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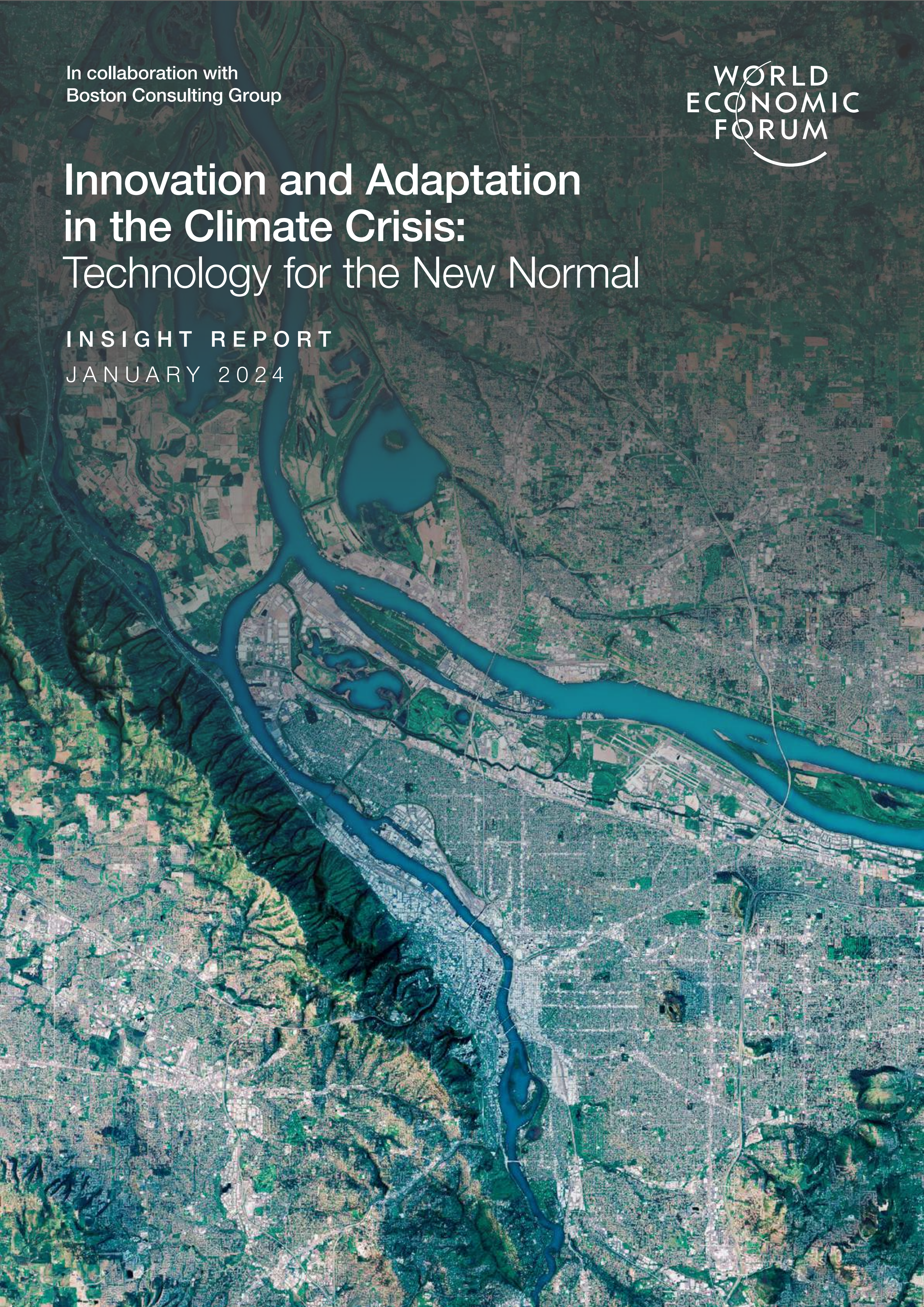
WORLD ECONOMIC FORUM

Innovation and Adaptation in the Climate Crisis: Technology for the New Normal

INSIGHT REPORT

JANUARY 2024



Images: Getty Images

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Foreword

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Recent years have seen extreme weather events wrack the globe – from the 2021 flooding in Germany to this past year's wildfires in Hawaii, Eastern Canada and Australia – leaving little doubt that the impacts of climate change are arriving. The climate science is clear that these impacts will become more volatile: the continuation of current emissions and nature degradation correlate with increased sudden- and slow-onset events within this decade. Mitigating greenhouse gas (GHG) emissions has never been more urgent. At the same time, communities, businesses and governments must adapt to present and oncoming changes.

Adaptation is the process of evolving to the effects of change – in this case, adjusting ecological, social and economic systems to alleviate the impacts of climate change. This includes crisis response for extreme events such as flooding and wildfires. It also encompasses multi-faceted, agile approaches for navigating a world where reliable climate and weather conditions can no longer be taken for granted. Leaders need new forms of intelligence to build resilience into their communities and businesses. Along the way, first-movers will find this is not only a risk mitigation strategy but also a source of competitive advantage.

There are multiple interdependent approaches to climate adaptation, including economic incentives, policy and regulation, locally-led intervention, and nature-based approaches. Technology is a key enabler across all of them – helping leaders not only to assess climate risk but also to identify solutions and to build resilience in the real world. Data-driven and digital technologies, in particular, will be a critical source of adaptive value protection and creation. Advances in these technologies – particularly artificial intelligence (AI) – have been one of the major stories of 2023. This report outlines the roles that data-driven and digital technologies can play in supporting climate adaptation, from strengthening risk analytics and climate-proofing supply chains to powering R&D and discovery processes to yield the next generation of climate technologies.

The Tech for Climate Adaptation Working Group, hosted by the World Economic Forum's Centre for the Fourth Industrial Revolution, convened to develop this report and advance applications and knowledge related to technology for climate adaptation. The working group includes leaders and experts from technology, industry, the public sector, academia and civil society. Its members have been essential to charting the scope of this report and bringing domain-specific insight to its chapters.

There is no technological silver bullet for climate change. More to the point, there is no substitute for deep and swift mitigation of GHG emissions. The impacts of climate change are here and cannot be ignored. Technology offers a way to manage these impacts – to adapt and bring more clarity to an uncertain future.

Executive summary

The impacts of climate change are intensifying and data-driven and digital technologies can help.

The impacts of climate change – in the form of extreme and slow-onset events – are increasing in frequency and intensity. The World Economic Forum's 2024 *Global Risks Report* ranked extreme weather events as the second-most severe risk over the next two years – and the most severe over a 10-year horizon. Nearly half of the world's population is vulnerable to the impacts of climate change. Virtually every sector of the global economy is exposed to some degree of climate-related risk.

Technology is integral to building adaptive capacity, propelling innovation and bringing new capabilities to leaders and communities. There is no technological panacea that can tackle climate change; there is no substitute for deep and swift mitigation of greenhouse gas (GHG) emissions. However, technology – specifically data-driven and digital technology – can help leaders manage the mounting risks associated with climate impacts and unlock new opportunities along the way. An emerging set of technologies – all synergistic with artificial intelligence (AI) and advanced computing – support a comprehensive strategy for adaptation and play a key role at each stage of the "adaptation cycle":

Comprehending risks and opportunities – AI, Earth observation, the internet of things (IoT) and drones are transforming how leaders gather, process and analyse information. These technologies provide intelligence on how the Earth is changing at the planetary level and how the impacts may be felt by businesses and local communities.

Building resilience against climate impacts – AI is helping build resilience into critical infrastructure, such as flood management systems, through optimization and real-time maintenance. Earth observation and IoT are bringing new precision to critical resilience tools such as early-warning systems.

Responding dynamically when impacts hit – Earth observation, along with drones, can provide a view of hard-to-reach areas in the aftermath of an extreme event. Drones are also being used to make deliveries of emergency aid and support search-and-rescue operations. AI's capabilities for prediction and optimization improve situational awareness.

The climate crisis demands adaptation. Data-driven and digital technologies already play a mission-critical role in adaptation efforts across the world; they are poised for scaled adoption and greater impact when supported by open collaboration, improved financing and an enabling policy environment.

Introduction

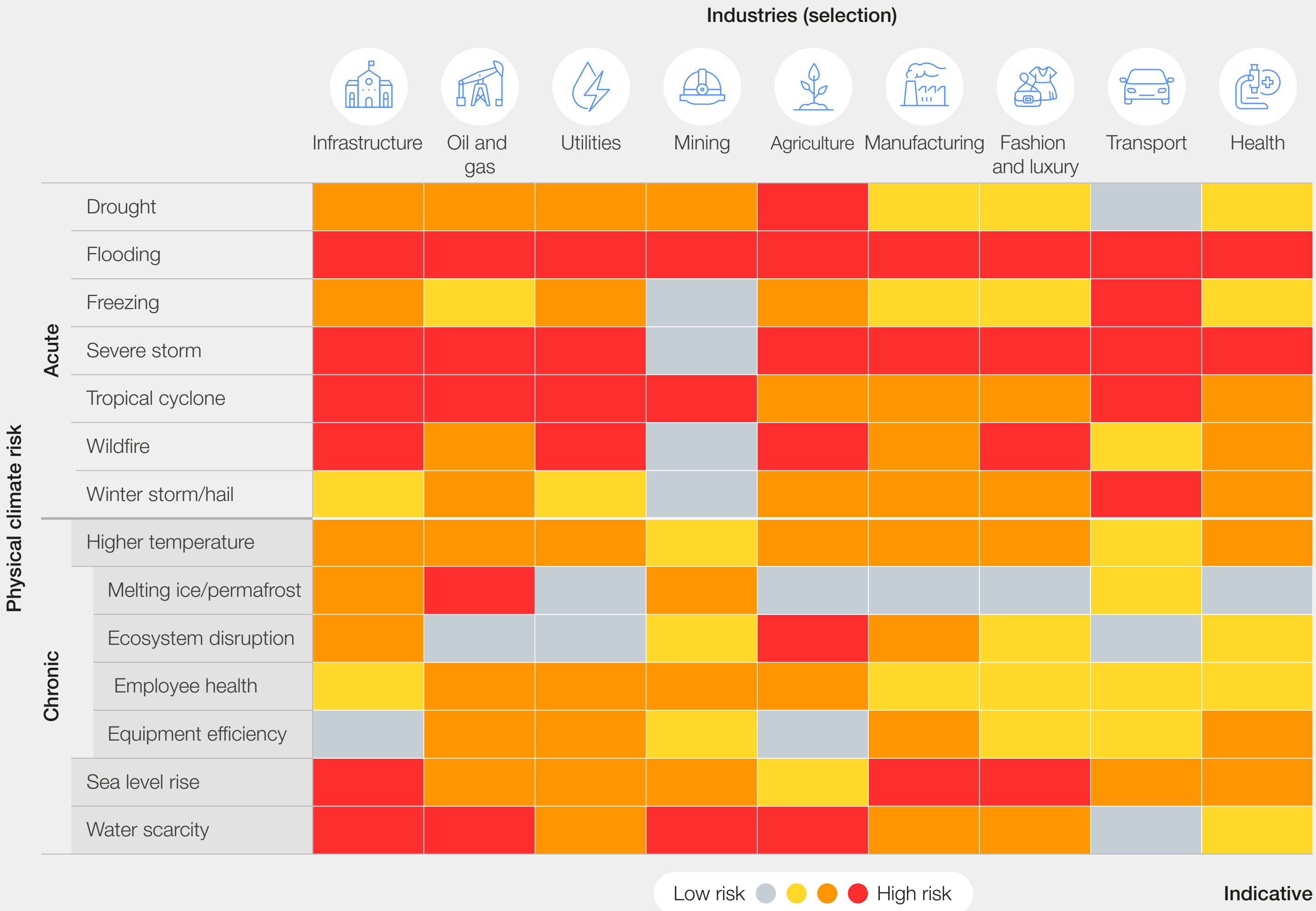
Towards a technology-led approach to climate adaptation.

It is official – 2023 was the hottest year in recorded history.[1] June was the warmest June on record, July the warmest July, August the warmest August, September the warmest September and October the warmest October.[2] Across the year, roughly one in every three days breached the 1.5ºC threshold.[3] Climate change is accelerating at an unprecedented pace.

The fallout is evident.[4] The number of extreme weather events, such as heatwaves, wildfires and hurricanes, has increased in recent years.[5] If these trends persist, extreme events could increase to 560[6] a year by 2030 – 1.5 a day – representing a 40% increase over 2015.[7] In addition to human suffering, the costs are huge; in 2022, natural disasters cost governments and businesses over $200 billion – 40% greater than the annual average for the past 20 years (excluding earthquakes).[8]

Extreme weather events are not the only impacts of climate change. Slow onset events,[9] such as increasing global temperatures, are damaging agriculture, biodiversity and human health. Glaciers and polar icecaps are melting, with rising sea levels threatening coastal communities through erosion, flooding and saltwater intrusion. Seasonal precipitation patterns are changing, resulting in greater rainfall in some areas and desertification in others. The United Nations Environment Programme's David Jensen states, "In many parts of the world, the predictability that used to exist in seasonal weather patterns is simply gone".

FIGURE 1 **All industries are exposed to some level of climate risk through acute and chronic hazards**



Sources: BCG analysis; Zawadzki, Annika, Lorenzo Fantini and Giovanni Covazzi, "Coming to Grips with Corporate Climate Risk", *BCG*, 20 November 2023, https://www.bcg.com/publications/2023/coming-to-grips-with-corporate-climate-risk.

In 2019, the Global Commission on Adaptation estimated that investing $1.8 trillion in climate adaptation measures by 2030 could yield $7.1 trillion in net benefits.

Climate change today threatens people, businesses and nature. In vulnerable regions across the world, between 3.3 and 3.6 billion people are exposed to the impacts of climate change.[10] "The impacts of climate change, while felt globally, do depend on where in the world you are. The vulnerable are hit the hardest," says Christer Solheim Gundersen of Norwegian Agency for Development Cooperation (NORAD). In business, $4 trillion in corporate assets could be at risk by 2030 due to the impacts of climate change.[11] Nearly every sector of the global economy is exposed to some degree of climate-induced risk (see Figure 1). In the natural world, six of nine planetary boundaries have been crossed,[12] painting a grim picture of the Earth's health. Climatic, natural and socioeconomic systems may be close to tipping points, where relatively small changes lead to irreversible shifts.

As history shows, it is not the strongest species that survives nor the most intelligent – but those most adaptable to change. Thus, these indicators not only heighten the urgency for mitigating anthropogenic impacts on the climate but also bring attention to the need for people, businesses and governments to adapt.

In recent years, studies have estimated the economic damages associated with climate impacts and the possible benefits of tackling them. In 2019, the Global Commission on Adaptation estimated that investing $1.8 trillion in climate adaptation measures by 2030 could yield $7.1 trillion in net benefits.[13] Based on these estimates and other analyses, an increasing number of governments have enacted laws and issued protocols related to climate adaptation. The number of countries with national adaptation plans is increasing year-on-year.[14] Moreover, the emergence of climate-resilient industries and technologies, such as resilient agriculture, have presented opportunities for governments and businesses to "climate-proof" their futures.

BOX 1

Climate adaptation definition

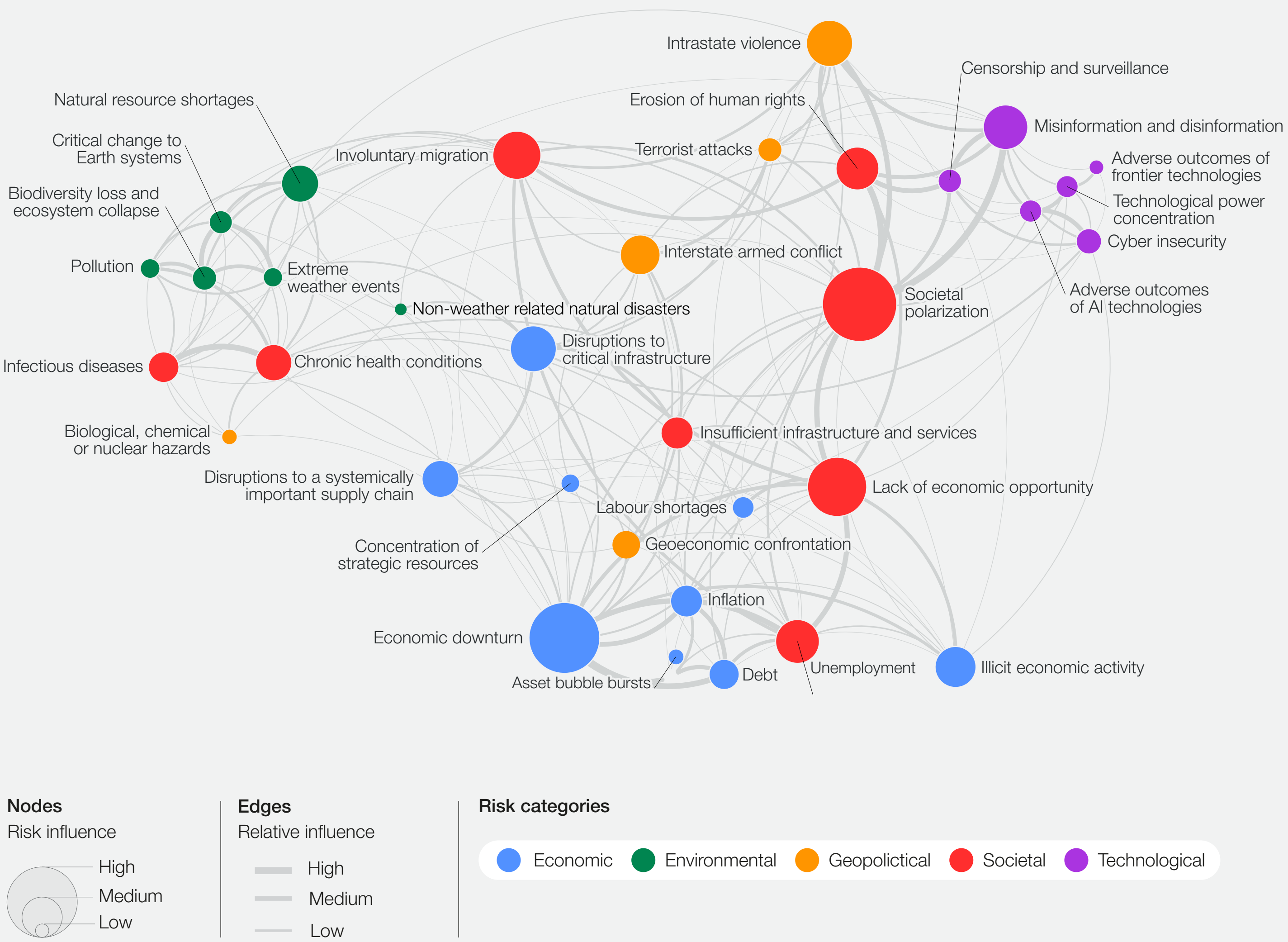
Actions taken to adjust processes, practices and structures to moderate potential damages or to benefit from opportunities associated with the **effects** of climate change.

Notes: 1. Based on the UNFCCC definition;
2. Encompasses activities referred to as "climate resilience" or "adaptation and resilience".

Numerous adaptation strategies have been developed to make the world more resilient to the impacts of climate change. They range from building stronger infrastructure and developing early warning systems to implementing flood control measures and changing agricultural practices. These strategies broadly fall into four groups: regulatory, economic, sociocultural and nature-based. Taken together, these interdependent strategies can be viewed through the lens of what climate and social scientists call adaptive capacity.[15] According to Gail Whiteman, Professor of Sustainability at the University of Exeter and Executive Director of Artic Basecamp, "It's all about building adaptive capacity. Focusing at the systems level to adapt our social, ecological and economic processes. Indeed, we can think of adaptation as an **ongoing process**".

Data-driven and digital technologies are uniquely suited to build adaptive capacity and tackle the multi-variable, complex problems involved in climate decision-making (see Figure 2). These technologies can deal with the inter-connectedness of natural, socioeconomic and economic systems, cope with many variables and degrees of uncertainty, and align climate action across multiple time horizons and imperatives. On this later point, Naoko Ishii, Director of the Center for Global Commons at the University of Tokyo, says, "Adaptation needs to take a long-term, strategic viewpoint. Historically, adaptation has been considered as a short-term or ad hoc response to specific events – separate from mitigation strategy. Data and technology can help to align these strategies for the long-term." This is the kind of intelligence that the climate crisis demands.

FIGURE 2 | **Global risks landscape**



Source: World Economic Forum, *Global Risks Perception Survey 2023-2024*, 2024

For global leaders, public and private alike, data-driven and digital technologies will create and protect value. They will enable leaders in a wide range of ways, from supporting decision-making and powering scientific discovery to changing behaviours. At the same time, technology-based adaptation requires policy development, community engagement and international cooperation to work. A multistakeholder approach is essential for efforts to scale rapidly and advance the world's response to climate change.

Mapping the technology landscape

A set of data-driven and digital technologies are emerging as mission-critical tools for climate adaptation.

FIGURE 3 **High-level definitions**

Artificial intelligence*	Drones	Earth observation
Family of **mathematical and computer science techniques**, including advanced analytics, big data analytics, machine learning, deep learning and large language models.	**Unmanned aerial vehicles (UAVs)** that can be equipped with cameras, cover large distances and carry small amounts of physical material.	**Remote-sensing** (e.g. satellites) or **in situ techniques** (e.g. weather stations) for gathering information about activities on Earth.
Advanced computing	**IoT**	**AR/VR****
Super-computing (including cloud-based) and **quantum computing processes** that enhance compute power, accuracy and speed.	**Networked devices** (including sensors and hand-held devices) that work together to **collect and share data and monitor systems.**	Tools that provide **immersive experiences**, either by superimposing digital features on physical environments or using hardware (e.g. headsets) to fully immerse users.

Notes: *Extended definition on p. 16. **Augmented reality/virtual reality

Technologies of the Industrial Revolution have been a significant driver of climate change[16] – but new and emerging technologies can help leaders adapt to the changing climate of the 21st century. Technology will enable leaders to enhance industry resilience, protect ecosystems and safeguard human well-being.

A confluence of factors, such as scientific and technological developments, policy support, market demand and a rising sense of urgency, are driving the development of path-breaking technologies for climate adaptation. This convergence is catalysing innovation and opening new pathways to build adaptive capacity into organizations and communities worldwide.

Introducing the technologies

A set of data-driven and digital technologies – all synergistic with artificial intelligence (AI) – are emerging as mission-critical tools for climate adaptation. The specific technologies that are the focus of this report are drones, the internet of things (IoT), Earth observation, augmented and virtual reality (AR and VR), advanced computing and AI. Together, they comprise a first-of-its-kind toolkit for climate adaptation.

Given the urgency of the climate crisis, the selection of these technologies is based on either of two key criteria: firstly, their readiness for immediate use, and secondly, their vast potential for impactful contribution. Consequently, emphasis has been placed firstly on technologies that currently provide vital solutions for climate adaptation, and secondly, on those that are developing rapidly and are expected to yield significant benefits for future climate resilience.

Moreover, these technologies have applications across the data life cycle.[17] Each phase embodies different challenges and opportunities. This report therefore endeavours to explore technologies located at various phases of the life cycle (e.g. how IoT can be used for data collection; and machine learning (ML), further downstream, for data analysis).

While the six technologies analysed in this report can work autonomously, their impact can be expanded when used in concert. This report covers both modes of operation. For instance, in the wake of a hurricane, Earth observation can work autonomously to capture images of damaged buildings, or these images can be used with AI-based systems to help insurers process damage claims.[18]

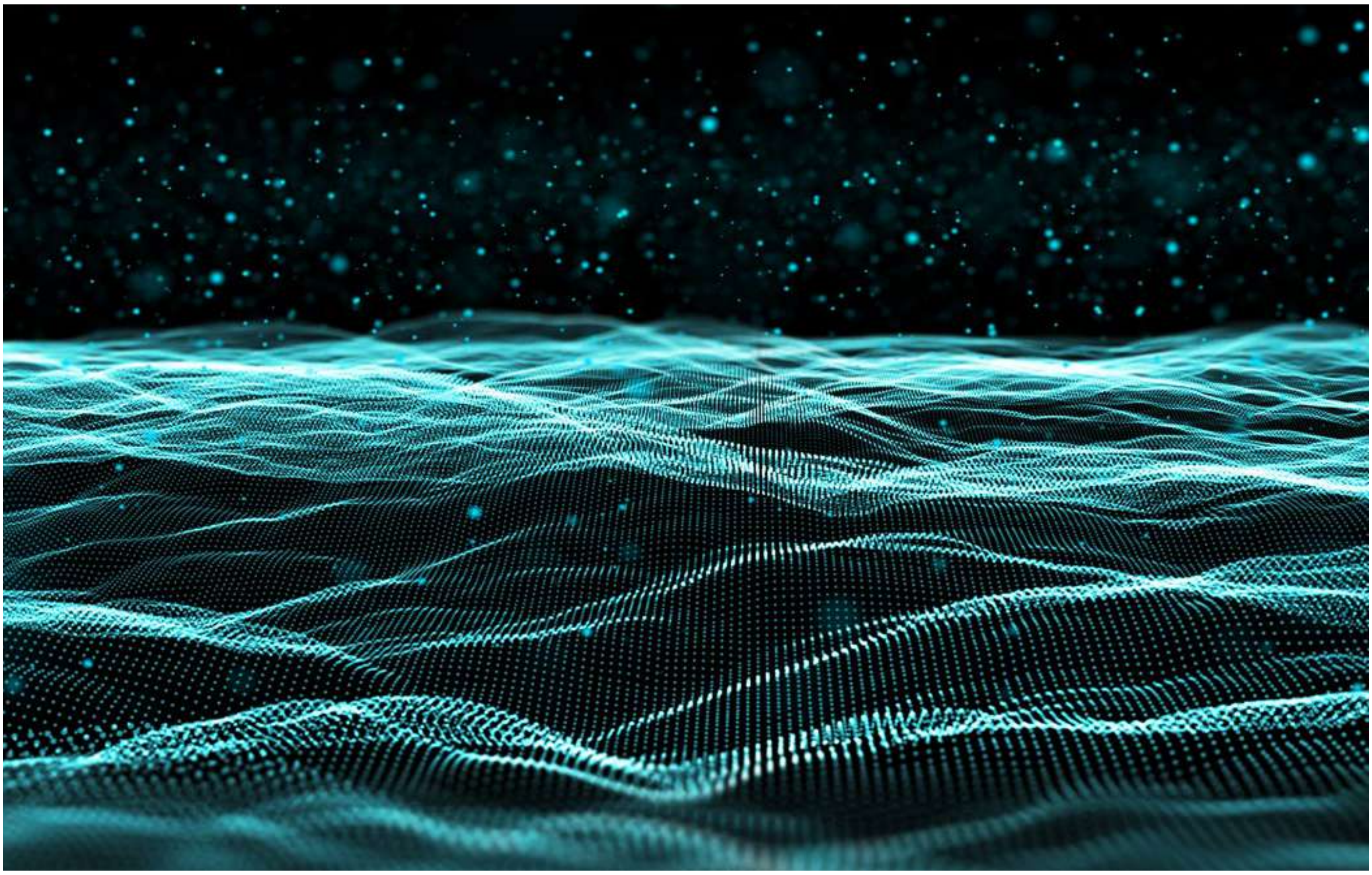
To secure a sustainable future, advanced technology should be centred in climate adaptation strategies. The key lies not just in developing and deploying these technologies, but also in using them for discovery processes that will invent future solutions.

FIGURE 4 | How technology powers climate adaptation

The technologies
A suite of advanced technologies, all synergistic with AI, are entering the mainstream and emerging as critical tools for climate adaptation. These tools are located at different points of the data life cycle; they are sometimes used autonomously, sometimes in concert.

Their capabilities
The technologies produce a set of capabilities that leaders can apply for real-world impact. These capabilities range from predictive decision-making to nudging behaviour change. In different ways, these capabilities rely on digital intelligence – and all are valuable for driving climate adaptation.

The adaptation cycle
Leaders can put these capabilities to work in their climate adaptation strategies. An effective and comprehensive strategy follows the "adaptation cycle", which encompasses: 1) comprehending risks and opportunities, 2) building resilience against future impacts, and 3) responding dynamically when climate impacts hit.



> The key lies not just in developing and deploying these technologies, but also in using them for discovery processes that will invent future solutions.

The "so what" – the capabilities rising from advanced technology

To realize technology's potential for adaptation, it is important to understand the **capabilities** that it provides to leaders. The set of advanced technologies featured in this report supports the development of five different capabilities:

Gather, process and complete datasets: Technology enables leaders to work with vast amounts of information. For instance, private companies have launched their own satellites, expanding the collection of planetary data. IoT, on the other hand, allows for sensor platforms that collect localized data. AI enables summary of this data[19] and delivers new capabilities to complete temporally- and spatially-sparse datasets.

Strengthen planning and decision-making: The flagship capability of AI is to study complex problems and predict future effects. These predictive powers are transforming planning and decision-making. For instance, AI makes it possible to calculate the financial, operational and social impacts of an investment in climate resilience – and, crucially, to predict the costs of inaction. Both are essential to prioritize potential actions and allocate resources efficiently.

Optimize processes in real-time: AI performs best when given enough data to capture underlying patterns. Certain classes of ML algorithms are well-suited for optimization problems – for example, identifying a trade route that minimizes climate risk – and can iterate through multiple strategies until they have identified the best outcome. Additionally, these algorithms can rapidly adjust parameters (e.g. in the event of an unexpected climate shock to the supply chain) and provide dynamic updates.

Power discovery processes: AI is transforming science because of the volumes and forms of data (i.e. structured and unstructured data) it can study and the speed at which it can do so. That is how deep learning tools, such as Google DeepMind's Alpha Fold, have pioneered methods to determine the structure of proteins from the sequence of amino acids.[20] Similarly, climate and weather researchers are using AI to approximate complex physical and chemical phenomena and embed them in next-generation modelling systems.[21] As Mehdi Ghissassi, Director and Head of Product at DeepMind has said, "AI is helping humans generate new knowledge that expands our understanding of various scientific fields. These advances can lead to better outcomes in the life sciences, climate, and energy, among other fields".

Nudge adaptive behaviour: In many domains, climate action requires change at the behavioural level. Technology can be applied in consumer- or user-facing systems (e.g. product recommendations, social media, etc.) to weigh decisions in favour of adaptive or risk-reducing choices.[22] Additionally, emerging technologies such as AR/VR can provide immersive experiences that give users a visceral sense of climate impacts.

Leaders must ask: How do we build short- and long-term resilience? How can we protect against both sudden-onset events and slow-onset events?

The climate adaptation cycle

How can these technologies and their capabilities be applied to climate adaptation, specifically? Since AI and other advanced technologies have entered the mainstream, technology and business players have raced to find commercial applications. While the market value of these technologies is evident, it is important to surface the **climate value** of technology, too. The subsequent sections of this report will serve as a map for how technology can be applied to climate adaptation.

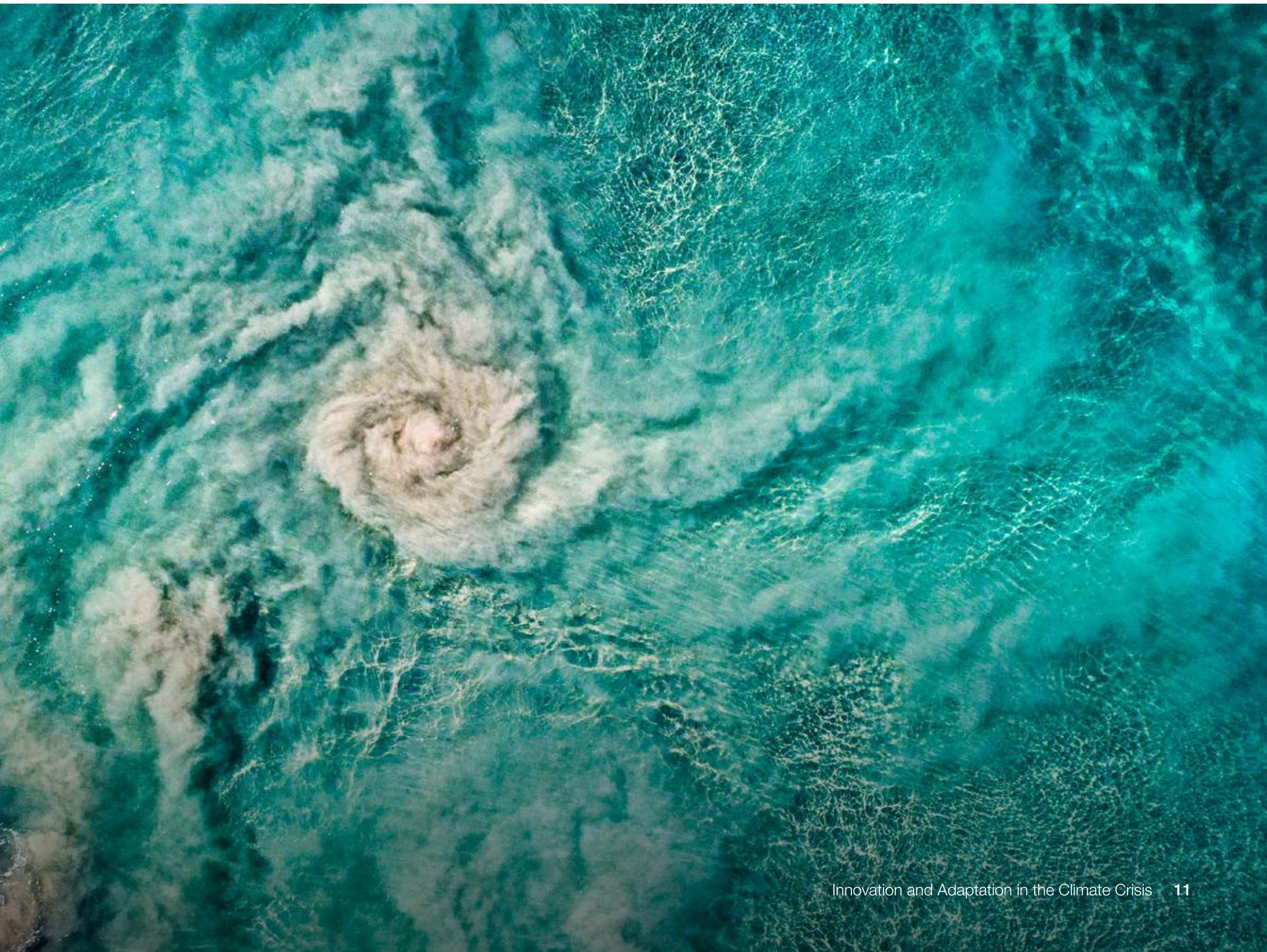
Climate adaptation is a multi-stage process involving different strategies, investments, risks and rewards. This report refers to the process as the "adaptation cycle", consisting of three stages:

Comprehend risks (and opportunities): The first stage in the climate adaptation cycle is to understand the risks – and, in some cases, opportunities – associated with the impacts of climate change. Leaders should ask: What are the main risks we face, and how vulnerable are we? What is the potential impact on our businesses, communities and stakeholders – and how do we quantify that impact? On what timeline(s) will these impacts occur? Gail Whiteman states, "You can't adapt if you don't know what impacts are coming at you. Advanced technology has a remarkable ability to pick out anomalies and 'weak cues' from huge amounts of data. We are starting to see the threats before they occur".

Build resilience: The next step is to build resilience against future climate change impacts and unlock new opportunities along the way. Leaders must ask: How do we build short- and long-term resilience? How can we protect against both sudden-onset events, such as extreme weather, and slow-onset events, such as desertification or sea-level rise? How will our actions align with current business or operating models – what do we stand to gain by building resilience?

Respond dynamically: When the impacts of climate change are realized – for instance, when an extreme weather event occurs – leaders must be prepared to respond. They must evaluate how to prioritize hardware, software and human response efforts optimally. This optimization can be the difference in saving lives, ecosystems and economic value.

Technology is a critical tool across all three steps of the adaptation cycle. David Jensen of UNEP states, "Technology is powerful for helping us to understand the accumulation of different types of risk – to understand that risk in different scenarios and across different time-scales".



1 Comprehend risks (and opportunities)

Adaptation starts with comprehending how climate-induced risk – and, in some cases, opportunities – manifest for specific geographies, communities and assets.

FIGURE 5 **Technology map for stage 1: Comprehend risks and opportunities**

1 Comprehend risks and opportunities

Note: Where applications employ multiple technologies in concert, groupings are indexed to the primary technology.

Gather, complete and process data	**Drones for aerial data collection** e.g. aerial data collection of physical assets to assess vulnerability to climate risks
	IoT for distributed data collection e.g. networked heat sensors to detect wildfires
	Earth observation for planetary intelligence e.g. satellite-enabled data collection to advance scientific understanding of atmospheric conditions
	AI for filling data gaps e.g. missing value inference to complete temporally- or spatially-sparse datasets
Strengthen planning and decision-making	**AI for climate modelling** e.g. digital twin of the planet, using AI to depict climatic conditions with greater resolution
	AI for weather modelling e.g. AI/ML surrogates that use inference to down-scale and tailor intelligence to specific regions or hazards
	AI for climate risk analytics e.g. AI-powered risk assessments that pin-point exposure in value chains and quantify the cost of inaction
Nudge adaptive behaviours	**AR/VR to visualize climate impacts** e.g. immersive digital experiences that show users how polar tipping points will impact rising sea levels
Cross-cutting	**Advanced computing to power intelligence** e.g. cloud-based supercomputing to power GPU-based climate models and make them accessible

> Leaders must develop an evidence-based understanding of the potential costs of climate change if left unaddressed; this "cost of inaction" can support the decision to invest in resilience.

For public- and private-sector leaders alike, comprehending climate risk begins with an exercise of assessment. Climate risks can be grouped into several categories based on their nature and source. This facilitates a risk assessment process, which entails analysing the consequences, probabilities and responses to climate impacts. Climate risk assessments call on organizations to:

Map the risk categories that may affect assets and operations: Risks can take the form of physical risks, such as a damaged factory, and transition risks, such as climate policy changes and changing consumer preferences.[23] These risks can impact an organization's capital assets and operations (including the people that operations depend on, from employees to vendors). This report's focus is on the technologies that sit behind risk assessment.

Understand the extent of exposure: Leaders must determine how exposed they are to the climate risks that threaten their communities, natural and economic assets, and value chains. Due to the wide range of exposure, leaders must conduct analyses that use historical data and various "what-if" scenarios. Certain stakeholders must consider events that have no historical precedent. For instance, how will melting Arctic ice impact maritime shipping routes? How will this impact how businesses manage their supply chains, and how governments approach foreign trade?[24]

Assess vulnerability: Once organizations understand exposure (e.g. the probability of a hurricane hitting a factory), they must assess vulnerability to climate risk (e.g. the structural integrity of the factory and its resilience to withstanding high winds). By identifying the extent to which their core assets and critical supply chains are vulnerable, organizations can figure out where to invest and build resilience.

Estimate the cost of inaction: Taking action to adapt to climate change can require significant capital and operational expense. Leaders must develop an evidence-based understanding of the potential costs of climate change if left unaddressed; this "cost of inaction" can support the decision to invest in resilience. For instance, the city of Lagos has built an adaptation and resilience plan that quantifies the costs of sea-level rise and extreme weather. This data is helping Lagos' leaders to broker novel public-private partnerships and raise finances to build climate resilience against those potential impacts.[25]

How advanced technology is shaping climate intelligence: Data-driven and digital technologies have a wide range of applications for the first stage of the adaptation cycle. Furthermore, these technologies are advancing rapidly; they are differentiated from legacy technologies that could provide similar capabilities; and they represent a step-change in adaptation capabilities, as made evident by the following applications:

1.1 Drones for data collection

How it works: Unmanned aerial vehicles (UAVs) or drones capture visual data from the air with the aid of advanced cameras,[26] with which they can be equipped. They cover vast distances, mapping factory sites, supply chains and natural systems. Organizations can analyse the visual data to identify impacts related to climate change. For instance, a factory manager may use drones to monitor water sources that are critical to its operations.

How it's innovative: Drones provide high-resolution images, especially of remote areas that are difficult for humans to survey. They can be equipped with sophisticated equipment, such as sensors to detect anomalies, and geo-positioning systems to track location with high precision. Connected to the cloud, drones can generate and store vast amounts of data that AI can process and analyse in real time.

INNOVATION SPOTLIGHT:

Capgemini has recently formed a partnership with IBM to provide a novel "drones-as-a-service" (DaaS) platform.[27] The platform enables users to manage and monitor a fleet of drones, carry out inspection missions and capture high-resolution visual data. In an adaptation context, the drones could run aerial surveys of physical assets, helping leaders comprehend their level of exposure to climate impacts (e.g. the proximity of physical assets to flood plains). DaaS also exemplifies how advanced technologies may be used in concert, as it has the potential to connect with technologies like IoT sensors, 5G and edge computing, thereby improving the monitoring and visualization of physical assets.

1.2 IoT and sensors for data collection

> For machines, sensors are their window into the world.

How it works: Through IoT networks, companies can embed devices with sensors and processors that allow them to communicate with each other. IoT enables leaders to gather new kinds of data, such as changes in air quality, temperature and ambient lighting. For example, sensor networks can be used to detect wildfires and provide advanced notice to forestry stations. Smartphones are invaluable tools in IoT networks, too. They can serve as distributed data-gathering platforms, turning individuals into "citizen scientists" who track changes in their local environments.[28]

How it's innovative: IoT melds physical worlds, and things, with virtual worlds and data. As Michael Spranger, Chief Operating Officer of Sony AI has said, "For machines, sensors (IoT) are their window into the world". IoT sensors can transmit data across devices (such as cameras and hand-held devices, creating an interconnected and distributed web of information) carry data in real-time to a centralized node and transmit data from sensors to communication tools. For instance, sensors that detect wildfires can push mobile phone alerts to people in the affected area.

INNOVATION SPOTLIGHT:

PanoAI is a California-based company that provides a connected, IoT-based platform for detecting wildfires and disseminating information to fire professionals and first responders. PanoAI's solution, Pano Rapid Detect, combines ultra-high-definition cameras placed on high vantage points, geospatial data and other third-party data feeds to rapidly detect wildfires and push actionable information to those that need it. PanoAI is now monitoring over 5 million acres and had thousands of fire detections in 2022. According to Chief Executive Officer, Sonia Kastner, "This is the most powerful solution out there for detecting wildfires. And it is not experimental. We are already having impact and delivering new capabilities to first responders and emergency managers today".

1.3 Earth observation for planetary intelligence

How it works: Earth observation is the gathering of information about Earth's activities and characteristics.[29] This is achieved through both remote sensing technologies (e.g. satellite-enabled data collection) and "in situ" data sources (e.g. temperature readings from a thermometer). Earth observation technologies enable leaders to monitor and measure the natural environment with breadth and precision. For example, some satellites can monitor large swathes of forest during a wildfire,[30] while others can trace temperature changes of Earth features as small as 3.5 metres.[31]

How it's innovative: Over 50% of climate variables can only be measured at scale from space.[32] Satellite Earth observation is fundamentally changing the data layer for climate science, providing vast amounts of information about planetary characteristics. More than 100 terabytes of satellite imagery data are collected daily – and that number continues to grow.[33] According to Pierre-Philippe Mathieu, Implementing Manager of the Civil Security from Space Programme of the European Space Agency (ESA), "Earth observation satellites such as [the ESA's] Copernicus missions are routinely delivering large amounts of data on the state of our planet, which are used to develop the next generation of information services supporting management of planetary resources."

INNOVATION SPOTLIGHT:

The ESA, through its Earth Explorers programme, has launched 10 research satellite missions. These missions, proposed and designed by the scientific community, have unlocked new knowledge about the climate system, including atmospheric dynamics, ice melt and freshwater resources. The satellite missions have employed a range of novel techniques for gathering data, including far-infrared radiation monitoring (FORUM mission), which will enhance climate models, vegetation fluorescence mapping (FLEX mission), which assesses planet health and stress, and biomass monitoring (Biomass mission), which will further the scientific community's understanding of forests. ESA has plans to launch two new missions, Earth Explorer 11 and 12, in the coming years. Additionally, Earth Explorers provides support for developing operational missions, including the suite of Copernicus Sentinel missions.[34]

1.4 Artificial intelligence

> AI is one of these enabling technologies that will permeate everything we do as humans.

How it works: The Massachusetts Institute of Technology defines AI as the ability of computers to imitate complex, cognitive functions such as learning and problem-solving.[35] AI uses math and logic to simulate the forms of human reasoning that help people learn from new information and make decisions. This set of mathematical and computer science techniques analyse data to help users understand and navigate real-world phenomena by:

– Providing better **information**[36]

– Delivering improved **predictions**

– Suggesting **optimal actions and recommendations** to reach targets.

These use cases can be attained by applying a wide range of techniques, including advanced analytics, ML, deep learning and generative models. Michael Spranger states, "AI is one of these enabling technologies that will permeate everything we do as humans".

AI for filling data gaps

How it's innovative: AI – and ML, specifically – is a powerful tool for filling in and validating datasets. ML algorithms can employ techniques, such as missing-value inference, to transform incomplete and unstructured datasets into usable information. For example, ML algorithms can identify patterns in data to construct a prediction – an inference – for the data that is missing. The algorithms then run tests on this inference to assess its accuracy, continually refining predictions until the internal model is accurate enough for analysis. Importantly, this AI capability can be used for structured and unstructured data. As Vijay Karunmurthy, Field Chief Technology Officer at Scale AI, has said, "AI is really good with both structured and unstructured data. It can work as a kind of augmented co-pilot and help us navigate massive data sets".

INNOVATION SPOTLIGHT:

In 2022, the FireAId project, a collaboration between KoC Holdings and the World Economic Forum, launched a pilot program that used AI to map and predict wildfires in Turkey. The pilot was launched in the wake of Turkey's worst-ever wildfire season, which saw fires burn 1,400 square kilometres of forest. FireAId built an AI-powered solution that successfully predicted wildfires with an 80% accuracy rate. In developing FireAId, Hatice Yildirim, Digital Transformation Programme Manager at KoC Holdings, underscores the importance of using AI for filling data gaps: "Initial tests showed that some of our forestry datasets were up to 42% incorrect or incomplete. Our engineers leveraged AI methods to improve the datasets to the point where they could be used to make high-confidence predictions".

AI for weather and climate modelling

How it's innovative: AI is powering the development of weather and climate models[37] that offer a step-change in terms of sophistication and precision. These advances can be categorized in two ways: 1) improving traditional, mathematics-based simulations, and 2) replacing those simulations completely with AI surrogates.

1. Improving traditional weather and climate simulations with AI

Generate vast amounts of high-quality data: AI is becoming a household name when it comes to data intake. To put things in perspective, Open AI's GPT-3, the predecessor to ChatGPT's foundation model, has approximately 175 billion parameters.[38] GPT-4 is thought to have over 1 trillion parameters.

While weather and climate models include fewer parameters than large language models (LLMs) like GPT-3 and GPT-4, they nevertheless rely on vast amounts of data to make accurate predictions. AI can discover relationships between and within datasets to allow forecasting systems to ingest data from a wide variety of sources. For example, AI has advanced the scientific community's understanding of ocean current speed by incorporating data on sea surface temperature into oceanic models – a feat that researchers could not independently perform.[39] With AI under the hood, weather and climate models can consume more data, from more places, in more forms.

Capture complex physical processes: In large part due to advanced computing (see Box 1) advanced models can run complex simulations of the weather and climate at high resolution.[40] These simulations can trace an arch of changing climate conditions, enabling near-real-time forecasting (NRT). This capability is essential for forecasting sudden-onset events, such as hurricanes and floods.

> **Modelling and understanding the Earth System is extremely challenging, as the Earth's processes are by nature highly non-linear, coupled and span multiple scales in time and space. Today, rapid advances in ML have enabled scientists to make relatively good predictions of weather and climate with high-resolution simulations that emulate physical processes. This is revolutionizing the way Numerical Weather Forecasting (NWP), along with climate modelling, will be done in the future, bringing together traditional, physics-based modelling with more statistically-based approaches into a dynamic hybrid.**
>
> Pierre-Philippe Mathieu, Implementing Manager, Civil Security from Space Programme, European Space Agency

INNOVATION SPOTLIGHT:

Researchers associated with M2Lines – an international collaborative that works to improve climate projections – have developed AI models that can reproduce (or emulate) the effects of turbulence, an often-intractable problem in mathematics and science. Using Hewlett Packard Enterprise's (HPE) open-source SmartSim library, these models were embedded inside realistic ocean simulations while only nominally increasing time-to-solution. Hybrid AI and equations-based simulations, such as these, can be used to increase the accuracy of low-resolution models – the workhorses of climate and weather applications.

2. Create AI model surrogates for complex weather simulations

Re-frame climate systems as images: An important advance in weather and climate modelling has been the introduction of AI/ML-based surrogates, trained on traditional equation-based simulations. While both types of systems will continue to be used going forward – they are synergistic toolsets – AI/ML-based approaches enable unique capabilities. These models can depict climate conditions through computer vision and neural networks, enabling a new mode of prediction. Additionally, AI/ML surrogates can take advantage of new types of computing including graphics processing unit (GPU) resources, which reduce time-to-solution.

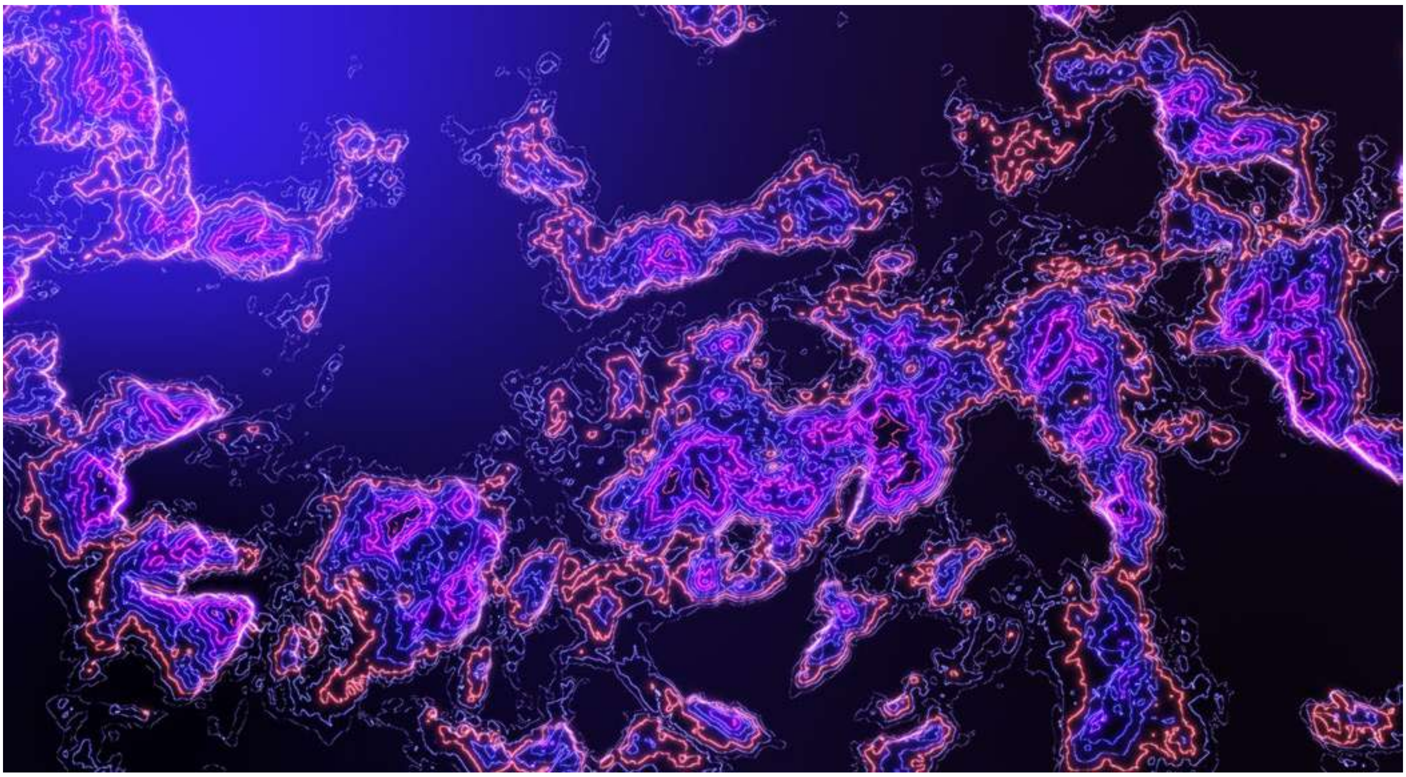
> **With GPUs, some climate problems can be construed as computer vision problems – as an example, a climate image that contains temperature, pressure and wind speed as the fundamental pixels of the image. Then the task of predicting a climate event such as El Nino becomes like predicting the next frame in a video.**
>
> Himanshu Gupta, Chief Executive Officer, ClimateAI

Enable customization and localized inference: In many scenarios, climate models are only useful if they are task-specific. For example, a business may want to know how a specific climate-induced risk (e.g. a major hurricane) may impact their supply chain in a specific part of the world. Or a local government may need to understand how rising sea levels will impact a particular part of their coastline over the next 20 years. The impacts of climate change can be idiosyncratic; to respond to this, models must be flexible and customizable.

The latest generation of foundation climate models (i.e. large, global models) are conducive to customization and localized inference. Machine learning's powers for pattern recognition enable it to zero in on specific variables and geospatial areas. Andrew Shao, Senior High-Performance Computing (HPC) and AI Research Scientist at Hewlett Packard Enterprises said, "AI models trained on high-resolution simulations can be used as localized surrogates for climatic conditions. Instead of needing a supercomputer, a customized ML model could be trained for your own purposes, geography, and flavour of climate risk." Christer Solheim Gundersen, NORAD, has emphasized the benefits of localized inference, too: "AI can make advanced modelling more accessible. You don't necessarily need localized data. If you have the basic data architecture, AI can perform an inference. This allows models to scale more easily, shortens time-to-market and reduces cost of investment."

INNOVATION SPOTLIGHT:

Many of these AI-powered capabilities converge in watsonx.ai, a new climate foundation model from IBM and NASA. The model consumes vast amounts of satellite data – much of it from NASA's Harmonized Landsat Sentinel-2 – and was trained for over 5,000 GPU hours on supercomputers. In addition to providing a global, geospatial picture of the planet, it is customizable and allows users to focus on specific regions and hazard types.[41] This level of customization is delivering positive results. According to Solomon Assefa, Vice-President of IBM Research, "From this model, you can potentially create flood detection models that are 15% more accurate".



AI for climate risk analytics

How it's innovative: This report has shown the power of AI to customize weather and climate models according to specific parameters, like hazard type and region. Yet, for many users – business leaders in particular – climate intelligence cannot stop there. It is not enough to forecast that a hurricane may occur in one week; leaders need to know the probability of this happening, what communities, natural systems and physical assets are exposed, whether they are ready, and what the costs may be.

AI powers risk analytics by integrating company- or community-specific parameters into models. ML algorithms can then construct risk portfolios by approximating the eventuality of different climate scenarios (e.g. will the hurricane make landfall or stay off-shore?). The final step of climate risk analytics is to quantify potential damages and costs across various scenarios. These costs may be economic, socioeconomic or natural. AI-powered tools can quantify the impacts, demonstrating to leaders the vital importance of building resilience.

INNOVATION SPOTLIGHT:

California-based company ClimateAI uses AI to help companies, asset managers and communities predict and mitigate climate risk on their supply chains, markets and operations. Recently, ClimateAI worked with one of the world's largest agriculture asset managers. The company used AI to perform an assessment of the asset manager's agricultural portfolio to understand how growing conditions will change in the coming decade. ClimateAI was also able to identify investment opportunities and growth markets. Chief Executive Officer Himanshu Gupta said, "Food and seed companies can draw a circle on a map of where they get strong yields today. Then we use algorithms to determine what growing conditions have contributed to yields historically – and where those conditions may exist going forward". ClimateAI's customer, a large agrochemical company, saw a 5-10% increase in sales revenue by adjusting their sales strategy to the new climate volatility observed in their demand markets.

1.5 AR/VR to visualize climate impacts

"Wearing a headset, users can experience what it would be like to live with altered weather patterns, depleted biodiversity and more.

How it works: AR/VR are tools that provide immersive experiences of a digital environment. As Google describes, these tools "expand how we experience the world and access knowledge… [allowing you] to take in information and content visually, in the same way you take in the world."[42] AR is often designed to superimpose digital features on the physical world, such as applications that apply visual filters on real-world images. VR, on the other hand, is often designed to fully immerse users in a digital world, aided by hardware like headsets and headphones.[43]

How it's innovative: AR/VR is becoming a key tool to nudge behaviour change related to climate action. For instance, immersive VR experiences can simulate the impacts of climate change. Wearing a headset, users can experience what it would be like to live with altered weather patterns, depleted biodiversity and more. While applications of these technologies remain nascent, there is potential for significant impact in the future. AR/VR can turn the abstract into the visceral.

INNOVATION SPOTLIGHT:

The World Economic Forum and its partners recently introduced a new, immersive experience called the Polar Tipping Points Hub. The hub uses 3D simulations and VR experiences to show how climate-induced tipping points will ramify across the globe. For example, artic summer sea ice could disappear within the next decade, contributing to significant sea-level rise. As Gail Whiteman and her colleagues have written, "By navigating this virtual realm (Polar Tipping Points Hub), users can delve into environments often beyond reach in the physical world, gaining a profound understanding of the significant impacts of climate tipping points".

1.6 Advanced computing to power intelligence

BOX 2

Cross-cutting: advanced computing

Many applications in this report – across the adaptation cycle – rely on the power of advanced computing. Cloud-based supercomputing and, on the frontier, quantum computing, provide more power, precision and speed to computing processes.

Cloud-based supercomputing: "Supercomputing" is a general term for the world's largest and most powerful computers. Among other capabilities, these computers are differentiated in their ability to rapidly run tests (e.g. product prototyping), engineer complex models (e.g. digital twins) and combine AI/ML with simulations to make predictions.[44] These computers have historically been available only to governments, universities and large corporations.

Recently, large providers of cloud-based services have made supercomputing accessible at lower cost. Andrew Shao, Senior HPC and AI Research Scientist at Hewlett Packard Enterprise, said, "Cloud supercomputing is one tool that is driving democratization of weather and climate models … catering to the requirements and requests of a wide variety of downstream stakeholders".

INNOVATION SPOTLIGHT:

Crusoe is a Colorado, US-based cloud computing company that focuses on delivering sustainable computing solutions, purpose-built for AI and other compute-intensive workloads. By delivering supercomputing in the cloud with GPUs and high-performance networking, Crusoe can cut costs on specialized infrastructure and increase access to the resources needed to fuel innovation. Critically, they have focused on the largest operating expense for supercomputing: the energy needed to power it. Crusoe co-locates their data centres alongside stranded-, wasted- and clean-energy resources, such as flared natural gas or stranded renewable energy. Repurposing this waste energy to power data centres enables both lower costs and reduced environmental impact. Crusoe's Chief Executive Officer and Co-Founder, Chase Lochmiller said, "Rich sources of clean energy are not in the places we need them. Moving data is easier than moving energy; AI requires a lot of both. We leverage stranded energy by co-locating our data centres near sources of energy production".

> Quantum-based systems hold value for climate adaptation, due to their power for optimization and learning, dealing with stochasticity, and potential to drive down the energy consumption of large AI/ML models.

Quantum computing: Quantum computing harnesses the laws of quantum mechanics – the fundamental theory which describes physics at the subatomic level – to redesign the computer.[45] These machines are divergent from classical computers (including supercomputers). Classical computers work in binary code (i.e. zero or one). Quantum computers can process the full range of values between zero and one simultaneously (i.e. zero and one). Accordingly, they can perform multiple calculations at once, expanding the computer's power. Quantum-based systems hold value for climate adaptation, due to their power for optimization and learning (e.g. aiding in scientific discovery, such as in the material sciences for resilient building materials), dealing with stochasticity (e.g. randomness and deep uncertainty that can exist in climate systems), and potential to drive down the energy consumption of large AI/ML models.

Quantum computing remains nascent, with only the largest technology companies, research institutions and well-funded start-ups able to afford the hardware. However, novel models are emerging to make quantum more accessible. Carlos Kuchkovsky, Chief Executive Officer of QCentroid, which offers quantum-as-a-service, describes how quantum could drive forward climate intelligence, "Quantum computing could be really good for climate modelling because you can predict nonlinear processes like fluid dynamics – essential to weather forecasting – which is difficult with classical computers".

2 Build resilience

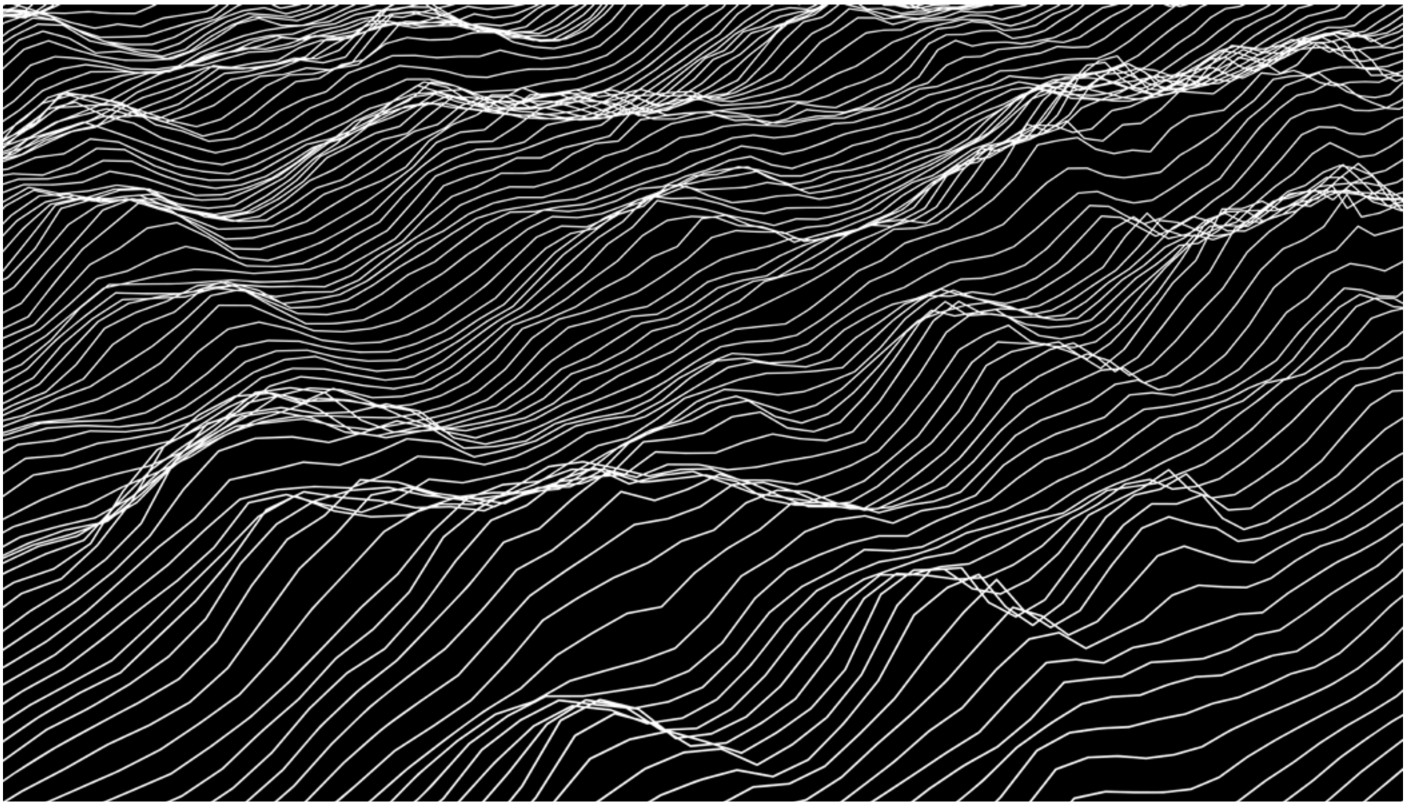
The second stage of the adaptation cycle requires building resilience in the physical world – in communities, businesses and environments.

FIGURE 6 **Technology map for stage 2: build resilience**

2 Build resilience against future impacts

Note: Where applications employ multiple technologies in concert, groupings are indexed to the primary technology.

Gather, complete and process data	**Resilience projects use data collected and processed in stage 1**
Strengthen planning and decision-making	**Earth observation for early warning systems (hazard monitoring)** e.g. satellite-enabled, near-real-time (NRT) monitoring to spot hurricanes before they happen
	IoT for early warning systems (dissemination) e.g. networked devices – phones, computers, televisions – that push out emergency alerts
Optimize processes in real time	**AI for supply chain optimization** e.g. climate-proofed supply chains that dynamically re-adjust sourcing when disruptions hit
	AI for resilient infrastructure e.g. smart sewer systems that optimize water flows and pump stations to avert flooding during heavy rainfall
Power discovery processes	**AI for resilient design at the molecular level** e.g. deep learning to unlock advances for designing drought-resistant crops or resilient building materials
Cross-cutting	**Advanced computing to power intelligence** e.g. quantum computing to accelerate AI discovery processes



Epigraph

...In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast Map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.

On exactitude in science, Jorge Luis Borges, *Collected Fictions*, translated by Andrew Hurley.

The map is not the territory. While comprehending the risks of climate change – aided by the modern cartography of AI, Earth observation and more – is an essential first step, it is only that. Leaders must use digital intelligence **as a means** to build resilience in the physical world. This begins with the development of adaptation and resilience plans – and culminates with their implementation in business environments, communities and natural settings.

The state of public sector adaptation planning and implementation

Adaptation planning climbed to the top of the agenda in November 2022 at COP27. In addition to global leaders' pledges and commitments, the conference saw the adoption of the Sharm El-Sheikh Adaptation Agenda, a global plan to attain 30 climate adaptation-related outcomes by 2030.[46] The Adaptation Fund announced $105 million of new pledges, and several countries, such as the UK, US, Egypt and Bangladesh, announced additional investments in adaptation initiatives.[47]

A year later, COP28, which took place in Dubai in November and December 2023, saw more activity related to adaptation. A historic "loss and damage" fund was agreed on the first day of the summit, focused on directing finance flows to countries most vulnerable to the impacts of climate change. By the conclusion of COP28, pledges to the fund totalled over $700 million.[48] While this represents only a

> Fewer than 500 cities in the world have developed climate adaptation plans – and those that have often failed to specify strategies to implement them.

fraction of overall adaptation funding needs (see section 4.2) the agreement signals the international community's growing recognition that adaptation is an integral component of climate action.

Even so, adaptation strategies face challenges in getting off the ground. Climate change may be a global problem, but adaptation is often perceived as a local or regional issue. As a result, some international actors are reluctant to invest – in a global adaptation fund, for example – if they expect others will be the primary beneficiaries of those outlays. Additionally, low-resource settings have a wide range of challenges, such as a lack of data, tools and capabilities to develop and implement adaptation strategies.

Despite these challenges, recent years have seen progress in the development of national adaptation plans (NAPs), with five out of six parties to the United Nations Framework Convention on Climate Change (UNFCCC) having submitted at least one NAP instrument, according to UNEP's *Adaptation Gap Report 2023*. However, less progress has been made at local levels of government. According to CDP, fewer than 500 cities in the world have developed climate adaptation plans – and those that have often failed to specify strategies to implement them.

The state of private sector adaptation planning and implementation

Momentum is building in the private sector around climate adaptation. Several governments are using regulations, policies and standards to accelerate private sector adaptation, while capital markets and investors are rewarding companies that implement those standards.

Despite the growing interest in adaptation, businesses are still lagging. Only one in five companies has a plan to adapt to the physical risks of climate change, according to data from S&P's *Global Corporate Sustainability Assessment Report*, while the number of companies implementing these plans is likely lower. Even among sectors that consider climate change a major risk, the report found gaps in physical risk and adaptation planning.

Catalysing public-private adaptation with technology

While public-private partnership is critical throughout the adaptation cycle, it is of particular importance to matters of implementation. Many of the resilience projects required for adaptation (e.g. building sea-walls) entail significant outlays of capital, labour and political will. At the same time, these projects have significant benefits for public and private actors alike (e.g. sea-walls that protect both a coastal community and a factory). For example, in Lagos, Nigeria, the Boston Consulting Group (BCG) worked with the local government to show that implementing a range of resilience projects (an investment valued at $10 billion) will help the city avoid $30 billion in loss and damages from climate-induced impacts.[49] These savings will benefit both the city government and private businesses.

It is imperative to take adaptation plans off the page and into the physical world; to take data out of the world of bits-and-bytes and into the world of atoms. So, just how can governments and business come together to build resilience – and what is the role of technology?

2.1 Climate-resilient infrastructure

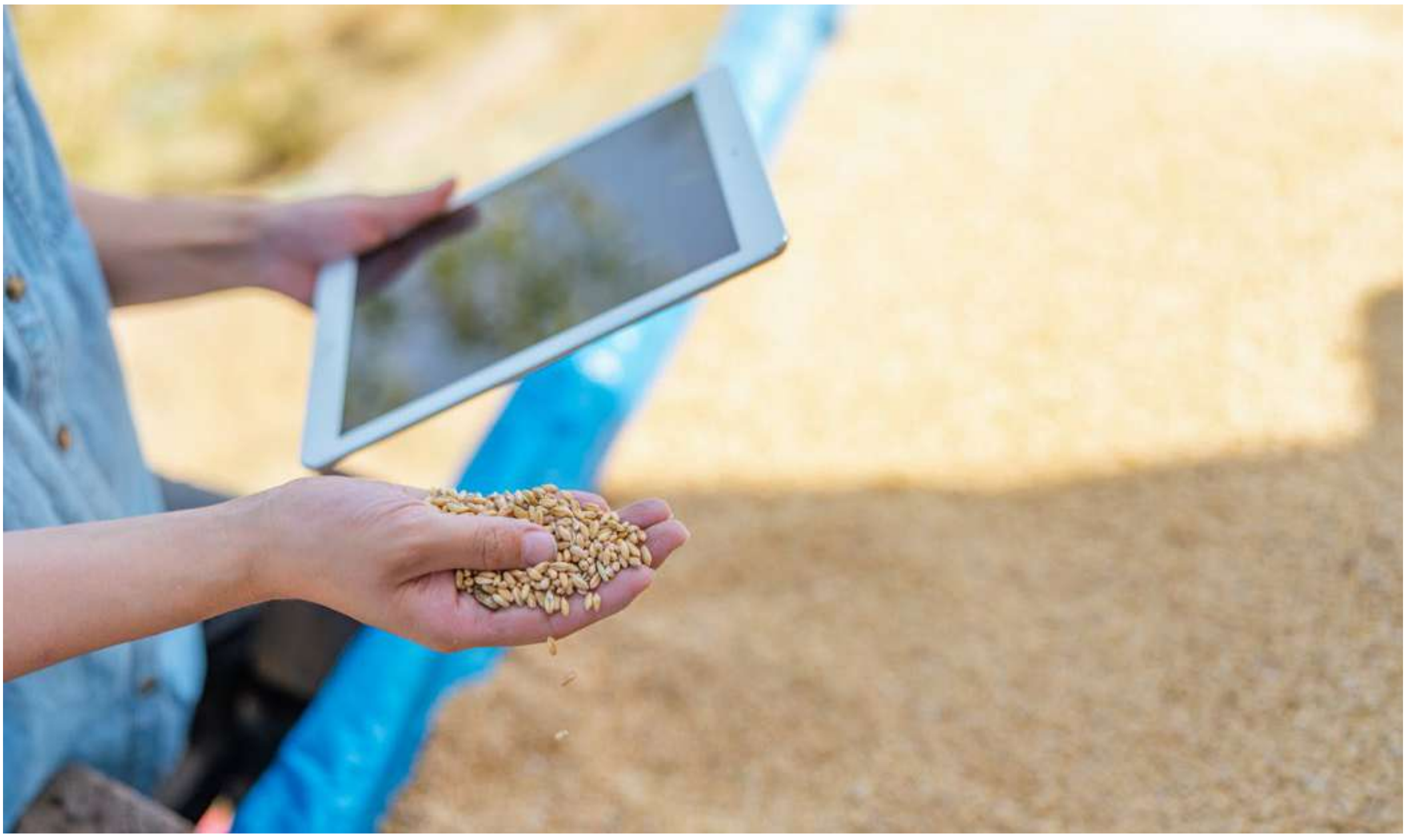
How to build it – with tech: When extreme weather events hit, the stability of basic infrastructure, such as power utilities, is at risk. Like other countries around the world, India's power grid was impacted by heat waves in 2022 – resulting in the country's worst electricity shortage in years. Electricity supply fell short of demand by 1.88 billion units in April 2022, before the summer really began. Extreme temperatures forced widespread power cuts, early closures of factories, offices and schools, and put the health of workers at risk.[50] The crisis demonstrated the fragile link between weather conditions, energy supply and grid resilience. Water systems and utilities are vulnerable to extreme events, too. Hurricane Irma was a category 5 hurricane, which made landfall in Florida in 2017. The hurricane caused power outages and significant flooding, causing many sewage pump stations to malfunction. In certain communities, this resulted in thousands of gallons of raw sewage spilling onto the streets.[51]

To ensure energy stability, public and private actors need to build resilient, smart grids that can withstand disruption and optimize supply during demand surges. To manage flooding, they need to turn sewer systems into intelligent, flood-management systems. These solutions are based in AI and real-time data flows, enabling leaders to optimize and maintain critical infrastructure.

> **Combined with sensors, AI can be used to pinpoint where assets are vulnerable – for example, pinpointing inefficiencies in energy grids – as well as being used to dynamically optimize these systems to enable objectives such as renewables integration and reliability. Indeed, this is one area where AI is the most catalytic: in the sense that these activities – real-time maintenance and optimization – are hard to envision being done without AI.**
>
> Priya Donti, Co-Founder and Chair, Climate Change AI; Assistant Professor, Massachusetts Institute of Technology

INNOVATION SPOTLIGHT:

Ichiro Yamanoi, Senior Researcher at Hitachi, has worked with local governments in Japan to build smart sewer systems. Governments have started using AI to automate decisions about the operation of pumping stations that move flowing rainwater through storm drains and discharge it into nearby rivers. Researchers have developed AI to predict the amount of inflow based on rainfall distribution data and rainwater-pipe water levels, and automatically calculates an appropriate operation plan for future rainwater pumps based on the results. This can prevent internal flooding. As Ichiro describes it, "AI is very effective in managing social infrastructure intelligently. For example, AI can be used in systems to predict flows to pumping stations, which play a key role in sewerage systems during periods of intense rainfall.



2.2 Climate-resilient food systems

> Satellite imagery can help farmers measure evapotranspiration, which informs the management of water balances.

How to build it – with tech: Food security is one of the most significant risks linked to climate change. In many parts of the world – particularly the Global South – climate change is disrupting agricultural production on multiple fronts: reduced water supplies, increased frequency of extreme weather events, heat stress and increased prevalence of pests, such as locust swarms. The World Bank has outlined three key strategies for building resilient agricultural systems:[52]

- Use water more efficiently and effectively, combined with policies to manage demand
- Switch to less-thirsty crops
- Improve soil health.

Regarding water use, innovative technologies are playing a role both "in the ground" and "in the air". As the World Bank points out, water accounting systems can employ in-ground sensors that measure soil moisture. In the air, satellite imagery can help farmers measure evapotranspiration (the process where water is transferred from land to atmosphere), which informs the management of water balances.[53] In terms of crop mixture and soil health, AI and IoT sensor networks are making an impact. Gail Whiteman states, "There is currently a focus on technology for resilient agriculture, drought resistance in particular. For example, identifying grains such as pearl millet, which use less water than rice. Another example is using data and sensors to optimize soil mix". Technology is bringing new intelligence to food systems – and presents an opportunity for private-sector technology providers to collaborate with local governments.

INNOVATION SPOTLIGHT:

The start-up Vertical Future is using technology to push the boundaries of resilient and sustainable agriculture. Vertical Future uses hydroponic and aeroponic systems – soilless cultivation methods – to grow crops year-round, independent of weather conditions. IoT technologies are used to collect data on environmental conditions, plant growth and resource use. Vertical Future uses AI to study these conditions in real time; the algorithms identify patterns, predict crop performance and offer data-driven suggestions for improving crop management. AI also aids in decision-making, such as when to change growing conditions and nutrient delivery. Vertical Future's approach demonstrates how technology is opening a path for resilient, indoor agricultural production.

2.3 Resilient global supply chains

How to build it – with tech: The vulnerability of global trade flows to extreme weather events is significant. According to a recent study by Oxford's Environmental Change Institute, over $122 billion of economic activity – $81 billion in trade alone – is at risk from climate-induced impacts.[54]

Governments and businesses can minimize the risks by using AI to optimize shipping routes. While climate-related optimization has mainly focused on emissions to date, leaders can use the same approach to optimize trade routes to avoid climate-induced hazards. ClimateAI is one of a growing number of technology companies that use AI to climate-proof supply chains. According to Himanshu Gupta, this presents a new paradigm for supply chain resilience: "AI is helping to innovate a new strategy for supply chain management – going from 'just-in-time' to 'just-in-case' supply chains, which shields against climate risk". By identifying climate-induced risks and building-in slack, companies can navigate disruptions with minimal impact on operations. In the public sector, the macroeconomic benefits to governments will be substantial.

INNOVATION SPOTLIGHT:

Another technology company at the innovative edge of supply chain resilience is Everstream Analytics. Everstream provides an AI-powered tool that uses applied meteorology to manage climate risk in supply chains. The tool goes beyond basic forecasting to provide event context, trends and actionable insights.

> **Rising temperatures and precipitation are environmental and economic concerns. Climate change will continue to reshape production and distribution landscapes. Companies that adopt advanced weather modelling and predictive analytics to anticipate and proactively address these challenges will outpace their competitors while making meaningful progress on their environmental, social and governance (ESG) commitments.**
>
> Julie Gerdeman, Chief Executive Officer, Everstream Analytics

2.4 Advanced early warning systems

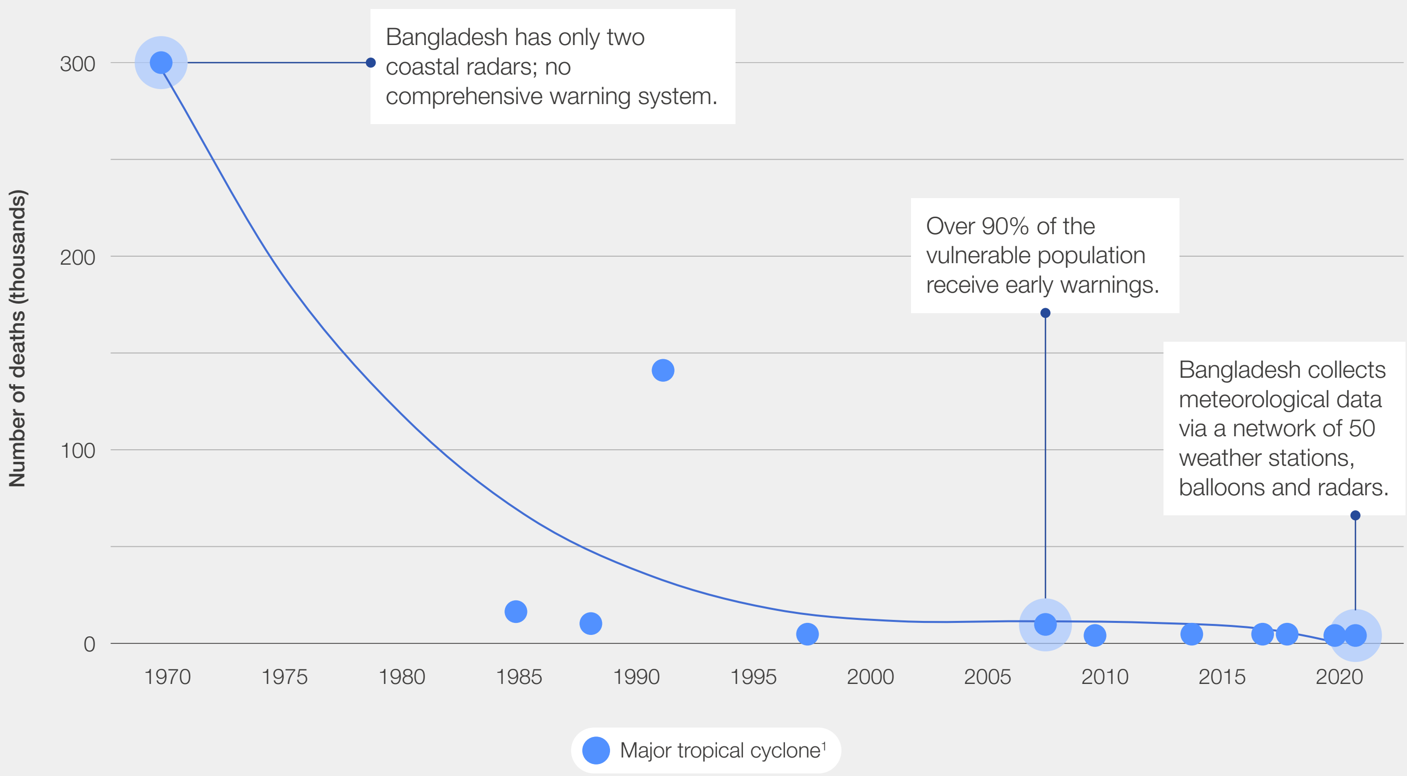
How to build it – with tech: Multi-hazard early warning systems (EWS) are among the most impactful technologies for saving lives (see Figure 3). EWS have been centred in recent global partnerships on adaptation. The UN's "Early Warnings for All" seeks to ensure that everyone on Earth is protected by EWS by 2027. The economic argument for EWS is strong: investing $800 million in EWS in developing countries can prevent losses of $3-$16 billion annually.[55]

The role of advanced technology – in the UN's initiative and EWS broadly – can be a game-changer. AI, Big Data and cloud computing are powerful tools that enhance the predictive precision of EWS. Additionally, IoT networks and AI can improve hydro-meteorological services, while satellite-based technology can optimize how alerts are pushed to at-risk individuals.

INNOVATION SPOTLIGHT:

Several big technology companies are working with the World Meteorological Organization (WMO) under the auspices of "Early Warnings for All". Microsoft is working to improve internet speeds and ensure that timely alerts from national meteorological and hydrological services are disseminated. Microsoft is also using AI and high-resolution satellites to map at-risk populations and conduct post-disaster damage assessments. Google is working with the WMO on flood forecasting. Antonia Gawel, Director of Sustainability Partnerships and Engagement at Google has said, "Google is working to bring AI-powered flood forecasting to every country. Our global hydrological AI model combined with publicly-available data currently predicts floods up to 7 days in advance for 460 million people in more than 80 countries". Alibaba, for its part, is using AI to assist in disaster prevention and reduction, with a focus on Asia.

FIGURE 7 **The lifesaving impact of early warning systems**



Notes: Graph depicts polynomial trendline (R2 = .81).
1. As categorized in "Climate change driven disaster risks in Bangladesh and its journey towards resilience", *Journal of the British Academy*.

Sources: "Climate change driven disaster risks in Bangladesh and its journey towards resilience", *Journal of the British Academy*, vol. 9, no. 8, 2021, pp. 55-77; *The New Humanitarian*; USAID; BCG Analysis

3

Respond dynamically

In the wake of climate impacts, leaders must respond dynamically to save lives, businesses and natural assets.

FIGURE 8 **Technology map for stage 3: respond dynamically when impacts hit**

3 Respond dynamically when impacts hit

Note: Where applications employ multiple technologies in concert, groupings are indexed to the primary technology.

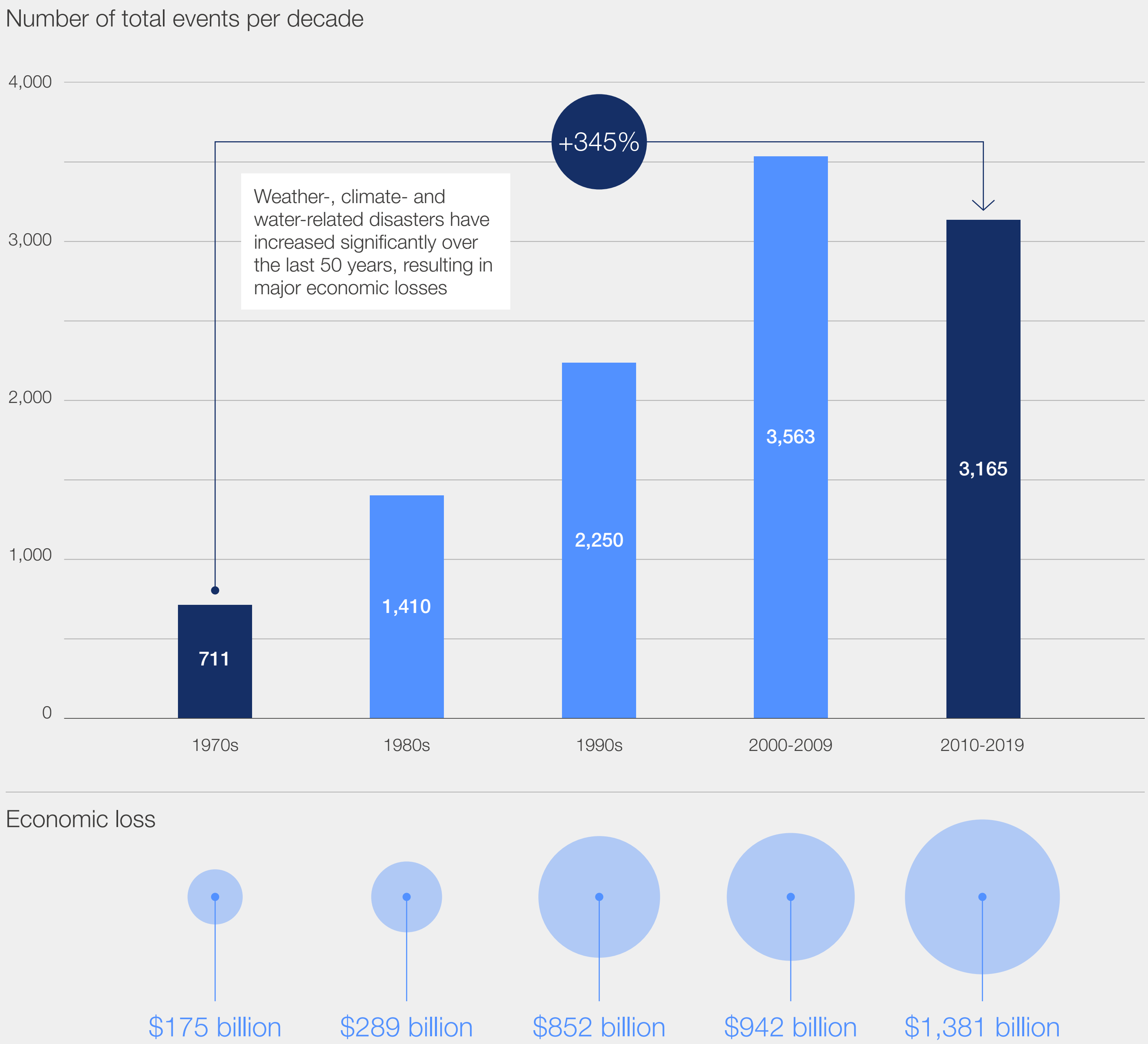
Gather, complete and process data	**AI for humanitarian data collection** e.g. social media scraping tools that can detect an uptick in messages about an extreme weather event
	Earth observation for post-crisis mapping and damage assessments e.g. satellite imagery to identify damaged buildings
Strengthen decision-making	**AI for situational awareness in a crisis** e.g. tools that predict how a crisis will unfold and make recommendations on how to deploy resources
Optimize processes in real time	**Drones for optimizing search-and-rescue** e.g. aerial imagery to identify affected communities in hard-to-reach areas
	AI for optimizing mobility during evacuations e.g. predictive tools that work with geospatial data to identify traffic congestion and recommend re-routing
Nudge adaptive behaviours	**AI for post-crisis mental health support** e.g. accredited chatbots that can provide basic support when in-person support is not accessible Nascent, not detailed in report
Cross-cutting	**Advanced computing to power intelligence** e.g. cloud-based supercomputing to support AI/ML tools for situational awareness

Climate- and weather-related disasters have surged over the last 50 years, peaking at a five-fold increase in the first decade of this century.[56] In that period, they have caused over 2 million deaths and $3.5 trillion in economic losses (see Figure 4). These damages have disproportionately impacted geographies in the Global South, where both pre-existing resilience and resources for recovery are limited. According to Constanza Gomez Mont, Founder and Principal of C-Minds, "Disasters come with a big toll here in Latin America. There are many vulnerable populations, particularly those in coastal areas. On top of that, mobilization of resources and recovery from a disaster are significant challenges".

The summer of 2023 witnessed multiple extreme events. Wildfires burned Lahaina, Hawaii, leaving residents with "no warning and no way out".[57] Derna, in Libya, was hit by torrential rains that led to devastating floods, costing thousands of lives.[58] The EU's Copernicus Atmosphere Monitoring Service logged record-high emissions from Canadian wildfire smoke.[59]

Advanced technologies can help. Due to improved early warning and disaster management systems, the number of fatalities due to climate- and weather-related disasters fell almost threefold in the last four decades: from over 50,000 in the 1970s to under 20,000 in the 2010s.[60]

FIGURE 9 **Extreme events during the course of the last 50 years**



Sources: WMO, *Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2019)*, 2021; BCG analysis.

3.1 The first 72 hours

Advanced technologies can be leveraged during the first 72 hours after a crisis – a critical window for saving lives and minimizing damage.[61] Providing medical care, delivering emergency shelter, food and water, and conducting search and rescue operations can reduce the adverse impacts of an extreme event.

David Jensen states, "There is much that technology can do in the wake of an extreme climate event. From mapping of individuals and communities impacted to optimizing the allocation of humanitarian support (e.g. routing of emergency vehicles) to automating damage and needs assessments".

The technologies that are transforming crisis response

3.2 AI for humanitarian data collection

How it works: In the wake of a climate- or weather-related disaster, it is critical to gather and analyse the large volumes of data that proliferate on the internet and social media. This opens a real-time window into how the crisis is unfolding. For instance, AI can be used to sift through data on social media and distil key insights (e.g. identifying where and how people are being affected). Equally, it can be used for outbound communications, enabling leaders to push critical information to affected communities.

How it's innovative: The latest generation of AI systems can build on different data sources – both structured and unstructured – to map the evolution of crises and forecast their consequences. According to Priya Donti, "Analysis of social media outputs to pinpoint exactly where people are (in the wake of a disaster) and assess other on-the-ground conditions is one potentially impactful application of AI". AI can also be combined with computer vision to provide innovative support during protracted events. For example, the International Committee of the Red Cross has developed a digital tool to help refugees and migrants find missing family members. It uses facial recognition techniques to automate the search-and-match process.

INNOVATION SPOTLIGHT:

Artificial Intelligence for Disaster Response (AIDR) is the AI component of the open-source MicroMappers, a joint initiative with the UN Office for the Coordination of Humanitarian Affairs (OCHA).[62] Its software platform automatically collects and classifies tweets posted during crises (e.g. filtering by keywords and hashtags such as "floods" and "#Libya"). As the classification is refined, AI applies this intelligence to all the tweets that it collects in real time. The tweets are automatically tagged and displayed, powering a live dashboard and crisis map.

3.3 Earth observation for post-disaster analytics

How it works: During crises, decision-makers should study as much of the affected areas as possible, with the highest resolution possible. Earth observation can help them understand the magnitude of impacts – the breadth of an area inundated by flooding, for example – and view areas that may not be accessible from the ground.

How it's innovative: Earth observation technologies provide net-new perspectives on the planet. The most advanced tools – equipped with high-resolution cameras – can map systems at a granular scale (down to 50 centimetres resolution[63]). With this degree of resolution, it is possible to perform damage assessments of individual buildings and parcels of land. According to Vijay Karunmurthy, Field Chief Technology Officer at Scale AI, in certain cases, "AI can be used to perform post-disaster damage assessments and even optimize the routing of insurance claims in the wake of a natural disaster". These consumer-scale applications are paired with planetary-scale capabilities. Remote-sensing satellites can produce up-to-date information on vast locations, measuring environmental change in NRT.[64] The data they capture generate critical insights for decision-makers in the wake of a crisis.

INNOVATION SPOTLIGHT:

Planet Labs is a technology company and one of the leading data providers for earth intelligence. Planet's platform processes a global stream of Earth observation data, pulling from over 200 satellites.[65] In 2017, multiple extreme events occurred in the United States, including Hurricane Harvey in Texas and the Santa Rosa wildfires in California. After these events, Planet partnered with Nvidia to test the power of Earth observation and AI for post-disaster damage assessments. Nvidia fed a neural network with image data from Planet's platform, training it to detect human-made features (e.g. buildings and physical assets). The neural network was then trained to detect *ex-post* changes in the physical and built environments (e.g. buildings that had lost parts of their structure). The results were powerful: the Planet-Nvidia tool identified damaged roads after Hurricane Harvey with an 89% accuracy rate. In California, it detected buildings damaged by wildfire with an 81% accuracy rate.[66]

3.4 AI for post-crisis decision-making

How it works: With its predictive powers and ability to distil huge amounts of data, AI is key to situational awareness after a climate- or weather-related disaster. AI-based systems can draw on large amounts of data to find patterns, draw inferences and make recommendations for action.[67]

How it's innovative: AI capabilities offer a step-change over legacy decision-making platforms. AI-based systems can rapidly integrate information from various sources – such as ground-level data from first responders and geospatial data from satellites – and analyse them in real time. Certain AI-based systems can even develop predictions about how the crisis will unfold – such as dynamic, geospatial maps of the affected areas – to help leaders cut through the fog of uncertainty.

INNOVATION SPOTLIGHT:

When extreme events occur, first responders often lack the information to make critical decisions. The Humanitarian OpenStreetMap Team (HOT) is a not-for-profit that uses open-source mapping and geographic information systems (GIS) technology to meet this need. These tools enable leaders and first responders to optimize relief efforts to save lives, minimize suffering and reduce long-term impacts. For example, HOT has developed an AI-assisted mapping tool that uses aerial images to delineate building damages. HOT's open-source tools are used by partners such as the Red Cross, Médecins Sans Frontières, UN agencies, government agencies, and local NGOs and communities.

3.5 Drones to optimize search-and-rescue operations

How it works: In addition to performing a range of observation duties, drones can be used for search-and-rescue operations and delivering first aid, particularly in hard-to-reach areas. Orchestrated in concert with AI and advanced geospatial mapping, drones can pilot to target locations accurately and reliably.

How it's innovative: Drones can be pre-emptively positioned in disaster-prone regions, may not require runways and can circumvent damaged infrastructure. In addition to their data-gathering capabilities, drones can deliver rescue equipment and humanitarian packages[68] to locations that have been cut-off by weather events. Moreover, they are well-suited for search-and-rescue operations, as they can cover large areas in short amounts of time, providing visual data to rescuers.[69]

INNOVATION SPOTLIGHT:

When Cyclones Idai and Kenneth struck Mozambique in 2019, the World Food Programme (WFP) deployed drones for the first time as part of its emergency response. It coordinated these efforts with the country's National Institute of Disaster Management. Thousands of drone images were collected and stitched into data-rich maps, providing the information that government and relief agencies needed to decide where and how to deliver aid. In this case, WFP also used AI to analyse the visual data collected. WFP's Digital Engine for Emergency Photo-analysis (DEEP) reduced the analysis time from weeks to hours. DEEP is based on open-source software, making its source code visible to programmers who can inspect, change or enhance it.[70]

3.6 AI to optimize mobility and evacuations

How it works: After a crisis, one common imperative is to get people to safer ground. AI can work with geospatial data to optimize the flow of people and traffic during evacuations. These AI-based tools can also predict how people's movements will progress, enabling leaders to proactively manage evacuation routes.

How it's innovative: AI-based tools can optimize routes to evacuate the maximum number of people in a minimum amount of time. These tools let users query a geospatial area of interest (the impact zone of a wildfire, for example) and see the level of traffic in that area. In some cases, the geo-referenced data can be overlayed with other datasets, such as street-level data of buildings, to provide a richer view of the situation. AI can also track individual people's movements, which could be critical during emergencies, but raises important questions about data privacy (see Box 2).

INNOVATION SPOTLIGHT:

The World Bank has built an agile platform that uses Google Maps data to track traffic congestion and mobility, providing a potential tool for evacuation scenarios. While Google Maps can display congestion according to one of four traffic levels, the data can be inflexible and difficult to work with during a crisis. To contend with this, the World Bank's tool – the Google Traffic R package – allows users to query specific areas and integrate that information with other spatially-referenced datasets. For example, combining traffic with street-level data to indicate overall congestion levels after a crisis. Additionally, the platform can operate at micro- and macro-scales, allowing users to depict traffic congestion for a specific neighbourhood or entire city.[71]

Bringing it all together

FIGURE 10 Technology map for the complete adaptation cycle (stages 1-3)

	1 Comprehend risks	2 Build resilience	3 Respond dynamically
Gather, complete and process data	Drones for aerial data collection IoT for distributed data collection Earth observation for planetary intelligence AI for filling data gaps	Resilience projects use data collected and processed in **stage 1**	AI for humanitarian data collection Earth observation for post-crisis mapping and damage assessments
Strengthen decision-making	AI for climate modelling AI for weather modelling AI for climate risk analytics	Earth observation for early warning systems (monitoring) IoT for early warning systems (dissemination)	AI for situational awareness and crisis decision-making
Optimize processes in real time	Stage 1 intelligence serves as input to optimization tools in **stages 2 and 3**	AI for supply chain optimization AI for resilient infrastructure	Drones for optimizing-search-and-rescue AI for optimizing mobility during evacuations
Power discovery processes	AI drives continuous improvement of step 1 intelligence tools	AI for resilient design at molecular level	N/A
Nudge adaptive behaviours	AR/VR to visualize climate impacts	IoT to direct people to cool buildings during heat waves	AI for post-crisis mental health support
		Nascent, not detailed in report	
Cross-cutting	Advanced computing to power intelligence		

4 Multistakeholder collaboration and key enablers

Collaboration on key enablers – open-source technology, financing and policy – will advance the role of technology in adaptation.

> Scalability and replicability across different regions and contexts will be essential to address the global nature of climate change.

The global approach to climate action must proceed at two levels. It must focus on developing and executing mitigation measures. At the same time, an increasing share of the global population, economy and natural world require adaptation. Antonio Guterres, Secretary General of the United Nations, has said, "Adaptation and mitigation must be pursued with equal force and urgency".[72]

As the Intergovernmental Panel on Climate Change (IPCC) demonstrated in their 2023 Synthesis Report (see Figure 5), adaptation and mitigation strategies are often synergistic. For instance, expanding renewable energy sources and improving their efficiency (mitigation) can reduce vulnerabilities to energy-related disruptions during extreme events (adaptation). Sustainable agriculture practices sequester carbon (mitigation) and enhance soil health and water retention, making communities more resilient to droughts (adaptation). Sustainable urban planning and transport reduce emissions (mitigation) while creating an opportunity to design more resilient cities (adaptation).

Both adaptation and mitigation are complex challenges that require expertise and resources from stakeholders such as government, academia, civil society and business. Collaboration among these groups leads to more effective climate action and facilitates resource pooling, making it easier to invest in climate technologies at scale. Scalability and replicability across different regions and contexts will be essential to address the global nature of climate change.

A multistakeholder approach will most impact the execution of adaptation and mitigation strategies in three areas: technology, financing and policy and regulation.[73] The remainder of this section will explore how multistakeholder collaboration in those areas can unlock the full power of climate action.

FIGURE 11 **IPCC assessed that most adaptation options are synergistic with mitigation**

Climate responses and adaptation, options		Synergies with mitigation
Energy supply	Energy reliability (e.g. diversification, access, stability)	●●● High
	Resilient power systems	●● High
	Improve water use efficiency	● Low
Land, water, food	Efficient livestock systems	●● Medium
	Improved cropland management	●●● High
	Water use efficiency and water resource management	●● Medium
	Biodiversity management and ecosystem connectivity	●●● High
	Agro-forestry	●●● High
	Sustainable aquaculture and fisheries	●● Medium
	Forest-based adaptation	●●● High
	Integrated coastal zone management	● Low
	Coastal defence and hardening	Not assessed
Settlements and infrastructure	Sustainable urban water management	● Low
	Sustainable land use and urban planning	● High
	Green infrastructure and ecosystem services	●● High

Level of synergies with mitigation: High, Medium, Low (dot colour)

Confidence level in synergies with mitigation: ●●● High, ●● Medium, ● Low

Note: Limited version of graphic presented; complete graphic available in: IPCC, *AR6 Synthesis Report: Climate Change 2023*, 2023.

Source: IPCC, *Climate Change 2023*, 2023.

4.1 Open source is the unlock

Open-source digital technologies for climate adaptation will be critical. They will ensure access, especially in the Global South, to the data and software that technology-led adaptation requires while fostering ecosystems of innovation. (Open source refers to technologies that are available for free, whose source code can be modified and redistributed, and are developed in a decentralized way and peer-reviewed.)

To be effective, an open-source model must extend across the technology pipeline, encompassing data, analytics and computing power. In that sense, climate technologies can emerge as a digital public utility, with the open-source model as its basis.[74] By applying open-source principles, governments and businesses can strengthen cooperation, identify different users' needs and build trust.

1. The global data commons

The most important part of the open-source technology pipeline is the data layer. The data layer is inclusive of model outputs that derive from upstream source data, providing the actionable information needed to make decisions (e.g. for finance and investment, strategy and planning and policy-making). For climate adaptation, in particular, the global data commons must include access to historical data contained in databases, data streams of live weather conditions and forward-looking data.

There has been a significant expansion of climate-related data in recent years. However, as David Green of NASA points out, "Just because data exists doesn't mean it's useable or findable. We need to bring information into shared data lakes and data commons". Making data available for free – and ensuring that data is actionable and accessible – is critical.

According to the IPCC, over 3 billion people live in regions that are vulnerable to climate change. Even so, most development of data-driven technology does not involve people living in these regions. According to the International Research Centre on Artificial Intelligence, over 80% of AI solutions related to the UN Sustainable Development Goals were developed in the Global North.[75] As Priya Donti has said, "The way technologies like AI exist today is path-dependent on the fact that they were developed with huge amounts of data, compute and capital. But this path wasn't inevitable – and it's not the only way that AI can exist." This issue is not limited to AI technologies alone. Chief Executive Officer of OS-Climate, Truman Semans, points out, "It's not just AI tools that are dominated by OECD countries. Deterministic and stochastic models, which are important for adaptation and resilience, are primarily developed in the North – though these can be made available to the Global South

Climate risks cut across sectors and government departments, and solutions for one can have positive or negative consequences for another.

and localized". Making data widely accessible is a critical first step to building solutions that work at the local level – wherever in the world that may be.

So, what is to be gained from the open-source approach? Recent World Resources Institute (WRI) and Open Data Charter studies show four benefits that countries can expect from open data policies:[76]

- **Better decision-making processes.** Climate risks cut across sectors and government departments, such as water, agriculture and energy, and solutions for one can have positive or negative consequences for another. Integrating data across sectors better informs decisions and ensures strategic alignment.

- **Greater collaboration.** Open data reinforces collaborative action by building an understanding of risks and priorities, as well as sustaining partnerships between organizations with different expertise. This is important for climate action since the analyses needed, such as creating vulnerability assessments, require complex techniques and specialized knowledge.

- **Better monitoring.** Open data plays a key role in monitoring climate policies and programmes. When data and information are made accessible, people can undertake formal and informal monitoring in a systematic, data-driven fashion.

- **Sophisticated modelling.** Modelling underlies many climate change analyses, from estimating risks to making predictions. For these models to generate reliable insights, data availability and quality are critical. It helps build context-specific models that can be used transparently in national and local planning.

2. Open-source analytical tools

In addition to open-source data, open-source analytical tools are crucial to transforming upstream data into the derived data necessary for decision-making. Moreover, tools for data interpretation – for example, open-source data visualization tools – can be crucial to turn analysis outputs into actionable insights.

INNOVATION SPOTLIGHT:

OS-Climate (OS-C), an initiative of the Linux Foundation, is creating a platform and open-source technologies to federate climate-related data and develop analytic and visualization tools. Additionally, OS-C works with partners and the Linux Foundation FINOS initiative to standardize data models. It is applying the same community-based governance, collaboration rules, licensing and standards-setting processes that have revolutionized innovation in the life sciences and digital industries, creating some of the most valuable and impactful public goods in existence.[77]

OS-Climate's goal is to create a community that will help boost global capital flows into climate adaptation and mitigation. It is developing scenario-based predictive analytics tools, which third parties can freely use to develop investment products that manage climate-related risk and finance climate solutions. OS-Climate's long-term goal is to help address data and analysis gaps across every geography, sector and asset class.

3. Accessible computing resources

For open-source data and analytical tools to have an impact, they need support from low-cost and accessible computing resources. Fortunately, recent technological advances have reduced the cost of cloud-based supercomputing (see innovation spotlight, p. 20). Given sufficient internet connectivity, this eliminates the need for on-premise or local supercomputers, making it easier for low-resource settings to access high-performance computing resources. The cloud is making computing mainstream and unlocking new ways for organizations to analyse climate-related data.

At the same time, it is important for leaders to recognize that these capabilities may come with a significant energy cost.[78]

Making computing resources accessible to developing countries is a complex task that will require international cooperation, financial support and long-term technical assistance. In addition to international partnerships between developed and developing countries, establishing regional data centres with shared supercomputing capabilities may also help tackle the challenge.

BOX 3

Trust and transparency

Many leaders and downstream technology users lack trust in data-driven technologies – particularly AI. This lack of trust spans several dimensions: trust that data inputs are representative, that algorithms are traceable and free of bias, and, importantly, that those who control technology will not abuse its capabilities. At the leadership level, the AI for the Planet Alliance (AI4P) indicates that 67% of leaders lack confidence in AI data analysis.[79] At the user level, a 2023 study by the Pew Research Center shows that 52% of people are more concerned than excited by AI (a percentage that has increased by approximately 35% since the debut of generative AI).[80]

Trust in the data layer

The quality of data inputs is essential to ensuring that the outputs of a technology (i.e. the derived intelligence) are accurate and equitable. For example, if an ML system is trained on datasets that do not include information from a particular global region, that ML system may behave as if the region does not exist. This can have significant consequences for the utility and localization of AI-driven tools.

Trust in the algorithms

It can be difficult to trace an algorithm's path to an output (i.e. the "black box" problem). This is due to the massive amounts of data that AI/ML systems consume and the complex set of analyses they run. Indeed, these are core capabilities of AI/ML – but they also raise significant questions about bias.[81]

One key measure to manage this risk is ensuring that human actors remain central to the decision-making process (e.g. having a human verify AI-derived outputs before they are used for decision-making).[82]

Trust in responsible use

AI and other advanced technologies are tools that **provide capabilities**. How exactly these capabilities are used is up to leaders. It is imperative that leaders prioritize technology use for climate action – and deploy technology in a manner that respects individual privacy and dignity. When it comes to AI, leaders and technology practitioners should employ a "responsible AI" approach.[83] This approach includes undergoing AI compliance audits, seeking input from domain experts, and adhering to design practices that mitigate risks to human privacy and negative societal impact.

“ It is imperative that leaders prioritize technology use for climate action – and deploy technology in a manner that respects individual privacy and dignity.

The invisible barriers to open source

Governments and companies may question the value of the open-source approach. This is often due to a lack of awareness about the ways in which open-source can support competitive business models. In many business environments, companies seek to lock in users and shield data and tool code from competitors, including through restrictive licensing terms. While commonplace, these competitive dynamics are not always necessary. According to Truman Semans, "We need to collectively identify the 'pre-competitive' layers of technology and data stacks for understanding climate risk and opportunity – the data and elements of models that users need and are investing effort to develop and maintain, but which are not the refined data and advanced modelling elements that are drivers of competitive advantage".

Integrating open technologies with existing systems can be challenging at a technical level. For tools to be used flexibly, there needs to be more standardization among big technology companies when it comes to infrastructure design and metadata. Andrew Shao of Hewlett Packard Enterprise underscores this barrier and its ramifications for climate intelligence: "There is a need for seamless migration across computing providers (cloud or otherwise). Customers would like to have re-deployable infrastructure. Flexibility is needed to provide burst modelling capability and operational response in the face of a developing extreme event".

Open-source technologies are of no value unless people can contribute to and use them. Many organizations lack open-source readiness: the capabilities to work with open technology stacks. Reskilling and upskilling need to be addressed globally, but the resources are skewed in favour of the Global North. For instance, insufficient access to expertise is the largest roadblock to using AI in the Global South, according to The AI for the Planet Alliance.[84] Priya Donti has said, "A huge precondition for technology-led adaptation is the democratization of capacity. We need leadership to be literate about these technologies and enable a diverse ecosystem of solutions providers, as well as in-house implementation capacity within public sector entities." Stakeholders should invest in training in technology-based disciplines, mentorship and networks for best practice sharing.

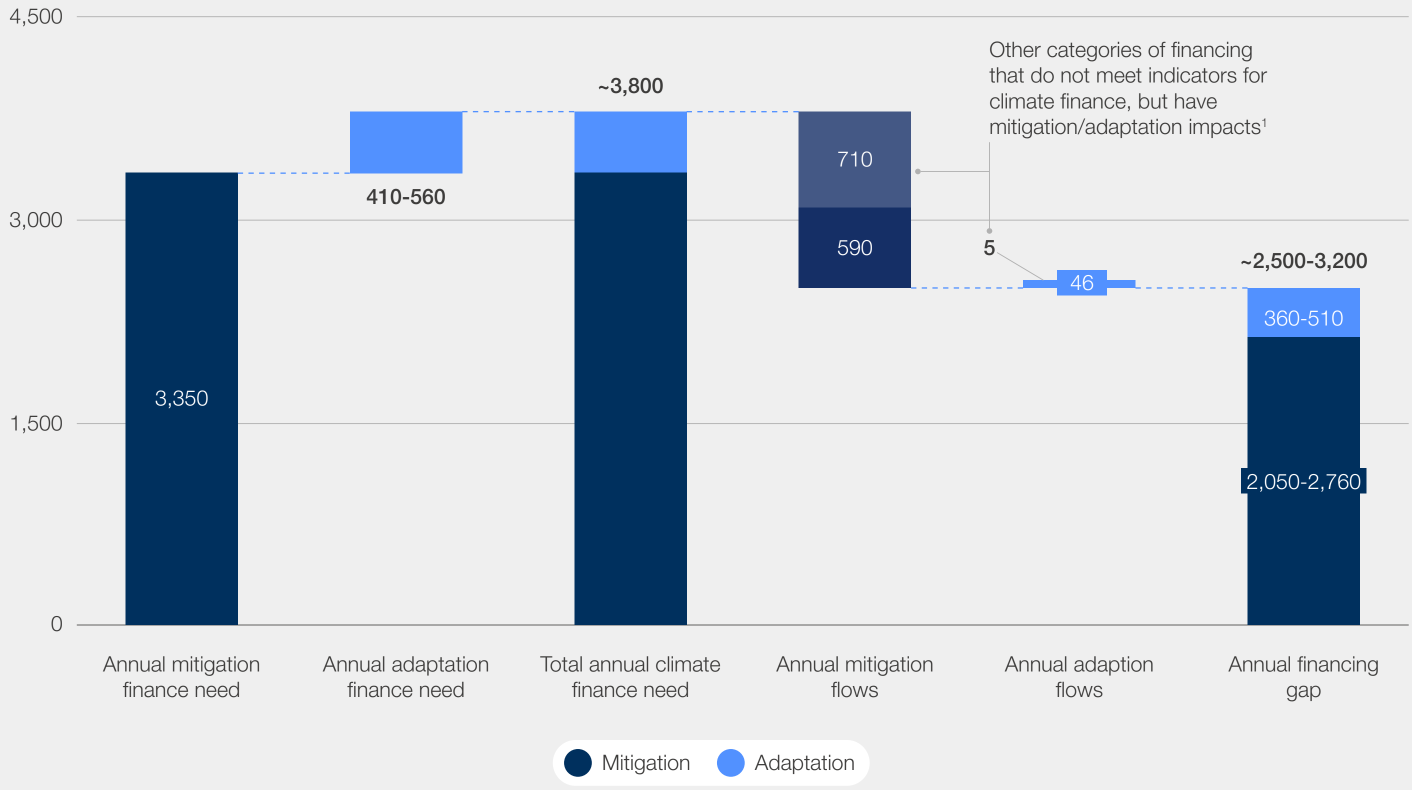
4.2 Repositioning adaptation to attract finance

While adaptation funding has increased over time, insufficient financing continues to slow progress. As the UN shows in its *Adaptation Gap Report 2023*,[85] adaptation finance flows to developing countries are 10 to 18 times below estimated needs. The annual adaptation needs of these countries are estimated at between $215 billion to $387 billion a year until 2030, and they are expected to rise across future decades. A 2022 study by The Rockefeller Foundation and BCG estimates that needs may be even larger (see Figure 6). Data-driven and digital technologies have been one of the casualties of the financing gap; in the least developed countries and small island developing states, less than 10% of basic weather and climates data are widely available.[86]

One way of increasing financial flows into climate adaptation is to change its framing – to emphasize the linkages between climate adaptation and innovation. As this report has shown, adaptation and innovation are twin activities. To build adaptive capacity, leaders must process new data, design processes and systems in an agile manner, and respond dynamically when disruptions occur. Climate change is an evolving phenomenon, so organizations must continuously innovate and develop novel technologies to keep pace.

By demonstrating the innovation and growth opportunities associated with climate adaptation, stakeholders can build ecosystems that will create the next wave of adaptive technologies. Business leaders are starting to take note. As Himanshu Gupta, Chief Executive Officer of ClimateAI, said, "Climate adaptation is the biggest growth opportunity for companies today. Companies can unlock new business models, new markets and new partnerships. We are seeing the conversation start to move from chief sustainability officers to chief strategy officers". Additionally, big technology companies, such as Google,[87] IBM[88] and HPE,[89] have started focusing on innovation and climate action to realize the synergies between them. In 2022, Google set up a $30-million climate challenge fund to finance projects accelerating technological advances in climate action. IBM recently partnered with the city and state of New York, which is building an international centre that will incubate new technologies to combat the climate crisis (the New York Climate Exchange). In September 2023, HPE set up three accelerators to support promising start-ups that are focusing on different aspects of the climate technology ecosystem.

FIGURE 12 | **Annual climate financing in 2020 ($, billions)**



Note: 1. Financing flows to companies and investment vehicles that will have climate impact, but are not directly focused on decarbonization and/or protecting human and ecological systems from the adverse impacts of climate change

Source: "What Gets Measured Gets Financed: Climate Finance Funding Flows and Opportunities", *Rockefeller Foundation and Boston Consulting Group*, November 2022

4.3 Policy and regulation as a catalyst

Climate adaptation technologies are most likely to achieve scale if policy and regulation play a central role. As Constanza Gomez Mont, Founder and Principal of C Minds, has said, "Technology is important. But then there is the larger question of how you prepare entire communities for the impacts of climate change. And that is where the role of policy is key".

In recent years, new regulations, policies and non-binding standards focused on climate risk and adaptation have been enacted in several countries around the world. Many focus on the financial sector and aim to compel markets to price in climate risk. As they expand, these policies and regulations will also have ripple effects on other sectors. They will particularly affect sectors and business models with high vulnerability to climate impacts, such as insurance and re-insurance, agriculture, electrical utilities and real estate.

Any sector that relies on global supply chains could be affected by policies and regulations around climate and environmental risk, due to their global exposure. The most comprehensive will be the EU's Corporate Sustainability Due Diligence Directive (CSDDD), proposed by the European Commission in February 2022. The EU is building on other recently passed laws, such as Germany's Supply Chain Due Diligence Act, which came into effect in January 2023. Alongside the policies and regulations, governments and NGOs are developing taxonomies to support public- and private-sector actors in advancing climate adaptation objectives.

Sound regulation and policy may pave the way for collaboration between stakeholders to shape climate solutions that are technology-led, equitable and effective. As Pierre Gentine of LEAP, Columbia University, has said, "These are exciting times. Technological developments have been dramatic. Specifically for adaptation. Now the question is: will that information be used? Regulation needs to move from being a bottleneck to being an enabler."

Conclusion

The most effective climate adaptation strategies make organizations and communities more agile, innovative and sustainable: they build “adaptive capacity”. Data-driven and digital technologies are pivotal in forming and implementing these strategies. At the technical level, these tools can use vast amounts of information to optimize actions in the present and make predictions about the future. At the operational level, they can enhance intelligence about climate-related risk and opportunity, decrease vulnerability to impacts and facilitate responses when they hit.

The most effective climate adaptation strategies weave together the technical and operational, powering action across the three-part adaptation cycle:

Comprehending risks – and, in some cases, opportunities – associated with the impacts of climate change. Comprehension is powered by a range of advanced technologies for data collection and processing (e.g. Earth observation, drones, IoT) and AI for turning data into insight.

Building resilience against the impacts of climate change. Leaders must take climate intelligence out of the world of bytes – and off the page of adaptation plans – and implement resilience in the physical world. Advanced technologies can play a major role in these implementation projects: Earth observation and IoT can improve early-warning systems, and AI can embed resilience in an array of critical systems, from supply chains to infrastructure.

Respond when climate-induced impacts hit. Data-driven and digital technologies are well-suited to dealing with the complexity and urgency that characterize extreme events and their aftermath. Earth observation technologies can remotely collect information on impact zones, and AI and drones can be used, individually or in concert, to improve situational awareness and optimize search-and-rescue efforts.

Multistakeholder collaboration is essential for technology-led adaptation to take hold in the public and private sectors. As climate impacts increase, leaders will focus on mainstreaming open-source technology, aligning climate adaptation and technological innovation to attract additional financing, and designing a policy and regulatory environment that supports adaptation. Leadership from a wide range of sectors and spheres – large technology companies, start-ups, public-sector and multilateral agencies, academia, civil society and NGOs – will be essential to this progress.

As the world’s economies transition towards a sustainable future, leaders that embrace climate adaptation will find themselves at a strategic advantage. In this transition, businesses can harness data-driven and digital technologies to not only mitigate emissions but also to enhance climate intelligence, form novel partnerships and tap into new markets for climate-resilient products and services. The fusion of these two climate imperatives – mitigation and adaptation – presents a compelling path forward. Indeed, technology and the climate will remain core strategic considerations well into the future. The future of leadership belongs to those who see climate adaptation not as merely an obligation, but as a catalyst for transformation.

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Acknowledgements

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