 2005.

those biases on estimated changes in future extreme precipitation. Finally, while there is temporal variation of the rainfall input, the flood model only allows for a spatially constant rainfall rate.

— Streamflow. The historical 100-year streamflow values were calculated from stream gauge data from the Water Information System of Japan.[280] Streamflow values start below the peak height, peak during the middle two hours of the simulation, and then decrease until the simulation is completed. The starting and ending streamflow values were estimated from previous flood events in the stream gauge records. Since the riverbed topography data were not available, the streamflow values were converted to river stage heights to prevent overestimation of flooding. The future streamflow values were estimated by completing a similar percentile-change extreme value analysis as was done for rainfall, but with discharge data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP).[281] Data from four hydrologic models, which were each forced by four GCMs totaling in 16 distinct model runs, were used for this analysis. As was done for future rainfall estimates, all analyses were completed assuming the RCP 8.5 scenario, and the median future percentile was taken across the 16 model runs. From this analysis, the 1971–2000 one-in-100-year streamflow event becomes a one-in-71-year event in 2035–64. It is noted that future extreme streamflow does not intensify as much as rainfall and that this is consistent with previous publications. Global results of projected changes in extreme streamflow calculated using ISIMIP show a divergence in intensification compared to projections of future precipitation using GCMs, which force the ISIMIP models. A recent ISIMIP study shows that five-day peak streamflow with a historical return period of 30 years increases in magnitude over Asia, Africa, and parts of South America but decreases in magnitude over Europe, North America, and other parts of South America under RCP 8.5 by the end of the 21st century.[282] Meanwhile, maximum five-day precipitation increases over the entire globe, except a few small coastal areas in South America, Africa, and southwestern Australia, by the end of the 21st century under an RCP 8.5 scenario.[283] Therefore, it should not be assumed that if precipitation intensifies, extreme streamflow will also intensify to the same degree. Additionally, a study that modeled future river flows for Japan using a high-resolution hydrologic model found that the historical (1971–2003) one-in-100-year hourly streamflow was 1.3 times more likely to occur in the near future (2015–39) and approximately 1.1 times more likely to occur in the late 21st century (2075–99) in the Tokyo region.[284] However, this study used the SRES A1B scenario which resembles the RCP 6.0 scenario, so it is expected that the results presented in this report will differ.

— Sea level and storm surge. Present storm surge was estimated using data from Hoshino et al. (2016) and Ruiz Fuentes (2014).[285] Sea level and storm surge estimates for 2050 were taken from the scientific literature. Hoshino et al. (2016) estimate an increase in storm surge of 0.2 meter to 0.5 meter in Tokyo Bay by 2100 using the SRES A1B scenario, which closely resembles RCP 6.0. Therefore, these storm surge values are underestimates of future storm surge if RCP 8.5 is assumed. The average increase in storm surge using the nine locations shown in Figure 8 of Hoshino et al. (2016) is 0.31 meter. The future storm surge estimates from Mori et al. (2019) assume a +4°C climate relative to the 1951–2000 climate.[286] Data from the Scenario Model Intercomparision Project for CMIP6 show that

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[280] Water information system, Ministry of Land, Infrastructure, Transport, and Tourism of Japan, 2020.

[281] Lila Warszawski et al., Research design of the intersectoral impact model intercomparison project (ISI-MIP). *Proceedings of the National Academy of Sciences*, accepted, 2013.

[282] Rutger Dankers et al., "First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble," *Proceedings of the National Academy of Sciences*, Volume 111, Number 9.

[283] Matthew Collins et al., "Long-term climate change: Projections, commitments and irreversibility," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[284] Tachikawa Yasuto et al., "Prediction of effects of climate change on river flow in Japan," *Proceedings of JSCE B1 (Water Engineering)*, 2011, Volume 67, Issue 1.

[285] M. J. Ruiz Fuentes, *Storm surge barrier Tokyo Bay: Analysis on a system level and conceptual design*, Delft University of Technology, 2014.

[286] Nobuhito Mori et al., "Future changes in extreme storm surges based on mega-ensemble projection using 60-km resolution atmospheric global circulation model," *Coastal Engineering Journal*, 2019, Volume 61, Issue 3, 295-307.

by 2050 there will be a +2°C climate relative to the 1960–2000 climate under RCP 8.5.[287] Therefore, half of the storm surge increase estimated by Mori et al. (2019) would roughly equal the change in storm surge in 2050 for this project. The increase in storm surge due to a +4°C climate is roughly 0.3 meter for Tokyo, so the increase in storm surge in 2050 would be 0.15 meter. We use 0.15 meter as the increase in storm surge by 2050 as a conservative estimate according to data presented by Hoshino et al. (2016). The 0.15 meter of storm surge was added to the 50th percentile of sea level rise, 0.28 meter, for the Tokyo II tide gauge for 2050 under RCP 8.5, which can be found in supplementary table 7 of Kopp et al. (2014).[288] The fifth percentile and the 95th percentile sea level rise values are 0.11 and 0.46 meter, respectively, for the Tokyo gauge in 2050 under RCP 8.5. The 2050 RCP 8.5 50th percentile global sea level rise is 0.29 meter, which is approximately equal to the sea level rise in Tokyo Bay.

— Floodplain friction values or Manning's n values. Each pixel in the model domain was assigned a friction value based on land cover. High-resolution land cover data are from the Japan Aerospace Exploration Agency, and the friction values come from an analysis completed by the USDA.[289]

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[287] Brian C. O'Neill et al., "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6," *Geoscientific Model Development*, September 2016, Volume 9, Issue 9.

[288] Robert E. Kopp et al., "Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites," *Earth's Future*, August 2014, Volume 2, Issue 8.

[289] ALOS/ALOS-2 Science Project and Earth Observation Priority Research: Ecosystem Research Group, Earth Observation Research Center, High-resolution land use and land cover map of Japan [2014-2016] / Version 18.03, Japan Aerospace Exploration Agency, March 2018; National Resource Conservation Service, USDA, "Manning's n values for various land covers to use for dam breach analyses by NRCS in Kansas," 2016.

Methodologies for climate modeling: Australian wildfires

Fire risk is evaluated using the fire weather index (FWI).[290] FWI is a general metric of fire danger developed by the Canadian Forestry Service and used globally.[291] Calculating FWI requires several meteorological fields; FWI is a function of precipitation, air temperature, wind speed, relative humidity, and snow cover as well as latitude and time of year.[292] Overall, FWI quantifies general fire intensity based on both fuel availability and ease of spread in a unitless daily metric ranging from zero to infinity—values in excess of 150 are rare—with higher numbers indicating more severe fire weather and thus more severe fire risk.[293]

Interpreting FWI values in a risk context is possible only relative to historical values—both of FWI and historical burned area—in a target region. Here, for each region of interest, FWI values are sorted into danger classes.[294] These are used to identify significant FWI thresholds relative to fire occurrence in the historical record and use only the fire season.[295] Because FWI levels associated with the same danger level can be expected to vary in space, these levels facilitate comparison across different geographies.[296] However, before fire danger classes are used for future fire risk, they must be verified for predictive skill. Verification is based on the probability of detection (POD), which quantifies the proportion of past fires that occurred when FWI exceeded a given danger class.

For verification, we calculate historical POD for each country in the Asia–Pacific region. This is a retrospective validation exercise using 2001–13 daily historical FWI and historical burned area. Historical FWI is derived using meteorological inputs from the ERA-Interim product, a global atmospheric reanalysis at approximately 80 km spatial resolution maintained by the European Centre for Medium-Range Weather Forecasts.[297] Historical burned area is based on the Global Fire Emissions Database Version 4.[298] The database is a global product derived mainly from satellite imagery that, in addition to fire emissions of carbon, tabulates daily burned area fraction by pixel on a 0.25-degree regular grid.

Higher levels of POD suggest that FWI has predictive capabilities relative to burned area, and thus fire risk. In the Asia–Pacific region, only Australia and Myanmar exhibited high levels of POD (79 percent and 86 percent respectively). Using Myanmar as an example, 86 percent of all historical fires occurred when FWI exceeded the high danger critical threshold. While we use the high danger class, we also evaluated the very high and extreme classes. But their PODs are always less than the high class. The FWI thresholds denoting the high danger class were 24 and five, respectively, for Australia and Myanmar. It is important to note that in determining the danger class, and thus POD, fire here refers to a fire-pixel-day, or a single pixel where the minimum threshold for area burned (50ha is used throughout) is exceeded for a single day. Historical fire events and perimeters may comprise multiple fire-pixel-days by occurring across multiple pixels, days, or both.

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[290] Joaquín Bedia et al., "Seasonal predictions of Fire Weather Index: Paving the way for their operational applicability in Mediterranean Europe," *Climate Services*, 2018, Volume 9; Francesca Di Giuseppe et al., "The potential predictability of fire danger provided by numerical weather prediction," *Journal of Applied Meteorology and Climatology*, November 2016, Volume 55, Issue 11.

[291] Francesca Di Giuseppe et al., "The potential predictability of fire danger provided by numerical weather prediction," *Journal of Applied Meteorology and Climatology*, November 2016, Volume 55, Issue 11.

[292] Francesca Di Giuseppe et al., "The potential predictability of fire danger provided by numerical weather prediction," *Journal of Applied Meteorology and Climatology*, November 2016, Volume 55, Issue 11; B. D. Lawson and O. B. Armitage, *Weather guide for the Canadian Forest Fire Danger Rating System*, Natural Resources Canada, Canadian Forest Service, 2008, http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/29152.pdf.

[293] B. D. Lawson and O. B. Armitage, *Weather guide for the Canadian Forest Fire Danger Rating System*, Natural Resources Canada, Canadian Forest Service, 2008; Claudia Vitolo, Francesca Di Giuseppe, and Mirko D'Andrea, "Caliver: An R package for CALIbration and VERification of forest fire gridded model outputs," *PLOS ONE*, January 2018, Volume 13, Issue 1; Claudia Vitolo et al., "A 1980–2018 global fire danger re-analysis dataset for the Canadian Fire Weather Indices," *Scientific Data*, February 2019, Volume 6.

[294] Claudia Vitolo, Francesca Di Giuseppe, and Mirko D'Andrea, "Caliver: An R package for CALIbration and VERification of forest fire gridded model outputs," *PLOS ONE*, January 2018, Volume 13, Issue 1; C. E. Van Wagner, *Development and structure of the Canadian Forest Fire Weather Index System*, Canadian Forestry Service, Forestry technical report 35, 1987.

[295] Claudia Vitolo, Francesca Di Giuseppe, and Mirko D'Andrea, "Caliver: An R package for CALIbration and VERification of forest fire gridded model outputs," *PLOS ONE*, January 2018, Volume 13, Issue 1.

[296] Claudia Vitolo et al., "A 1980–2018 global fire danger re-analysis dataset for the Canadian Fire Weather Indices," *Scientific Data*, February 2019, Volume 6.

[297] D. P. Dee et al., "The ERA-Interim reanalysis: Configuration and performance of the data assimilation system," *Quarterly Journal of the Royal Meteorological Society*, April 2011, Volume 137, Issue 656, Part A.

[298] Louis Giglio, James T. Randerson, and Guido R. van der Werf, "Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4)," *JGR: Biogeosciences*, March 2013, Volume 118, Issue 1.

For these two countries, fire risk is quantified using the change in fire days. Here, we apply the FWI threshold defining the high danger class from the validation exercise to denote a fire day. Otherwise, all meteorological inputs—both past and RCP 8.5 for the future—are taken from REMO2015, a 22 km regional climate model based on three global climate models (HadGEM2-ES, MPI-ESM-LR, and NorESM1-M) and a standardized protocol executed globally by CORDEX region.[299] We note that FWI was originally derived based on meteorological conditions at local noon for air temperature, wind speed, and relative humidity, and for the previous 24 hours of total accumulated precipitation. REMO2015 output is significantly coarser in temporal resolution, for example, with only precipitation is available at an hourly timestep. However, the central benefit of using REMO2015 simulations to characterize fire risk is the internal consistency in time and space of a regional climate model. We use REMO2015 mean daily data to calculate FWI.

Before calculating fire days, we apply a simple mean bias correction.[300] The bias between 1998–2017 ERA-Interim and each REMO2015 realization at the percentile corresponding to the FWI high danger class is used to adjust that same REMO2015 realization. These bias-corrected values (median across the three REMO2015 realizations) are then used to quantify 1998–2017 baseline fire risk. After bias correction, the difference (relative bias) in 1998–2017 fire days is 0.5 percent for Australia and 3.4 percent for Myanmar. For each REMO2015 realization—one per global climate model—future fire risk is then quantified as the change in the number of fire days, expressed on a per-year basis, in the 2021–40 and 2041–60 periods relative to the 1998–2017 baseline period. The final mapped values represent the grid cell median across all three realizations. We note that future fire risk is agnostic relative to the simple mean bias correction because the adjustment factor cancels due to differencing.

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[299] Armelle Reca Remedio et al., “Evaluation of new CORDEX simulations using an updated Köppen–Trewartha climate classification,” *Atmosphere*, November 2019, Volume 10, Issue 11.

[300] Douglas Maraun, “Bias correcting climate change simulations—a critical review,” *Current Climate Change Reports*, December 2016, Volume 2, Issue 4.

Wind turbines at sunset.
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Bibliography

A

Ahmed, Justin, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, *Agriculture and climate change: Reducing emissions through improved farming practices*, McKinsey & Company, April 2020.

AIR Worldwide, *Global modeled catastrophe losses*, November 2018.

Allen, Myles R. et al., *Special report: Global warming of 1.5°C*, Intergovernmental Panel on Climate Change, 2018.

Allen, Myles R. et al., "Warming caused by cumulative carbon emissions towards the trillionth tonne," *Nature*, April 2009, Volume 458, Issue 7242.

ALOS/ALOS-2 Science Project and Earth Observation Priority Research: Ecosystem Research Group, Earth Observation Research Center, *High-resolution land use and land cover map of Japan [2014-2016] / Version 18.03*, Japan Aerospace Exploration Agency, March 2018.

The Aotearoa Circle, *Sustainable Finance Forum interim report*, 2019.

Archer, David, "Fate of fossil fuel CO_2 in geologic time," *Journal of Geophysical Research: Oceans*, March 2005, Volume 110, Issue C9.

Asian Development Bank, *Ho Chi Minh City adaptation to climate change*, 2013.

Asian Development Bank, *Investing in natural capital for a sustainable future in the Greater Mekong Subregion*, 2015.

Asian Development Bank, *Meeting Asia's infrastructure needs*, 2017.

Asian Development Bank, *National REDD+ strategies in Asia and the Pacific: Progress and challenges*, 2010.

Asian Development Bank and the Climate Investment Fund, *Developing a private sector portfolio*, 2016.

Asian Development Bank Climate Change and Disaster Risk Management Division, *Country fact sheets*, second edition, Asian Development Bank and the Climate Investment Funds, 2016.

Asuncion, Ruben Carlo, and Minsoo Lee, *Impacts of sea level rise on economic growth in developing Asia*, ADB Economics Working Paper Series number 507, Asian Development Bank, January 2017.

B

Bank of England, *Climate change: What are the risks to financial stability?* https://www.bankofengland.co.uk, November 2020.

Bapna, Manish et al., *Adapt now: A global call for leadership on climate resilience*, Global Commission on Adaptation, September 2019.

Bastin, Jean-Francois et al., "The global tree restoration potential," *Science*, July 2019, Volume 365, Issue 6448.

Bates, P. D., and A. P. J. De Roo, "A simple raster-based model for flood inundation simulation," *Journal of Hydrology*, September 2000, Volume 236, Issues 1–2, pp. 54–77.

Bedia, Joaquín et al., "Seasonal predictions of Fire Weather Index: Paving the way for their operational applicability in Mediterranean Europe," *Climate Services*, January 2018, Volume 9, pp. 101–10.

Belcher, Stephen, Olivier Boucher, and Rowan Sutton, *Why results from the next generation of climate models matter*, Carbon Brief, March 2019.

Bell, M. J. et al., "Effect of breeding for milk yield, diet and management on enteric methane emissions from dairy cows," *Animal Production Science*, August 2010, Volume 50, Number 8.

Bevere, Lucia et al., "Natural catastrophes and man-made disasters in 2018: 'Secondary' perils on the frontline," Swiss Re Institute, *Sigma*, 2019, Number 2.

BP, *BP statistical review of world energy 2019*, 2019.

Burkett, Virginia R. et al., "Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications," *Ecological Complexity*, December 2005, Volume 2, Number 4.

C

C40 Cities, "Case study: Tokyo—Super levees," in *Good practice guide: Climate change adaptation in delta cities*, 2016.

Center for Disaster Philanthropy, *2019–2020 Australian Bushfires*, 2020.

Centre for Research on Epidemiology of Disasters, *Natural disasters 2018*, 2019.

Chakraborty, Debashis et al., "A global analysis of alternative tillage and crop establishment practices," *Scientific Reports*, August 2017, Volume 7.

Chen, Jie et al., “Bias correcting climate model multi-member ensembles to assess climate change impacts on hydrology,” *Climatic Change*, April 2019, Volume 153, Issue 3.

Ciais, Philippe et al., “Carbon and other biogeochemical cycles,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2013.

Climate Action Network Europe, *Climate change adaptation and the role of the private sector*, 2013.

Climate Bonds Initiative and China Central Depository & Clearing Company, *China Green Bond Market 2018*, 2019.

Collins, Matthew et al., “Long-term climate change: Projections, commitments and irreversibility,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

Coulthard, Tom J. et al., “Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: Implications for modelling landscape evolution,” *Earth Surface Processes and Landforms*, December 2013, Volume 38, Issue 15, pp. 1897–906.

D

Dankers, Rutger et al., “First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble,” *Proceedings of the National Academy of Sciences*, March 2014, Volume 111, Number 9, pp. 3257–61.

Dee, D. P. et al., “The ERA-Interim reanalysis: Configuration and performance of the data assimilation system,” *Quarterly Journal of the Royal Meteorological Society*, April 2011, Volume 137, Issue 656, Part A, pp. 553–97.

Di Giuseppe, Francesca et al., “The potential predictability of fire danger provided by numerical weather prediction,” *Journal of Applied Meteorology and Climatology*, November 2016, Volume 55, Issue 11, pp. 2469–91.

Diaz, Delavane B., “Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM),” *Climatic Change*, July 2016, Volume 137, Issue 1–2, pp. 143–56.

Ding, Helen, and Wee Kean Fong, *4 Investment Areas to Stimulate China’s Economy After COVID-19*, World Resources Institute, April 2020.

Dunne, John P. et al., “Reductions in labour capacity from heat stress under climate warming,” *Nature Climate Change*, February 2013, Volume 3, pp. 563–66.

E

Efron, Beran, “Bootstrap methods: Another look at the jackknife,” *The Annals of Statistics*, January 1979, Volume 7, Number 1, pp. 1–26.

Ellen MacArthur Foundation, *Completing the picture: How the circular economy tackles climate change*, 2019.

Emanuel, Kerry, *The Coupled Hurricane Intensity Prediction System (CHIPS)*, MIT, 2019.

F

Farm Progress, *High temperature effects on corn, soybeans*, 2012.

Flato, Gregory et al., “Evaluation of climate models,” in *Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

Forest Stewardship Council Asia Pacific, *Forests and FSC in Asia Pacific*, 2016.

Foster, Josh et al., “A new paradigm to quantify the reduction of physical work capacity in the heat,” *Medicine & Science in Sports & Exercise*, June 2019, Volume 51, Issue 6S.

Free, Christopher M. et al., “Impacts of historical warming on marine fisheries production,” *Science*, March 2019, Volume 363, Number 6430.

G

Gandhi, Prashanti et al., “Which industries are the most digital (and why)?,” *Harvard Business Review*, April 1, 2016.

Giglio, Louis, James T. Randerson, and Guido R. van der Werf, “Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4),” *Journal of Geophysical Research Biogeosciences*, March 2013, Volume 118, Issue 1, pp. 317–28.

Government of India, Department of Environment, Forests, and Climate Change, *India Cooling Action Plan*, 2018.

Government of India, Ministry of Statistics and Programme Implementation, *Statistical Year Book India 2017*, 2017.

Grotch, Stanley L., and Michael C. MacCracken, “The use of general circulation models to predict regional climatic change,” *Journal of Climate*, March 1991, Volume 4, Number 3, pp. 286–303.

H

Haq, Saleemul, *Adapting to climate change: A challenge and an opportunity*, World Resources Institute, 2010.

Harmsen, Jan Hartger Mathijs, *Non-CO_2 greenhouse gas mitigation in the 21st century*, Utrecht University, 2019.

Hasselmann, Klaus, "Is climate predictable?," in *The Science of Disasters: Climate Disruptions, Heart Attacks, and Market Crashes*, Armin Bunde, Jürgen Kropp, and Hans Joachim Schellnhuber, eds., Berlin, Germany: Springer, 2002.

Haustein, Karsten et al., "A real-time Global Warming Index," *Scientific Reports*, November 2017.

Hayhoe, K. et al., "Climate models, scenarios, and projections," in *Climate Science Special Report: Fourth National Climate Assessment (NCA4)*, Volume I, D. J. Wuebbles et al., eds., Washington, DC: US Global Change Research Program, 2017.

Henderson, Kimberly, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020.

Hennemuth, Barbara et al., *Statistical methods for the analysis of simulated and observed climate data: Applied in projects and institutions dealing with climate change impact and adaptation*, Climate Service Center, CSC report number 13, 2013.

Heron, Scott F. et al., *Impacts of Climate Change on World Heritage Coral Reefs: A First Global Scientific Assessment*. Paris, UNESCO World Heritage Centre, 2017.

Hillen, M. et al., "Coastal defence cost estimates: Case study of the Netherlands, New Orleans and Vietnam," *Communications on Hydraulic and Geotechnical Engineering*, Delft University of Technology, April 2010.

Hoegh-Guldberg, Ove et al., "The ocean," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part B: Regional Aspects*, Intergovernmental Panel on Climate Change, New York, NY: Cambridge University Press, 2014.

Hoffmann, Christian, Michel Van Hoey, and Benedikt Zeumer, *Decarbonization challenge for steel*, McKinsey & Company, 2020.

Hoshino, Sayaka et al., "Estimation of increase in storm surge damage due to climate change and sea level rise in the Greater Tokyo area," *Natural Hazards*, January 2016, Volume 80, Issue 1, pp. 539–65.

Hosking, J. R. M., and J. R. Wallis, *Regional Frequency Analysis: An Approach Based on L-Moments,* Cambridge, UK: Cambridge University Press, 2005.

Huber, Markus, and Reto Knutti, "Anthropogenic and natural warming inferred from changes in Earth's energy balance," *Nature Geoscience*, January 2012, Volume 5, Number 1.

Huss, Matthias, and Regine Hock, "Global-scale hydrological response to future glacier mass loss," *Nature Climate Change*, January 2018, Volume 8, Number 2.

I

India Water Portal, *Ice stupas: Water conservation in the land of the Buddha*, 2015.

Insights, "17 countries, home to one-quarter of the world's population, face extremely high water stress," blog entry by Rutger Willem Hofste, Paul Reig, and Leah Schleifer, August 6, 2019.

International Energy Agency, *The future of cooling in China*, 2019.

International Energy Agency, *Southeast Asia Energy Outlook 2019*, 2019.

International Energy Agency, *World Energy Outlook 2019*, 2019.

International Renewable Energy Agency, *Renewable capacity statistics 2020*, March 2020.

International Union for Conservation of Nature, *Issues brief: The ocean and climate change*, 2017.

Ivanov, Martin Aleksandrov, Jurg Luterbacher, and Sven Kotlarski, "Climate model biases and modification of the climate change signal by intensity-dependent bias correction," *Journal of Climate*, August 2018, Volume 31, Number 16.

J

Jaafar, Hadi H., Farah A. Ahmad, and Naji El Beyrouthy, "GCN250, new global gridded curve numbers for hydrologic modeling and design," *Scientific Data*, 2019, Volume 6.

Jat, M. L. et al., *Laser land leveling: A precursor technology for resource conservation*, Rice-Wheat Consortium technical bulletin series 7, Rice-Wheat Consortium for the Indo-Gangetic Plains, 2006.

K

Kew, S. F. et al., "The simultaneous occurrence of surge and discharge extremes for the Rhine delta," *Natural Hazards and Earth System Sciences*, August 2013, Volume 13, Issue 8.

Kirtman, Ben et al., "Near-term climate change: Projections and predictability," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

Knowlton, Kim 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*, April 2014, Volume 11, Issue 4.

Knutson, Thomas R., Fanrong Zeng, and Andrew T. Wittenberg, “Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth century simulations,” *Journal of Climate*, November 2013, Volume 26, Number 22.

Kopp, Robert E. et al., “Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites,” *Earth’s Future*, August 2014, Volume 2, Issue 8, pp. 383–406.

Krinner, Gerhard, and Mark G. Flanner, “Striking stationarity of large-scale climate model bias patterns under strong climate change,” *Proceedings of the National Academy of Sciences*, September 2018, Volume 115, Number 38.

L

Lalit, Radhika, and Ankit Kalanki, *How India is solving its cooling challenge*, Rocky Mountain Institute, 2019.

Lawson, B. D., and O. B. Armitage, *Weather guide for the Canadian Forest Fire Danger Rating System*, Natural Resources Canada, Canadian Forest Service, 2008.

Lenssen, Nathan J. L. et al., “Improvements in the GISTEMP uncertainty model,” *Journal of Geophysical Research: Atmospheres*, June 2019, Volume 124, Number 12.

Li, Xiaochun et al., “CO_2 point emission and geological storage capacity in China,” *Energy Procedia*, February 2009, Volume 1, Issue 1, pp. 2793–800.

Lindner, Marcus et al., “Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems,” *Forest Ecology and Management,* February 2010, Volume 259, Number 4.

Linquist, Bruce A. et al., “Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis,” *Field Crops Research*, August 2012, Volume 135.

Lowe, Jason A., and Daniel Bernie, “The impact of Earth system feedbacks on carbon budgets and climate response,” *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Number 2119.

Lybbert, Travis J. et al., “Targeting technology to increase smallholder profits and conserve resources: Experimental provision of laser land-leveling services to Indian farmers,” *Economic Development and Cultural Change*, January 2018, Volume 66, Number 2.

M

Maraun, Douglas, “Bias correcting climate change simulations—a critical review,” *Current Climate Change Reports*, December 2016, Volume 2, Issue 4, pp. 211–20.

Matthews, H. Damon, and Ken Caldeira, “Stabilizing climate requires near zero emissions,” *Geophysical Research Letters*, February 2008, Volume 35, Issue 3.

Matthews, H. Damon, and Susan Solomon, “Irreversible does not mean unavoidable,” *Science*, April 2013, Volume 340, Issue 6131.

Matthews, H. Damon et al., “Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets,” *Environmental Research Letters*, January 2018, Volume 13, Number 1.

Maurer, J. M. et al., “Acceleration of ice loss across the Himalayas over the past 40 years,” *Science Advances*, June 2019, Volume 5, Number 6.

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

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

McKinsey & Company, *Meeting Japan’s Paris Agreement targets—more opportunity than cost*, 2020.

McKinsey Energy Insights, *McKinsey Global Energy Perspective 2019: Reference case*, 2019.

McKinsey Global Institute, *Climate risk and response: Physical hazards and socioeconomic impacts*, January 2020.

McKinsey Global Institute, *The future of Asia: Asian flows and networks are defining the next phase of globalization*, September 2019.

McKinsey Global Institute, *How will African farmers adapt to changing patterns of precipitation?*, May 2020.

McKinsey Global Institute, *Resource revolution: Meeting the world’s energy, materials, food, and water needs*, November 2011.

McKinsey Global Institute, *Will India get too hot to work?*, November 2020.

McKinsey Global Institute, *Will the world’s breadbaskets become less reliable?*, May 2020.

Meehl, Gerald A. et al., “Decadal prediction: Can it be skillful?,” *Bulletin of the American Meteorological Society*, October 2009, Volume 90, Number 10.

Millar, Richard J., and Pierre Friedlingstein, “The utility of the historical record for assessing the transient climate response to cumulative emissions,” *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Number 2119.

Miller, Ron L. et al., “CMIP5 historical simulations (1850–2012) with GISS ModelE2,” *Journal of Advances in Modeling Earth Systems*, June 2014, Volume 6, Number 2.

Mockus, V., and A. Hjelmfelt, “Estimation of direct runoff from storm rainfall,” in *SCS National Engineering Handbook*, Washington, DC: US Department of Agriculture, Soil Conservation Service, 1972.

Mori, Nobuhito et al., “Future changes in extreme storm surges based on mega-ensemble projection using 60-km resolution atmospheric global circulation model,” *Coastal Engineering Journal,* 2019, Volume 61, Issue 3, pp. 295–307.

Mudelsee, Manfred, “The bootstrap in climate risk analysis,” in *In Extremis: Disruptive Events and Trends in Climate and Hydrology,* Jurgen P. Kropp and Hans Joachim Schellnhuber, eds., Heidelberg, Germany: Springer, 2011.

N

National Bureau of Statistics of China, *China Statistical Yearbook 2018,* 2017.

Neal, Jeffrey et al., “How much physical complexity is needed to model flood inundation?,” *Hydrological Processes,* July 2012, Volume 26, Issue 15, pp. 2264–82.

New Economic Foundation, *The Marine Socio-Economics Project (MSEP): Valuing the environment in economic terms,* 2011.

New Zealand Ministry for the Environment and Stats NZ, *New Zealand’s Environmental Reporting Series: Environment Aotearoa 2019,* 2019.

Nguyen Thi Bich Thuy, *Case study: reduced climate change resilience—the need for a new model*, SNV Netherlands Development Organisation, August 2019.

O

Ocean Acidification International Coordination Centre, *Ocean acidification in the IPCC Special Report: Global warming of 1.5°C,* October 2018.

Olhoff, Anne et al., *The adaptation finance gap report,* UNEP DTU Partnership, 2016.

O’Neill, Brian C. et al., “The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6,” *Geoscientific Model Development,* September 2016, Volume 9, Issue 9.

Oppenheimer, Michael et al., “Sea level rise and implications for low-lying islands, coasts and communities,” in *IPCC special report on the ocean and cryosphere in a changing climate,* Hans-Otto Pörtner et al., eds., Intergovernmental Panel on Climate Change, 2019.

Organisation for Economic Co-operation and Development, *The future of hydrogen: Seizing today’s opportunities,* 2019.

Organisation for Economic Co-operation and Development, *OECD Green Growth Policy Review of Indonesia 2019,* 2019.

P

Parnell, Andrew C., “Climate time series analysis: Classical statistical and bootstrap methods,” *Journal of Time Series Analysis,* March 2013, Volume 34, Issue 2.

Peng, Shushi et al., “Surface urban heat island across 419 global big cities,” *Environmental Science & Technology*, January 2012, Volume 46, Issue 2.

Practical Action, *Floating gardens in Bangladesh: Technical brief,* The Schumacher Centre for Technology and Development, 2006.

Prather, Michael et al., “Climate system scenario tables,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

Q

Quantified Ventures, *Atlanta: First publicly offered environmental impact bond,* 2019.

R

Raymond, Colin, Tom Matthews, and Radley M. Horton, “The emergence of heat and humidity too severe for human tolerance,” *Science Advances*, May 2020.

Remedio, Armelle Reca et al., “Evaluation of new CORDEX simulations using an updated Köppen–Trewartha Climate Classification,” *Atmosphere,* November 2019, Volume 10, Issue 11.

Republic of Indonesia, *National Action Plan for greenhouse gas emissions reduction (RAN-GRK),* Presidential Decree number 61/2011, 2011.

Riahi, Keywan, Arnulf Grubler, and Nebojsa Nakicenovic, “Scenarios of long-term socio-economic and environmental development under climate stabilization,” *Technological Forecasting and Social Change*, September 2007, Volume 74, Issue 7.

Riahi, Keywan et al., “The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview,” *Global Environmental Change*, January 2017, Volume 42.

Ritchie, Justin, and Hadi Dowlatabadi, “The 1000 GtC coal question: Are cases of vastly expanded future coal combustion still plausible?,” *Energy Economics*, June 2017, Volume 65.

Ritchie, Justin, and Hadi Dowlatabadi, “Why do climate change scenarios return to coal?,” *Energy*, December 2017, Volume 140, Part 1.

Rosenzweig, Cynthia et al., “The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies,” *Papers in Natural Resources,* 2013.

Rosenzweig, Cynthia et al., “Coordinating AgMIP data and models across global and regional scales for 1.5C and 2C assessments,” *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Issue 2113.

Royal Norwegian Embassy in Jakarta, Project Support, 2020.

Rubel, Franz, and Markus Kottek, “Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification,” *Meteorologische Zeitschrift (Contributions to Atmospheric Sciences)*, April 2010, Volume 19, Number 2.

Ruiz Fuentes, M. J., *Storm surge barrier Tokyo Bay: Analysis on a system level and conceptual design*, Delft University of Technology, 2014.

S

Sass, Ronald L., “CH_4 emissions from rice agriculture,” in *IPCC good practice guidance and uncertainty management in national greenhouse gas inventories*, IPCC, 2003.

Schmidli, Jurg et al., “Downscaling from GCM precipitation: A benchmark for dynamical and statistical downscaling methods,” *International Journal of Climatology*, April 2006, Volume 26, Number 5, p. 679–89.

Schwalm, Christopher R., Spencer Glendon, and Philip B. Duffy, “RCP8.5 tracks cumulative CO_2 emissions,” *Proceedings of the National Academy of Sciences*, August 2020.

Seidl, Rupert et al., “Forest disturbances under climate change,” *Nature Climate Change*, June 2017, Volume 7, Number 6.

Shastri, Hiteshri et al., “Flip flop of day-night and summer-winter surface urban heat island intensity in India,” *Scientific Reports*, January 2017, Volume 7.

Sherwood, Steven C., 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, pp. 9552–5.

Shrestha, Arun Bhakta et al., eds., *The Himalayan climate and water atlas: Impact of climate change on water resources in five of Asia’s major river basins*, CIMOD, GRID-Arendal, and CICERO, 2015.

Sillmann, Jaana et al., “Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities,” *Weather and Climate Extremes*, December 2017, Volume 18.

SNV Netherlands Development Organisation, *MAM-II: Scaling up ecosystem-based adaptation in the Mekong Delta*, https://snv.org, November 2020.

Stern, Nicholas, *The Economics of Climate Change: The Stern Review*, Cambridge, UK: Cambridge University Press, 2007.

Stull, Roland, “Wet-bulb temperature from relative humidity and air temperature,” *Journal of Applied Meteorology and Climatology*, November 2011, Volume 50, pp. 2267–9.

Sun, Yin et al., “Anthropogenic influence on the heaviest June precipitation in southeastern China since 1961,” *Bulletin of the American Meteorological Society*, January 2019, Volume 100, Number 1.

Survey Committee on How to Prepare for the Future of the Nakagawa River in Tokyo, *How to prepare for the future of the Nakagawa River in Tokyo*, Tokyo Metropolitan Construction Bureau, 2012.

T

Takashi, Sakakibara, *Current Status and Future of Urban Stormwater Management on Wastewater System in Japan*, National Institute for Land and Infrastructure Management of Japan, 2010.

Tata Trusts, *Defeating drought*, 2019.

Taylor, Karl E., Ronald J. Stouffer, and Gerald A. Meehl, “An overview of CMIP5 and the experiment design,” *Bulletin of the American Meteorological Society*, April 2012, Volume 93, Number 4.

Tonby, Oliver, Jonathan Woetzel, Noshir Kaka, Wonsik Choi, Jeongmin Seong, Brant Carson, and Lily Ma, *How technology is safeguarding health and livelihoods in Asia*, McKinsey & Company, May 2020.

The Treasury of New Zealand, *Natural capital and the Living Standards Framework*, 2018.

Triyono, Budi et al., *Study on Utilization of Indonesian Non-Recycled Municipal Solid Waste as Renewable Solid Fuel*, 2017.

Tukimat, Nurul Nadrah Aqilah, “Assessing the implementation of bias correction in the climate prediction,” *IOP Conference Series: Materials Science and Engineering*, April 2018, Volume 342.

U

UNICEF Philippines and International Organization for Migration, *Building safe spaces for the community*, 2018.

United Nations Framework Convention on Climate Change, *Paris Agreement*, 2015.

US Army Corps of Engineers, *Hydrologic modeling system HEC-HMS: Technical reference manual*, 2000.

V

van de Vuurst, Paige, and Luis E. Escobar, “Perspective: Climate change and the relocation of Indonesia’s capital to Borneo,” *Frontiers in Earth Science*, January 2020.

van Oldenborgh, Geert Jan et al., “Attribution of the Australian bushfire risk to anthropogenic climate change,” *Natural Hazards and Earth System Sciences*, March 2020.

van Oldenborgh, Geert Jan et al., “Extreme heat in India and anthropogenic climate change,” *Natural Hazards and Earth System Sciences*, January 2018, Volume 18, Number 1, pp. 365–81.

van Vuuren, Detlef P. et al., “The Representative Concentration Pathways: An overview,” *Climatic Change*, November 2011, Volume 109, Issue 1–2.

van Wagner, C. E., *Development and structure of the Canadian Forest Fire Weather Index System*, Canadian Forestry Service, Forestry technical report number 35, 1987.

Velasquez, Patricio, Martina Messmer, and Christoph C. Raible, “A new bias-correction method for precipitation over complex terrain suitable for different climate states,” *Geoscientific Model Development* preprint, July 2019.

Viking Genetics, *Lower methane production through breeding*.

Vitolo, Claudia, Francesca Di Giuseppe, and Mirko D’Andrea, “Caliver: An R package for CALIbration and VERification of forest fire gridded model outputs,” *PLOS ONE*, January 2018, Volume 13, Issue 1.

Vitolo, Claudia et al., “A 1980–2018 global fire danger re-analysis dataset for the Canadian Fire Weather Indices,” *Scientific Data*, February 2019, Volume 6.

von Peter, Goetz, Sebastian von Dahlen, and Sweta C. Saxena, *Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes*, BIS Working Papers, number 394, December 2012.

W

Warszawski, Lila et al., “The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework,” *Proceedings of the National Academy of Sciences*, March 2014, Volume 111, Number 9.

Wester, Philippus et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Cham, Switzerland: Springer, 2019.

Wing, Oliver E. J. et al., “Validation of a 30 m resolution flood hazard model of the conterminous United States,” *Water Resources Research*, September 2017, Volume 53, Issue 9, pp. 7968–86.

Woetzel, Jonathan, Kimberly Henderson, Mekala Krishnan, Haimeng Zhang, and Grace Lam, *Leading the battle against climate change: Actions for China*, McKinsey & Company, 2020.

Woetzel, Jonathan, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Peter Cooper, *Can coastal cities turn the tide on rising flood risk?*, McKinsey & Company, April 2020.

World Bank, *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium*, Washington, DC: World Bank, 2011.

World Resources Institute, *A once in a generation opportunity*, 2012.

World Wildlife Fund and Asian Development Bank, *Ecological footprint and investment in natural capital in Asia Pacific*, 2012.

Y

Yao, Tandong et al., “Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding regions,” *Arctic, Antarctic, and Alpine Research*, November 2007, Volume 39, Number 4.

Yasuto, Tachikawa et al., “Prediction of effects of climate change on river flow in Japan,” *Proceedings of JSCE B1 (Water Engineering)*, 2011, Volume 67, Issue 1.

Z

Zhang, Guoqing et al., “Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009),” *Remote Sensing of Environment*, July 2011, Volume 115, Number 7.

Zhang, Shaohui et al., “Integrated assessment of resource-energy-environment nexus in China’s iron and steel industry,” *Journal of Cleaner Production,* September 2019, Volume 232, pp. 235–49.

Zhu, Chunwu et al., “Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries,” *Science Advances*, May 2018, Volume 4, Number 5.

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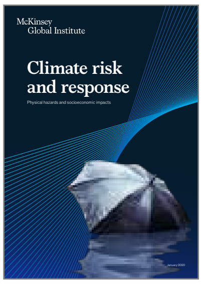

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McKinsey Global Institute
November 2020

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