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Climate risk and response: Physical hazards and socioeconomic impacts

Could climate become the weak link in your supply chain?

Case study
August 2020

McKinsey Global Institute

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Introduction to case studies

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

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

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

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

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

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

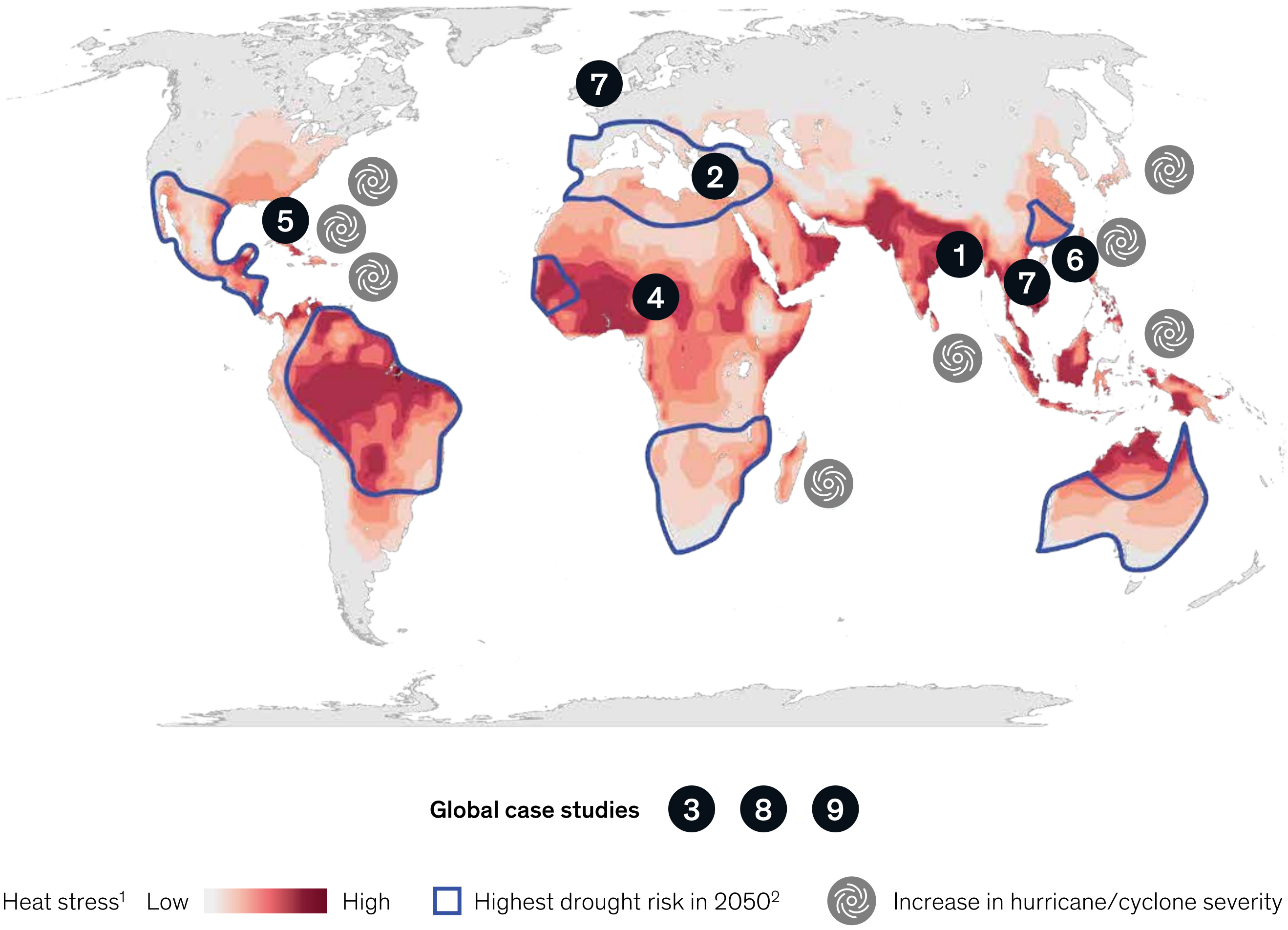
- For physical assets, we look at the potential impact of storm surge and tidal flooding on Florida real estate and the extent to which global supply chains, including for semiconductors and rare earths, could be vulnerable to the changing climate.

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

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

Exhibit 1

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



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

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

Source: Woods Hole Research Center; McKinsey Global Institute analysis

Dark, stormy skies, ships and the port of Colon, Panama.
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Supply chains

Could climate become the weak link in your supply chain?

Much of global economic production is organized around a complex system of interdependent supply chains. Supply chains facilitate the production of everything from computers and cars to lifesaving medicines and food, and support world trade in goods that is worth almost $20 trillion annually.[1] End products may have up to many thousands of parts, sourced from diverse geographies around the world. Over time, these supply chains have been honed to deliver maximum efficiency and speed.

But questions about supply chain risks and resilience are now being raised in the context of the global Covid-19 pandemic as well as acute weather events.[2] A changing climate and the greater frequency and/or severity of hazards may increase disruptions in supply chains that interrupt production, raise costs, hurt corporate revenues, and lead to higher prices or shortages for consumers. According to a recent Allianz survey of companies, business interruptions are the number-one risk facing the corporate sector today.[3] A similar poll by the World Economic Forum found natural catastrophes as the greatest concern for businesses in East Asia and the Pacific.[4] Hurricanes and floods contribute to the majority of economic losses in natural disasters, accounting for 50 percent and 20 percent of total losses since 2000, respectively.[5]

In this case study, we examine how risks from climate hazards, already present in global supply chains, are likely to evolve over the next few decades. We focus specifically on the risk from hurricanes and extreme precipitation and find that supply chains can be disrupted in different ways. For example, access to plants or production at plants can be shut down or production of critical inputs or access to them can be disrupted, impacting production downstream and potentially increasing prices to manufacturers and consumers. We identify three broad types of supply chains that illustrate how climate risks vary across a spectrum: specialty, intermediate, and commodity. Typically, the more specialized the supply chain, the more severe the impact for a downstream player could be as supply of a critical input may only be available from the source that has been disrupted. However, the more commoditized the supply chain is, the larger the number of downstream players that may be affected by spiking prices from a sudden reduction in supply.

For a deeper appreciation of the extent of risks, we focus on two supply chains that illustrate how disruption may play out. As an example of specialty supply chains, we examine the semiconductor industry; for commodity supply chains, heavy rare earth metals. Both create critical inputs for advanced industries. Semiconductor chips are ubiquitous in electronics from computers to smartphones to electronic watches. Rare earths are critical in aerospace and defense, electric vehicles, wind turbines, drones, medical appliances, and other electronics. Both supply chains are highly geographically concentrated in regions with an increasing probability of relevant climate hazards. However, these are only examples illustrating broader trends.

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[1] *World Trade Statistical Review*, 2018. See also *Globalization in transition: The future of trade and global value chains*, McKinsey Global Institute, January 2019.

[2] Recent MGI research examines how industry value chains are exposed to a broader set of risks, including climate events. This work also examines vulnerabilities within specific companies and broader value chains, financial losses, and ways to bolster resilience. See *Risk, resilience, and rebalancing in global value chains*, McKinsey Global Institute, August 2020.

[3] *Allianz Risk Barometer 2019,* Allianz, January 2019.

[4] World Economic Forum, *Regional risks for doing business 2019,* World Trade Organization, 2019.

[5] NatCatSERVICE, Munich Re, 2019.

Assessing the inherent risk to supply chains without any adaptation action and based on an RCP 8.5 scenario, the probability of a hurricane occurring that is severe enough to disrupt semiconductor manufacturing (defined as a hurricane with more rainfall than manufacturing assets typically are designed to withstand) could increase from 1 percent per annum currently to 2 to 4 percent by 2040 across much of the western Pacific.[6] Increase in hurricane wind hazard is less homogenous but is projected to increase from 1 percent per annum currently up to 2 percent by 2040 in some parts of Taiwan and Japan. In other words, risk of a disruptive hurricane could be expected to approximately double.[7] We estimate that in this scenario, such hurricanes could lead to months of lost production for the directly affected player and could cause up to 35 percent revenue loss for unprepared downstream players in a disaster year. In the case of rare earths, we find that the likelihood of extreme rainfall in any given year which is sufficient to trigger mine and road closures could roughly double by 2030 in southeastern China. This could reduce global production by 20 percent in a disaster year.[8]

Global supply chains could adapt to manage these risks. For semiconductor supply chains, two key areas of adaptation include building disaster-proof plants (for producers) and raising inventory levels in order to continue production even if a supply chain is interrupted (for downstream players). We find that building disaster-proof plants means additional costs of roughly 2 percent of the building costs, which equals an additional $20 million for an average plant. Raising the inventory to provide a meaningful buffer in case of supply disruption, with estimated costs for warehousing and working capital, may increase input costs by less than a percent.

Companies using rare earths could protect themselves from climate-change-induced physical risk by raising inventory levels at the costs of additional working capital and storage space needed. Rare earth miners could, for example, by using leaches that decrease the risk of landslides or moving leach holes away from the steepest slopes.[9] We estimate these measures could lead to a cost of goods sold (COGS) increase of less than 5 percent.

Supply chains are already being disrupted by extreme weather, and this risk will increase with climate change

Floods, storms, drought, and fires are all climate hazards that have already disrupted supply chains in recent years, halting production and resulting in lost revenues and profits. While this case study focuses on the impact of storms and floods, drought can also impact supply chains (See Box 1, “How drought can affect supply chains”). As climate change makes extreme weather more frequent and/or severe, it increases the annual probability of events that are more intense than manufacturing assets are constructed to withstand, and supply chain disruptions become more common.

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[6] If not indicated differently, we follow standard practice and define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060. For the analysis of 2040, the average of 2031 and 2050 was used. Also, if not indicated differently, the climatological analyses in this case use RCP 8.5 to represent the changes in atmospheric greenhouse gas concentrations that could occur absent a mitigation response. Please see technical appendix of the full report for details.

[7] Woods Hole Research Center analysis drawing on: Kerry Emanuel, *The Coupled Hurricane Intensity Prediction System (CHIPS),* Massachusetts Institute of Technology, 2019; Water and Climate Resilience Center, RAND Corporation. While total hurricane frequency is expected to remain unchanged or to decrease slightly under increased global warming, cumulative hurricane rainfall rates, average intensity, and proportion of storms that reach Category 4 or 5 intensity are projected to rise, even for an increase of two degrees Celsius or less in global average temperatures. Thomas Knutson et al., “Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming,” *Bulletin of the American Meteorological Society,* 2019.

[8] Probability increases from approximately 2 percent per year in 1965 to approximately 2.5 percent currently, approximately 4 percent in 2030, and approximately 6 percent in 2050.

[9] Heavy rare earths are mined in open-pit clay mines using an in situ leaching technique, making them sensitive to extreme rainfall. Shallow holes of a few meters are dug, and hydrochloric acid leach is sprayed over the clay. The acid acts as an extraction agent; after 150 to 400 days, leach containing heavy rare earths has concentrated in the leach holes. This leach is then brought to a treatment pond, where a precipitation agent (such as ammonium bicarbonate) is applied, causing the heavy rare earth to form roughly 92 percent grade rare earth oxides that accumulate at the bottom of the solution.

Box 1.

How drought can affect supply chains

Drought has already impacted supply chains across the world. In Europe, for example, drought has had a significant impact on the flow of goods through waterways. In the third quarter of 2018, transport on the Rhine was down 27 percent year on year due to low water levels. Transport performance was also 10 percent lower on the Danube.[1] This resulted in a 10 percent drop in Germany's production of chemicals and pharmaceuticals from September to November, as major industrial players shut down plants that were unable to secure raw material, reporting in some instances over $220 million in additional logistics costs. The Panama Canal, which shortens the 8,000-mile journey around Cape Horn to just 48 miles, is already having to reduce weight on ships due to reduced water levels in drought conditions.[2] Similarly, along the Mississippi River in the United States, both floods and droughts have disrupted logistics and agricultural production over the past decade.[3] A tow on the upper Mississippi River typically has 15 barges, each capable of carrying more than 1,000 tons. A one-inch drop in river level can reduce tow capacity by 255 tons.[4]

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[1] Holly Ellyatt, "A major river in Europe hit by drought could create economic havoc," CNBC, July 31, 2019.

[2] "Climate change threatens the Panama Canal," *Economist,* September 21, 2019. Henry Fountain, "What Panama's Worst Drought Means for Its Canal's Future", New York Times, May 17, 2019.

[3] Karl Plume, "Floods stall fertilizer shipments in latest blow to U.S. farmers," Reuters, April 25, 2019; Debbie Elliott, "Drought causes ripple effect along mighty Mississippi River," NPR, January 23, 2013.

[4] "U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather," US Department of Energy, 2013.

Extreme events that exceed the design threshold of physical assets can cause major supply chain disruptions. One of the costliest floods in the past decade occurred in Thailand in 2011. Flood defenses that were supposed to keep industrial facilities dry broke and became overwhelmed by extreme rain, disrupting production of food, automobiles, and consumer electronics and raising prices for consumers (See Box 2, "What happened in Thailand in 2011 when the floods hit?"). Design thresholds vary but are typically defined to be tolerant up to a specific magnitude of event, which in turn has a specific frequency or likelihood associated with it (often referred to as the historical return period of the event). Common design thresholds for manufacturing assets are typically in the range of 1 to 2 percent probability events (also known as "100-year" and "50-year" events, respectively), depending on what is required either by local regulations or by reinsurers.[10]

As climate change makes extreme weather more frequent and/or severe, it increases the annual probability of events that are more intense than manufacturing assets are constructed to withstand and supply chain disruptions become more common.

Research suggests that thunderstorm conditions will become more frequent due to climate change, and furthermore that hurricane rainfall, average intensity, and proportion of storms that reach Category 4 or 5 will increase, magnifying disruption risk for manufacturing in Asia and along the US Gulf Coast.[11]

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[10] Based on expert interviews.

[11] Noah S. Diffenbaugh, Martin Scherer, and Robert J. Trapp, "Robust increases in severe thunderstorm environments in response to greenhouse forcing," *PNAS,* Volume 10, October 8, 2013; Resilinc, EventWatch annual reports, 2014–18; Thomas Knutson et al., *Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming,* American Meteorological Society, 2019.

Box 2.

What happened in Thailand in 2011 when the floods hit?

In 2011, Thailand suffered the worst flooding in 50 years with many regions under 3 meters of water at peak severity, inundating entire provinces in the industrial areas near Bangkok.[1] Flooding lasted 30 to 60 days, disrupted global electronics, automotive and food supply chains, and resulted in losses totaling $40 billion to $50 billion.[2] The impact on local industry was severe; industrial output in Thailand dropped almost 50 percent in November 2011 compared with the previous year. Manufacturing accounted for 70 percent of damages and losses, representing about one-third of manufacturing value added in Thailand at the time.[3] While climate attribution studies broadly suggest no link of the Thai floods to climate change, they are a good illustrative example of how increasing frequency of extreme events can threaten specific supply chains.[4]

There were several factors that made the impact from these floods so severe:

— **Production was concentrated in a high-hazard region:** Thailand has a "supercluster strategy," where incentives such as tax breaks, grants, infrastructure upgrades, workforce support, etc. encourage the colocation of academia, research, and multiple industries. As a result, manufacturing is concentrated in a few estates in the Chao Praya river basin (which has extreme precipitation in the monsoon season) near Bangkok.

— **Resilience was insufficient:** Flood defenses in industrial estates could not withstand the flood, and either broke or were overrun.

— **Reconstruction took time:** The most resilient small and medium-size enterprises (SMEs) in manufacturing returned to business after only one to three months, almost as soon as the floodwaters receded. Larger firms, took three to five months to restart production as they were using more advanced equipment with longer replacement times, which delayed recovery. The least resilient SMEs had even longer delays and higher levels of bankruptcy, reflecting a lower financial capacity to tolerate outages. By June 1, 2012, seven to eight months after the onset of the floods, 70 percent of Thai factories were restored or partly restored, 20 percent were not yet restored, and 5 to 10 percent of factories had shut down permanently as a result of the floods.[5] Even a year after the floods, utilization of Thai electronics SME facilities was still only at 40 percent.

There were significant knock-on effects globally in key supply chains. The electronics and automotive industries were hardest hit and experienced an 80 percent year-on-year decline in production in November.[6] While the automotive sector returned to positive growth after four months, recovery for the electronics industry took longer and year-on-year growth was still negative seven months after the onset of the floods.

Japanese manufacturers in the electronics and automotive industries were particularly affected as they were sourcing large parts of their inputs from Thailand. Most of the manufacturing facilities of the suppliers to Japanese automotive companies were disrupted for only one to three months; however, some factories were closed for up to six months, as plants were critically damaged and needed significant repairs. In total, car manufacturers produced at least 750,000 fewer cars because of the flood. Car manufacturers with smaller inventories, concentrated supply, and a long recovery time were more affected than others.[7]

Prices of hard disk drives (HDD), the key product segment in the Thai electronics industry, spiked 80 to 190 percent (reflecting different products) as up to 40 percent of global HDD production capacity was flooded, with prices remaining elevated for more than a year.[8] Industries downstream of and adjacent to HDD manufacturing were affected unevenly; the share prices of a major computer manufacturer fell 5 percent, while share prices for a manufacturer of solid state disks (SSDs), a substitute product, rose 5 percent.[9] This illustrates that while downstream players suffer when suppliers are disrupted, producers of substitute products may actually gain a temporary competitive advantage.

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[1] Royal Thai Government and World Bank, *Thai flood 2011: Rapid assessment for resilient recovery and reconstruction planning,* 2012; Surapong Sarapa, *The status of current meteorological alert of Thailand,* Regional Workshop on Impact-Based Forecasts in RA II (Asia), Seoul, Korea, November 7–9, 2017, wmo.int/pages/prog/amp/pwsp/documents/2-2-1_SurapongSARAPA_Thailand.pdf.

[2] Christophe Courbage, Meghan Orie, and Walter R. Stahel. "Thai floods and insurance." The Geneva Reports, 2012.

[3] T. W. Bank, "Thai Flood 2011: Rapid assessment for resilient recovery and reconstruction planning." Bangkok: The World Bank, 2012.

[4] See for example, Thomas C. Peterson, Peter A. Stott, and Stephanie Herring, "Explaining extreme events of 2011 from a climate perspective," *Bulletin of the American Meteorological Society,* July 2012, Volume 93, Number 7.

[5] Masahiko Haraguchi and Upmanu Lall, "Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making," *International Journal of Disaster Risk Reduction,* December 2015, Volume 14, Part 3.

[6] David S. H. Rosenthal et al., *The economics of long-term digital storage,* Stanford University, September 2012.

[7] Bank of Thailand; Masahiko Haraguchi and Upmanu Lall, "Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making," *International Journal of Disaster Risk Reduction,* December 2015, Volume 14, Part 3.

[8] Ibid.

[9] "Thai floods hit global hard drive production," *Financial Times,* October 20, 2011.

The risk of disruption has increased as supply chains have become optimized for efficiency rather than resiliency

Increasingly global and efficient supply chains have underpinned economic growth and productivity improvements over the past few decades. However, the drive for efficiency and the resulting greater complexity and intricacy have increased the vulnerability of supply chains to disruption.

Changes in inventory levels contribute to increased vulnerability. Since lean manufacturing gained popularity in the 1970s, with Just-in-Time and Just-in-Sequence production, companies have been striving to reduce metrics like inventory levels. Lower inventories reduce working capital, but also reduce supply chain resilience as the leanest companies are most reliant on receiving inputs from their suppliers on time. One industry where it is very costly to hold large inventories is aerospace, because parts like an airplane fuselage are so big. This also applies to some commodities, like the petrochemical gas ethylene, which either takes up a large amount of space or needs expensive pressurized containers; only a few days of ethylene inventory exists, and much of it is in transit in tankers or pipelines. Large inventories are also expensive in the semiconductor industry, because rapid innovation cycles cause inventory to depreciate fast.

Vulnerability is also exacerbated by changes in production strategy. To achieve economies of scale, suppliers often only have one production site with the necessary technology to produce the goods they are making. For example, in a 2018 survey, 88 percent of suppliers across industries responded that they have only one production site available for each of their products. This was especially true in aerospace and defense and pharmaceuticals, where high safety requirements and long lead times to acquire regulatory approval increase the cost of new manufacturing facilities.[12] Very specific requirements for production conditions (for example, in pharmaceuticals, semiconductors, or automotive) also mean that even small changes in the manufacturing environment can create production disruptions. Furthermore, these specific requirements make it harder to quickly get new sources of input during a disaster. For example, Hurricane Maria in 2017 created a shortage of saline bags in the United States as 40 percent of saline bags are produced in Puerto Rico, which suffered a power outage for 90 days following the hurricane. Strict requirements for the sterility of the manufacturing environment prevented other manufacturers from rapidly stepping in to compensate for lost capacity.[13] There are also examples of raw materials that require specific natural conditions, like lithium. Lithium is extracted by drying lithium brine in an evaporation pond for two years in areas with very low precipitation. However, shifting weather patterns are already interfering with this process as historically dry regions in Chile have experienced torrential rainfalls over the past few years, reducing lithium output.[14]

In some instances, production has also become more concentrated in regions with high climate hazards. With the goal of maximizing returns, companies have shifted manufacturing production centers to areas with preferable operating characteristics. Historically, this was in part due to labor arbitrage, but more recently, another driver has been to co-locate in specialized clusters.[15] However, many of these areas are more susceptible to climate hazards. We identify two aspects of increased globalization that may be increasing climate risk in supply chains.

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[12] *EventWatch 2018 annual report,* Resilinc, 2019.

[13] Philip J. Palin et al., *Supply chain resilience and the 2017 hurricane season,* CNA Corporation, 2018.

[14] Ernest Scheyder, “Albemarle’s lithium sales drop after Chilean rains,” Reuters, May 8, 2019.

[15] *Globalization in transition: The future of trade and value chains,* McKinsey Global Institute, January 2019.

Firstly, the value of trade in goods as a proportion of all economic activity has increased from 10 percent in 1960, peaking at 25 percent in 2008 and then retreating to 23 percent in 2018.[16] This means that supply chains are more exposed to climate hazards from all over the world. This particularly applies to companies that assemble specialized manufactured goods containing many thousands of parts, like consumer electronics companies or automotive and airplane OEMs, as they require reliable inputs of a broad range of specialized parts that often are sourced from many different locations. The increased trade intensity also increases reliance on functional infrastructure services (for example, ports, rails, roads, and airports). Logistical infrastructure is often less well defended than manufacturing assets. Chronic flooding can cause regular short infrastructure interruptions of days or weeks. Even if businesses can absorb these interruptions, they can still add costs to production (for example, cost of relying on a private power generator), disproportionately affect small businesses (who typically lack the ability to run to private infrastructure services). The cost of self-generation is typically three times larger than that supplied from the grid.[17] Acute tail events can cause significant damage to infrastructure systems, resulting in longer service outages that may cause bankruptcy to even larger and more prepared businesses.

Secondly, economic activity has moved to higher-hazard countries, on average. For example, in 2018, countries with high hurricane hazard contributed 45 percent of global value of traded goods compared with 40 percent in 1991.[18] Some industries are particularly concentrated in one region, driven by a focus on regional competitive advantage and the self-reinforcing effects of regional ecosystems. These industries have higher volume of output at risk, as a significant share of the global supply capacity can be disrupted simultaneously. For instance, 40 percent or more of global refinery capacity of metals like copper, cobalt, and aluminum is in China.

Production asset resilience has generally increased with improved technology, increased regulatory pressure for safety, and higher capital expenditures increasing value at risk and so incentivizing increased investments. However, this is partly offset by an increase in the requirements of the manufacturing environment—for example, moisture, temperature, or dust levels in manufacturing areas due to requirements from regulations or advanced automated technology. Automation in industries like automotive and semiconductors has grown rapidly. Automated manufacturing robots often are less resilient than laborers in several ways: some robots may be damaged by dust and moisture levels that workers can tolerate; repairs of specialized machines may take several months; and power consumed by the robots makes it necessary to install more emergency power to continue operations. Industries in rapid growth (like cobalt, lithium, medical appliances, or industrial robotics) may also experience "growth pains" like tight inventories and high utilization rates, further increasing climate risk. If the growth is fueled by high innovation rates, then leading-edge technology will be less commoditized, and fewer suppliers will be available to ramp up if one is disrupted. Therefore, some of the fastest growing and most technically advanced and innovative industries may be the most at risk and so the most in need of adaptation.

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[16] Ibid.

[17] Stephane Hallegatte, Jun Rentschler, and Julie Rozenberg, *Lifelines: The Resilient Infrastructure Opportunity,* World Bank, July 2019.

[18] World Bank; Woods Hole Research Center.

We identify three broad types of supply chains based on varying risk characteristics of downstream disruption from climate change

We identify a spectrum of supply chains to help assess the nature of climate risk that companies may face. These include specialty and commodity at either end and intermediate in the middle (Supply chain-1).

Specialty

In specialty supply chains, OEMs typically secure their inputs through long-term contracts or strategic collaborations with suppliers. Critical supplies may even be secured internally if players are vertically integrated. Suppliers may have unique manufacturing equipment that is designed specifically to produce the components of their customers. The necessary technology may exist in only one or a handful of manufacturing plants in the world. A good example is leading-edge semiconductors (see below for more details on semiconductor supply chains). In the supply chain of semiconductors, a supply disruption could lead to long production disruptions for downstream players, up to a year in extreme cases. The end products are designed for specific inputs, which means that inputs with different designs—for example, a microcontroller from another supplier—may change the functionality of the end product. If a supplier is disrupted, a downstream player without access to the usual inputs would have to requalify their product with their customers, using different inputs. As the alternative input would have somewhat different properties, this could require a full redesign of the product, which is typically not a viable strategy.

Therefore, downstream players are reliant on getting the specific inputs they have planned for. Manufacturing of these inputs requires specific, advanced, and costly equipment. This machinery typically exists in only one to five locations around the world, due to economies of scale.[19] Even if several machines exist, utilization may already be near 100 percent, preventing unaffected suppliers from scaling up if one of the machines breaks.[20] Therefore, the machines must be replaced before production can resume. As this equipment is costly and specialized, it is manufactured on-demand, which typically takes several months. Specialized industries are thus often in turn reliant on another specialized supply chain, compounding downtimes. Additionally, industries like semiconductor equipment already have a production backlog of several months, driving the equipment replacement time up to a total of 6 to 12 months for some manufacturing devices.[21] During the production disruption, the players downstream of the disrupted supplier are likely unable to maintain production unless they have access to alternative sources of inputs.

Intermediate

Intermediate supply chains are between specialty and commodity in their characteristics. Bilateral supply relationships are common but are shorter-term and of a less strategic nature than for the specialty supply chains. It is typically cheap for customers to switch suppliers, and several suppliers offer goods of comparable quality. Examples include standardized or lower quality chips; airplane interiors (for example, seats); and niche commodity chemicals. The less specialized the supply chain is, the easier it will be for unaffected suppliers to take over for a supplier that is disrupted. Therefore, downstream players will have to compete for the remaining supply capacity.

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[19] *World fab forecast,* SEMI, September 2019.

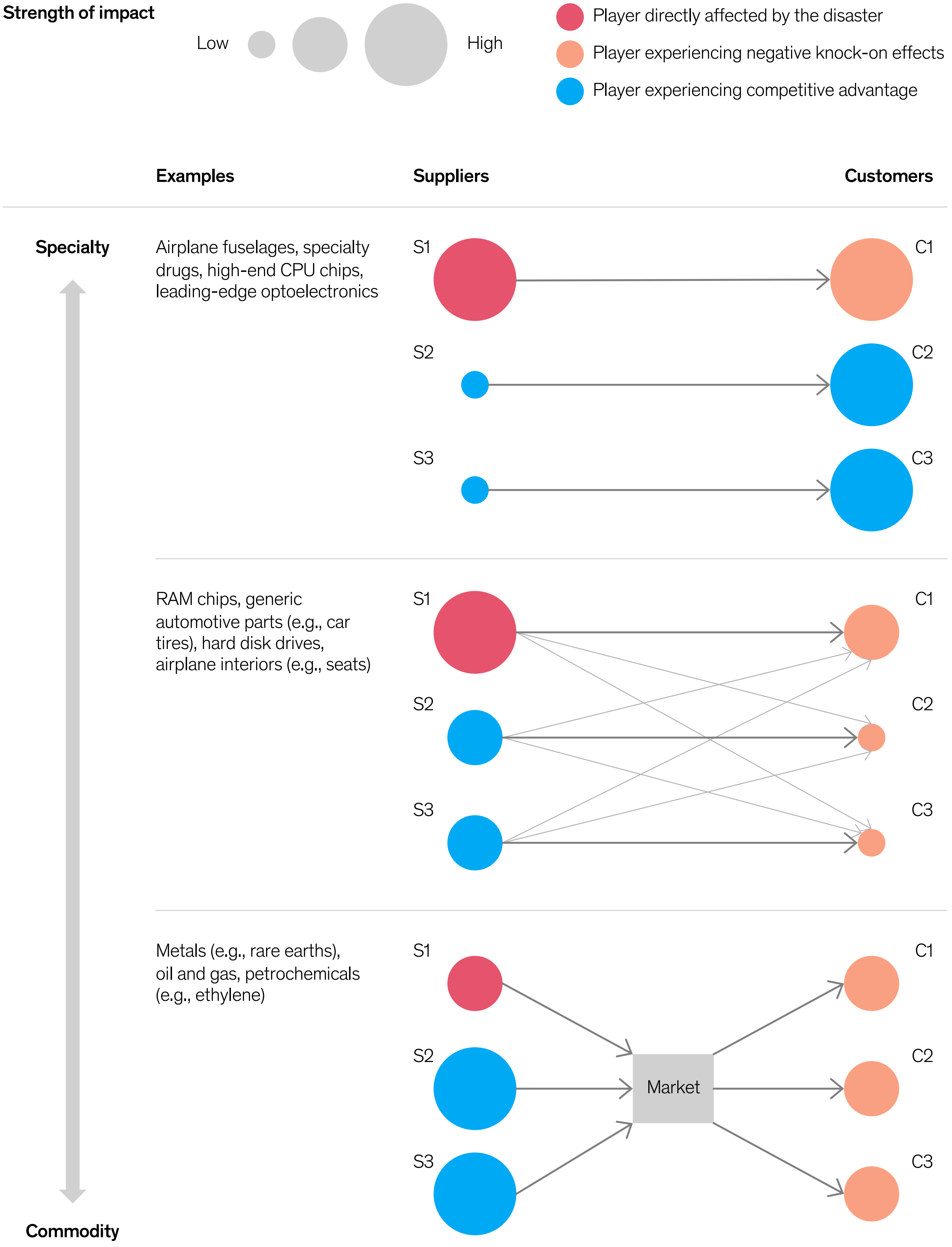
[20] McKinsey Semiconductor Practice expert interviews.

[21] Ibid.

Case study Supply chain-1

Supply chains face different knock-on effects from production disruption depending on the degree of commoditization.

Illustrative



Source: McKinsey Global Institute analysis

Commodity

In commoditized supply chains, downstream players acquire their inputs on a commodity trading exchange or via commodity brokers, and there is typically no direct bilateral relationship between the supplier and the customer. Products are standardized, and several suppliers are selling goods of comparable quality. Heavy rare earths are an example of a commoditized supply chain (see below for more details on heavy rare earth supply chains). Rare earth producers sell their product to brokers who resell it to industries that use rare earths in the production of EV batteries or specialized electronics.[22] Therefore, all downstream players would be affected by the supply disruption as prices would rise. The effects of Hurricane Harvey caused US steam cracker utilization rates to drop by more than 20 percent between August and September 2017. Ethylene prices increased over 25 percent during this period.[23]

To better illustrate what happens due to disruptions in supply chains, we consider two examples of supply chains at the bookends of this distribution.

The probability of a hurricane of sufficient intensity to disrupt semiconductor supply chains may grow two to four times by 2040

As an example of a specialty supply chain, we analyze supply chains for semiconductor manufacturing, more than a $400 billion industry.[24] By 2040, a company using leading-edge chips (for example, with applications in memory, logic, communication, or optoelectronics) such as an automotive OEM, sourcing from geographies in Korea, Japan, Taiwan, or other hubs in the western Pacific, can expect that hurricanes sufficient to disrupt their suppliers will become two to four times more likely.[25] Some of these disruptions may last for several months. This has implications for many industries as chips are increasingly critical to the modern economy. For example, electrical content in cars increased from 2 percent in 1960 to 35 percent in 2010.[26]

Several stages of the supply chain are highly concentrated in Asia–Pacific, including:

- Raw material, for example, wafer and chemical-mechanical polishing (CMP) slurry
- Chip manufacturing in segments within different application areas, for example, logical components like CPUs, communication technologies like 5G, memory technologies like RAM
- Chip packaging
- Chip assembly, creating specialized electronic circuitry for automotive, consumer tech, and industrial electronics, for example

More than 50 percent of chip foundry production capacity of about 45 nanometer or smaller chips (typically focused on logic chips) is concentrated in ~15 facilities (factory modules) in Taiwan. About 98 percent of manufacturing capacity of 350 nanometer and smaller optoelectronic chips (for example, used in image sensors, lasers, LEDs) is in nine facilities in southern Japan, and about 40 percent of memory chip capacity is in ten facilities in Seoul and surrounding cities.[27] A product using such chips will typically be reliant on many parts working at the same time. Therefore, a supply disruption in any one component category (for example, memory) may lead to many downstream production disruptions. The downstream assembled product will sell at a price higher than the sum of its components, and may be 100 times or

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[22] Nawshad Haque et al., “Rare earth elements: Overview of mining, mineralogy, uses, sustainability and environmental impact,” *Resources,* October 2014, Volume 3, Number 4, mdpi.com/2079-9276/3/4/614/htm.
[23] IHS Markit Economics and Country Risk.
[24] Arne Holst, Semiconductor industry sales worldwide 1987-2020, Statista, Jan 7, 2020.
[25] McKinsey Global Institute analysis; Woods Hole Research Center.
[26] McKinsey Automotive Practice expert interviews.
[27] *World fab forecast,* SEMI, September 2019.

even several thousand times the price of any individual part. For this reason, the disrupted gross output from an extreme weather event may become much larger if disruptions cascade through supply chains.

Hurricane intensity can be measured in wind speeds, using the Saffir-Simpson scale, or in precipitation, measured in millimeters of precipitation per event, or precipitation over a time period. High wind speeds can be a hazard directly to vulnerable structures (for example, distribution power cables) or by causing storm surge that inundates coastal infrastructure and properties. Precipitation can directly harm sensitive manufacturing assets, particularly if the building exterior is already damaged by high wind speed, and cause flooding or landslides. This analysis keeps exposure constant to highlight how much climatic factors are driving risk. In other words, it assumes the distribution of facilities in 2040 is largely similar to today, which can be considered a "business as usual" scenario on the basis of clustering effects discussed in the introduction. Facility owners may decide to take action and relocate future or indeed current facilities. This analysis shows what the inherent risk is and how to best manage it.

The increase in annual probability of hurricanes with extreme precipitation is driven primarily by an increase in temperature driving increased water-carrying capacity of hurricanes.[28] This increased water-carrying capacity leads both to more intense rainfall (measured in millimeters per day), and longer-lasting rainfalls. Moreover, hurricanes could move slower, making rainfall last even longer in each location. Both the increase in intensity and duration of rainfall increase the risk of landslides and risk of rainwater directly contaminating the manufacturing assets. Increased rainfall intensity contributes more to increased flooding hazard than longer duration does. The reason is that the longer duration increases the opportunity for runoff, softening the severity of floods, compared with storms with similar total rainfall levels but over shorter durations.

We analyzed hurricanes with a 1 percent annual probability of occurring in each location, based on cumulative event rainfall. With increasingly severe storms, events that currently have a 1 percent probability of occurring could become two to three times as common by 2040 across ten major semiconductor hubs, under an RCP 8.5 scenario (Supply chain-2). In Taiwan, this means that cities like Hsinchu, Taichung, and Tainan could see hurricanes with 1,500- to 2,500-millimeter precipitation or more approximately twice to three times as often, depending on the specific location.[29] In Japan, precipitation levels for these events range from 500 millimeters in Tokyo to 950 millimeters in Kirishima, on the southern tip of the main islands. This is more than the recent Typhoon Jebi, which MunichRE's NatCat database estimates is the costliest hurricane to date in the western Pacific.[30] The precipitation from a 1 percent hurricane precipitation hazard in Korea is much lower, only 100 to 150 millimeters of rainfall near Seoul, but this is where the increase in annual probability is highest—up to four times.[31]

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[28] Thomas Knutson et al., "Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming," *Bulletin of the American Meteorological Society,* 2019; Geert Jan van Oldenborgh et al., "Attribution of extreme rainfall from Hurricane Harvey, August 2017," *Environmental Research Letters,* December 2017, Volume 12, Number 12.

[29] This is higher than the 1,539 millimeters of rainfall observed in the US during Hurricane Harvey; Harvey was the wettest tropical cyclone on record in the United States and resulting flood waters, combined with wind speeds, caused damages of $100 billion. Munich Re, NatCatSERVICE, 2019. Jack F. Williams and Ch'ang-yi David Chang, Taiwan's Environmental Struggle Toward a green silicon island, Routledge 2008.

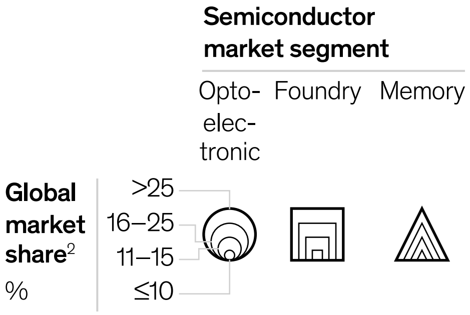
[30] Munich Re, NatCatSERVICE, 2019.

[31] Kerry Emanuel, *The Coupled Hurricane Intensity Prediction System (CHIPS),* Massachusetts Institute of Technology, 2019; Water and Climate Resilience Center, RAND Corporation. Woods Hole Research Center.

Case study Supply chain-2

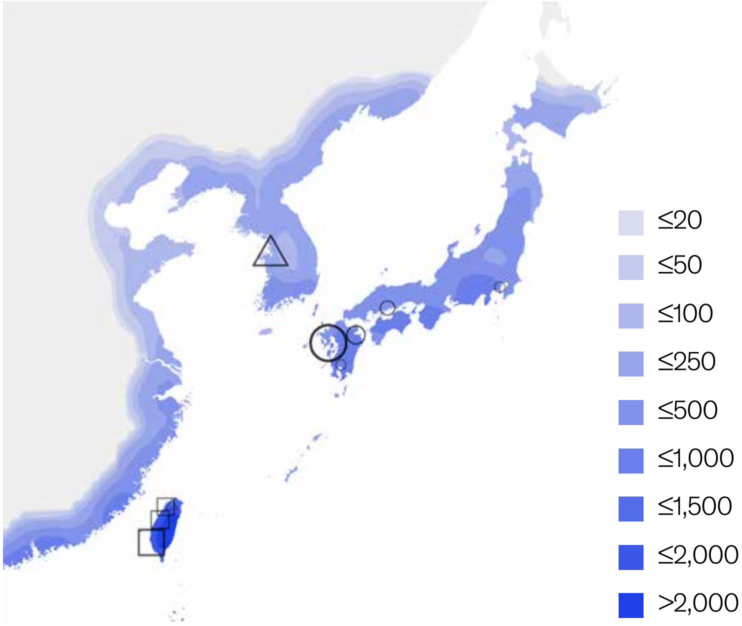
Semiconductor manufacturing hubs in the Western Pacific are expected to experience disruptive extreme hurricanes two to three times as often by 2040 compared to today.

Based on RCP 8.5



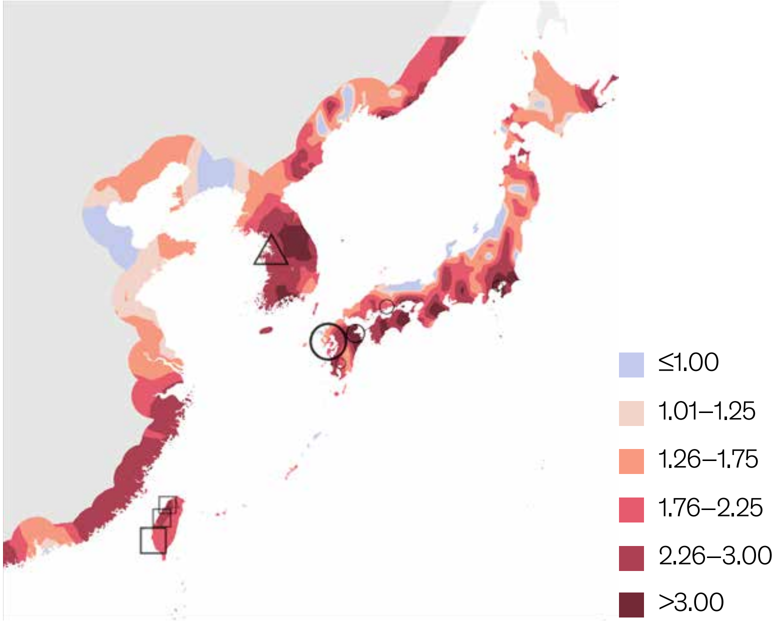
Rainfall during historical 1-in-100 year hurricanes (with potential to disrupt production, as assets are typically engineered to withstand up to 1-in-100 year events)[1]

Millimeters per hurricane



Change in frequency of hurricanes of this intensity by 2040

Historical = 1



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1. Hurricanes with 100-year historical return period, using 1980–2000 as reference period.
2. Global market share of each hub in given product segment (e.g., foundry for 26% of chips of <47mm size globally concentrated in Tainan).

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble.

Source: Woods Hole Research Center; McKinsey Global Institute analysis

Change in wind speed evolution is also expected to be uneven across geographies. Hurricanes with annual probability of 1 percent today, based on maximum wind speed, will reach 1.25 to 2 percent annual probability in some locations by 2040, like western Taiwan and southwestern Japan. But there are winners as well as losers—such hurricanes are also set to decrease to 0.7 percent in parts of Korea and the Philippines. For exposed locations in Taiwan or Japan that see an increase, the historical 1 percent probability storm is either a category 4 or 5, with wind speeds above about 200 kilometers per hour.[32]

There are three drivers of near-term losses for suppliers that are hit by such events, potentially leading to losses of up to 200 percent of annual profit and 35 percent of revenues: physical damages to assets, including facilities, production equipment, and inventories; reduced sales, either because production is disrupted or because goods cannot be shipped to the market; and higher costs in the reconstruction phase and after the plant is back in production, as market prices of labor, energy, and logistics may spike following a disaster (as seen in the 2011 Thai floods). The combination of these impacts may also limit suppliers' ability to quickly and efficiently restore production, by reducing their ability to raise capital for repairs or by choking short-term cash flow and presenting unusual operational obstacles. However, these effects can be partly mitigated if manufacturers hold disaster insurance, have asset hardening or tighter design standards, or if the government offers disaster support.

Semiconductor supply could be reduced by an extreme hurricane in several ways. First, common losses during extreme events include loss of infrastructure services, for example due to flooding of roads near the facilities preventing workers from accessing the facility, power grid outages, or closures of ports and airports.

Second, direct damages to manufacturing assets are rarer, and historically direct damages have been minor. For instance, building exteriors may experience minor damages from wind pressure, water, or physical objects, but in itself, this is unlikely to lead to a production disruption. Other damages that have been observed in the past include damages to raw materials, work in progress inventory and finished chips, as well as unplanned shutdowns that may require rebooting the production robotics and requalifying that conditions in the manufacturing environment (for example, dust levels, humidity, temperature) are within required limits. This could disrupt several weeks and potentially months of production, particularly if the manufacturing area is contaminated by water, dust, or moisture that damages large amounts of inventory. These damages contributed to the slow recoveries following the 2011 Thai floods.

Third, damages to the internal power system, building main structure, or specialized manufacturing equipment could be particularly costly as it could cause up to or beyond a full year of supply disruptions. For this reason, suppliers invest in making these parts of the factory particularly resilient. For instance, suppliers may have two connections to the central power grid, each sufficient to supply the plant with enough power on its own if the other should break. The manufacturing area clean rooms containing the manufacturing devices are typically placed on the upper floors to prevent any flooding. The clean rooms are often protected by an additional inner shell. If factories are flooded during the extreme weather, the manufacturing devices may be moved to particularly robust safe rooms to ensure that they are unharmed.

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[32] Woods Hole Research Center Analysis, drawing from: Kerry Emanuel, *The Coupled Hurricane Intensity Prediction System (CHIPS),* Massachusetts Institute of Technology, 2019. National Hurricane Center and Central Pacific Hurricane Center, Saffir-Simpson Hurricane Wind Scale.

We find that a severe supply disruption can cause cascading production disruptions downstream, particularly for unprepared players (Supply chain-3). Using a hypothetical example, we estimate that downstream players could lose up to a third of annual revenue if supply is disrupted for an illustrative period of five months, a duration seen in some of the more severely disrupted players in the 2011 Thai floods. This could be the case if no alternative source or substitute was able to keep supply going (beyond a minimal inventory of finished goods) and if no measures had been taken to limit losses from disrupted downstream production (for example, insurance or negotiations with customers to delay supply).

A well-prepared player, on the other hand, may only lose about 5 percent of revenue in a similar event. Preparations may include dual sourcing (so only 50 percent of supply is lost), increasing supplier resiliency through due diligence and collaboration with suppliers on asset hardening; this can limit the recovery time to less than one month. Several other actions can help further reduce the losses, including insurance, even faster recovery through best practice emergency procedures, and discounted cross-selling of substitute products (for example, premium models or older product versions) to end consumers. These adaptations come with a cost that needs to be considered, but many of these investments may be smaller than the loss avoided.

Adaptation areas for semiconductor supply chains include two key areas: building disaster-proof plants (for producers) and raising inventory levels in order to continue production even if a supply chain is interrupted (for downstream players). We find that building disaster-proof plants means additional costs of roughly 2 percent of the building costs which equals an additional $20 million for an average plant. Raising the inventory to provide a meaningful buffer in case of supply disruption, with estimated costs for warehousing and working capital, could increase input costs by less than a percent.

The value of preparedness can be even higher if the supply disruption happens before a new product launch. In consumer electronics, product global change: life cycles are short, with new smartphone models being launched every year, and product lifetimes rarely exceeding five years. If product launch is delayed by five months, the technology may be outdated shortly thereafter, and competitors may gain a significant advantage.

Case study Supply chain-3

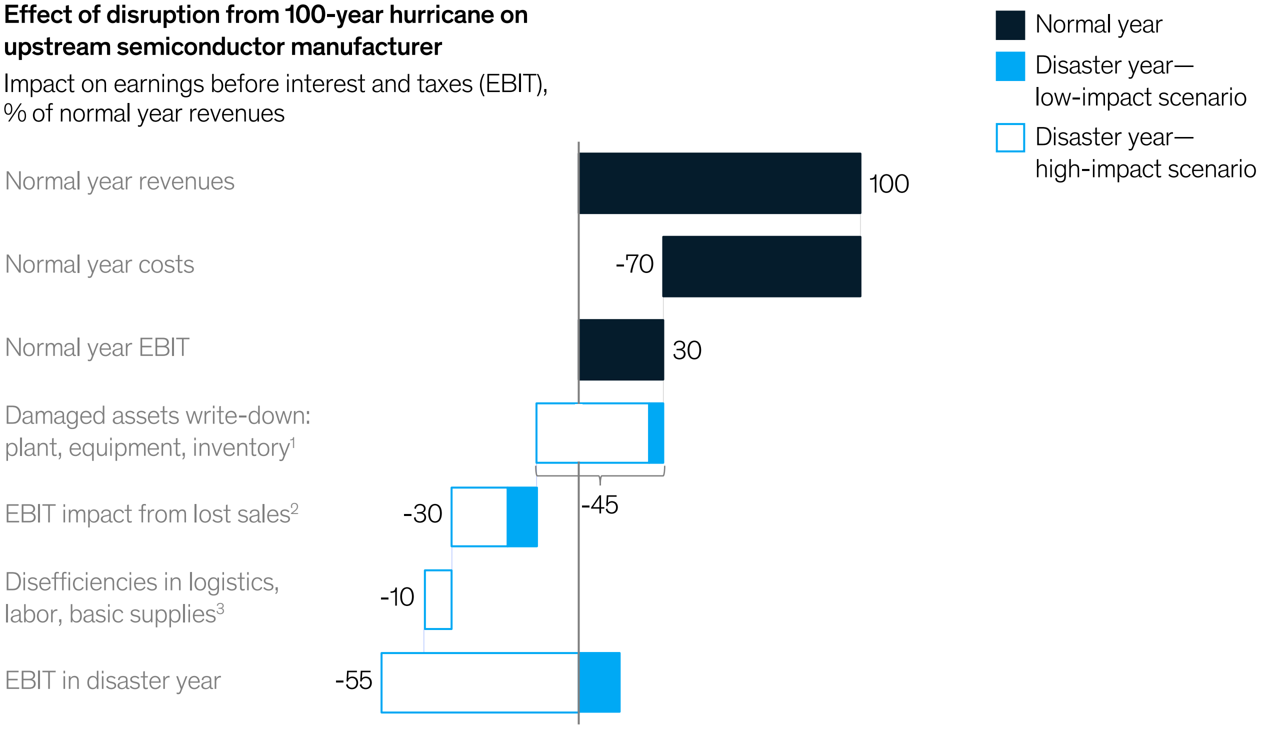
Being prepared for extreme weather impacts can minimize supply chain disruptions.

In the case of disruption to the semiconductor supply chain, an unprepared downstream company could lose about 35% of annual revenue while preparation limits the loss to about 5%.

Illustrative

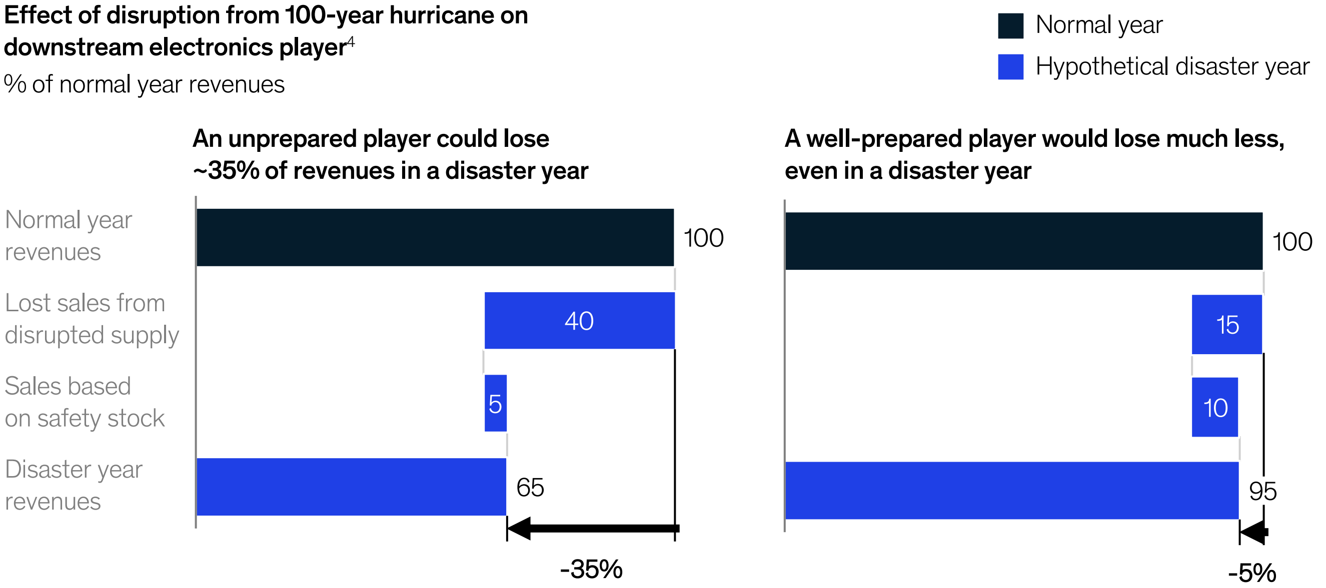
Effect of disruption from 100-year hurricane on upstream semiconductor manufacturer

Impact on earnings before interest and taxes (EBIT), % of normal year revenues



Effect of disruption from 100-year hurricane on downstream electronics player[4]

% of normal year revenues



An unprepared player could lose ~35% of revenues in a disaster year

5-month disruption of 100% of single-sourced supply

With 2 weeks of safety stock, resulting production disruption of 4.5 months

A well-prepared player would lose much less, even in a disaster year

Dual sources and stronger asset resilience: only 3 months of 50% of supply disrupted

2x safety stock, spending at half pace due to dual sourcing, lasting for 2 months

Only 1 month disruption of 50% supply

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1. Includes structural plant failure, replacement, repairs, and/or requalification of equipment, as well as raw material, work-in-progress inventory, and finished goods.
2. Lost revenues from disrupted sales, partly mitigated by reduced cost of goods sold proportional to reduction in sales volumes.
3. Includes costly additional labor, expensive backup power during grid failure, makeshift logistics solutions during rail or road disruptions, etc.
4. Excludes impact of insurance; exact outcomes vary considerably with local conditions and other factors.

Source: CP Analytics; Thailand government reports on 2011 floods; McKinsey Global Institute analysis

The probability heavy rare earths production is severely disrupted from extreme rainfall may increase two to three times by 2030

Heavy rare earths production is concentrated in southeastern China, which is increasingly exposed to extreme rainfall. About 80 to 90 percent of global production is concentrated in only 60 mines in a 150-kilometer-radius circle around Anyuan, in the province of Jiangxi. Heavy rare earths are vital in permanent magnets and electronics used in the defense sector, electric vehicles, wind turbines, consumer electronics, and medical appliances and typically cannot be substituted with light rare earths or other materials without a significant drop in quality. We examine this as an example of a commodity supply chain facing potential disruption.

Scientists are confident that continued increasing global temperatures will drive an increase in intensity and frequency of heavy precipitation events in many regions.[33] We find that heavy rare earth production in southeastern China will experience extreme precipitation events (defined as events that occurred historically with an annual probability of about 2 percent, corresponding to precipitation of about 170 millimeters per day in the relevant region) twice as often by 2030. Expert estimates and historical events indicate that such rainfall events significantly increase the risk of landslides in the region.

This region already has some of the strongest rainfalls in the world, with pluvial flooding nearly every year, and some mines already close for a couple of months during the wet season in mid-June to mid-September. Moreover, annual probability of extreme precipitation events has already increased to 2.5 percent compared with the historical baseline of 1951–80, and will continue evolving past 2030, reaching 6 percent annual probability by 2050.[34] While China has invested significantly in flood defenses in the past 20 years this has primarily focused on urban areas, and has done little to reduce risk to rare earth mines.

We estimate that the manifestation of an extreme precipitation event, or series of events, could cause at least a 20 percent drop in heavy rare earth output, and potentially much more in a worst case scenario. Damage mechanisms include excessive mud and landslides in mines, flooding treatment ponds, and disrupted logistics to and from mines (Supply chain-4). Landslides are of particular concern, as they could both disrupt the ongoing leaching process in the mine if leach holes collapse and prevent production after the landslide if on-site repair works are required before new leach holes are dug (for example, to make sure that the soil has stabilized). This means a large landslide could disrupt production for up to 12 months in severely hit mines, though for most mines the disruption would be shorter if the landslide is shallow and only affects parts of the mine.

Even a limited supply shortfall could cause prices to rise substantially (Supply chain-5). During the supply crisis in 2010—11, prices of several rare earths increased more than ten times.[35] The supply crisis was caused by market fears and diplomatic tensions after China reduced export quotas from about 50 metric tons to about 30 metric tons.[36] According to Chinese authorities, environmental reasons and a crackdown on illegal mining caused the supply shortage. The magnitude of the global shortfall in production is uncertain as reliable data on the extent of the illegal mining prior to 2010 are scarce, but estimates range from 10 to 40 percent.[37]

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[33] Richard Wartenburger et al., “Changes in regional climate extremes as a function of global mean temperature: An interactive plotting framework,” *Geoscientific Model Development,* September 2017, Volume 10, Number 9.

[34] It is important to note that near-term regional projections of precipitation extremes have been assessed as highly sensitive to the influence of natural variability, particularly in lower latitudes, and therefore the 30-year projection is more robust than the decadal projection. Furthermore, there is recent evidence from observational records indicating that in many regions climate models may underestimate changes in precipitation volume. For more details on the relevant uncertainties, please see: Ben Kirtman et al., “Near-term Climate Change: Projections and Predictability,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014. Woods Hole Research Center.

[35] Molycorp, 2014.

[36] March Humphries, Rare Earth Elements: The Global Supply Chain, Specialist in Energy Policy December 16, 2013.

[37] Wayne M. Morrison and Rachel Tang, *China’s rare earth industry and export regime: Economic and trade implications for the United States,* US Congressional Research Service, April 30, 2012*;* Xibo Wang et al., “Production forecast of China’s rare earths based on the Generalized Weng model and policy recommendations,” *Resources Policy,* March 2015, Volume 43.

Case study Supply chain-4

The frequency of rainfall events in Southeast China with the potential to cause landslides in mines producing heavy rare earth metals is projected to continue to increase.

Based on RCP 8.5

Future and annual probability of extreme precipitation

Defined as precipitation exceeding ~170mm per day

Multiple, compared to historic[1]

▢ 0–2.0x
▢ 2.1–3.0x
▢ 3.1–4.0x
▢ 4.1–5.0x
▢ >5.0x

Number of mines producing heavy rare earths[2]

○ 1
○ 2–3
○ 4–9
○ >9

Today

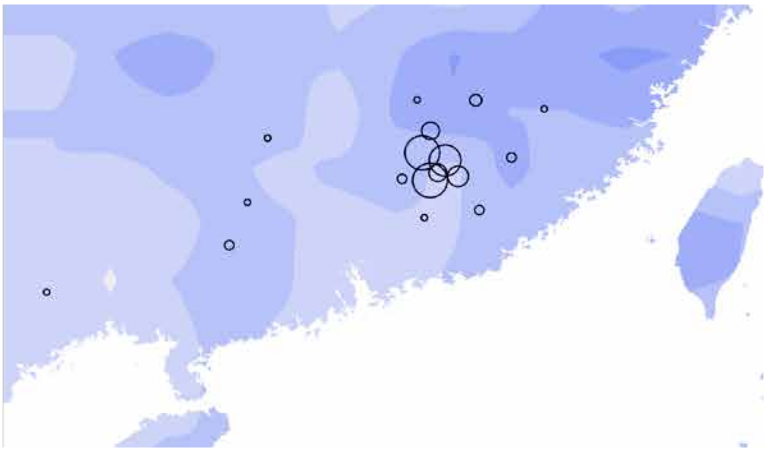
Increase from historical reference period (1951–81) to current (1998–2017).

2030

Increase relative to historical reference period

2050

Increase relative to historical reference period

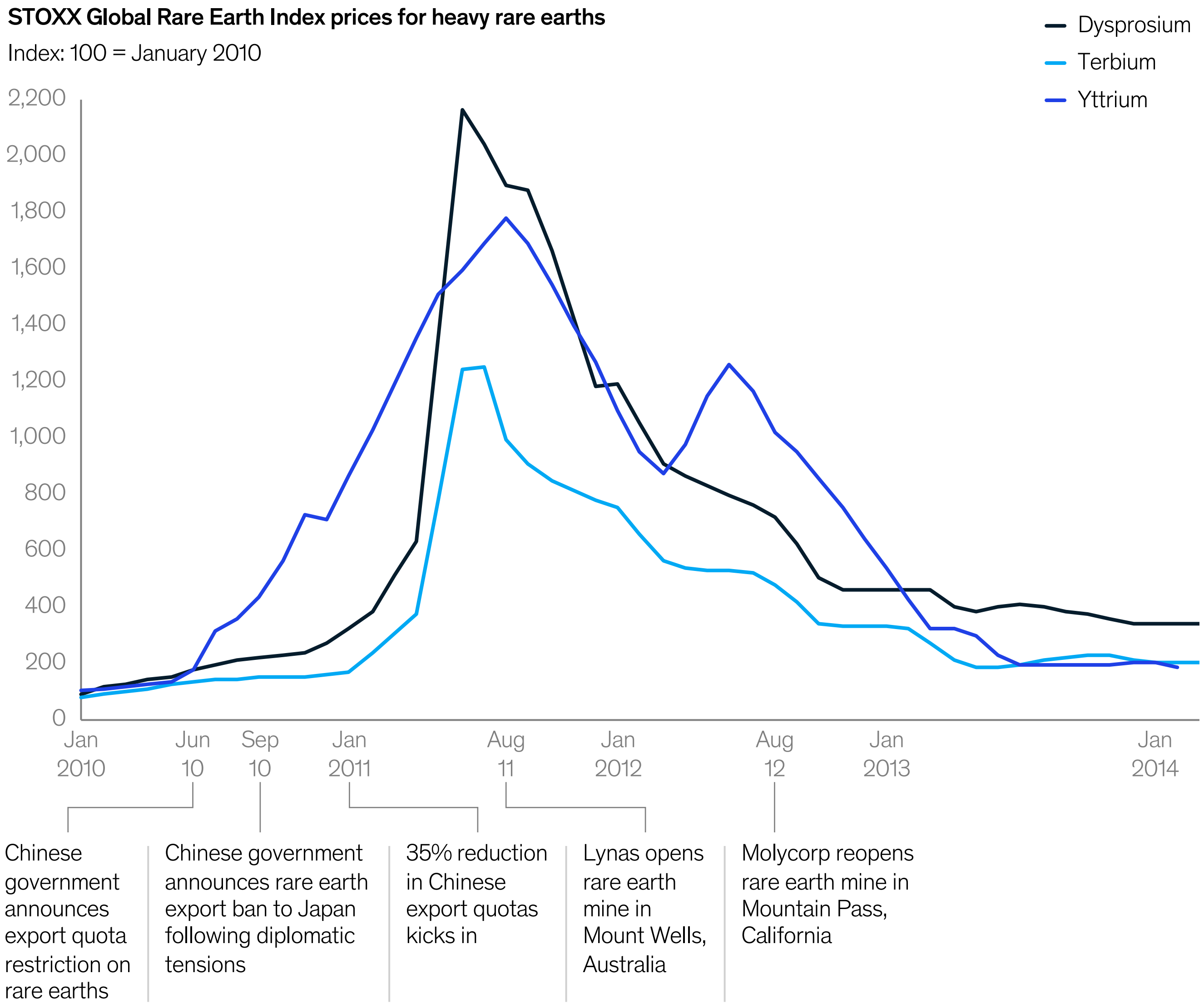


1. Multiple relative to historical reference period (1951–81).
2. Map shows 66 of 67 mines producing heavy rare earth metals globally, representing >90% of global production; some mines producing light rare earths, e.g., Bayan Obo in Inner Mongolia, produce limited quantities of heavy rare earths.

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

Source: Chinese Ministry of Information and Technology through NengApp.com; Woods Hole Research Center; McKinsey Global Institute analysis

Supply shortfalls in rare earths could cause price spikes as happened in 2010–11.



STOXX Global Rare Earth Index prices for heavy rare earths

Index: 100 = January 2010

Chinese government announces export quota restriction on rare earths

Chinese government announces rare earth export ban to Japan following diplomatic tensions

35% reduction in Chinese export quotas kicks in

Lynas opens rare earth mine in Mount Wells, Australia

Molycorp reopens rare earth mine in Mountain Pass, California

Source: Croat, 2018; Lynas Corp.; Molycorp, 2014; *New York Times*; Wiley Rein

Since the supply shortages, some rare earth consumers have attempted to build stockpiles in case of price spikes, but public data on the scale of the stockpiling are scarce. For downstream players without substantial inventories, a price spike would mean they either have to reduce their consumption of heavy rare earths or increase their spending.

A supply shortfall would be more critical for some heavy rare earths than others. Since the supply shortage in 2010–11, significant effort has been put into researching alternatives to rare earths, but with limited success in the key application areas. Going forward, there is concern about whether supply can keep up with demand for the materials that are used in high-growth segments like cleantech and consumer electronics, as well as high-end segments like aerospace and defense and medical appliances. Disruptions from climatic disruptions will add extra pressure to a supply chain that has little to no slack. This particularly applies to dysprosium (used in batteries, wind turbines, electric vehicles, and missile guidance systems), erbium (used in fiber optics), and terbium and yttrium (used in display electronics and low energy lighting). All of these materials are further used in high-end electronics (for example, for radiation detection equipment and X-ray screens) as well as glass coloring. Of these, dysprosium, terbium, and yttrium, together with the light rare earths neodymium and europium, are considered "critical to advancement in a clean energy future" by the

US Department of Energy.[38] In the case of a supply shortfall, prices of these materials would be particularly likely to spike, and customers with low inventories and low willingness to pay would have to reduce their consumption through lower quality substitutes or reduced output.

Downstream players dependent on rare earths can protect themselves from climate-change-induced physical risk by raising inventory levels at the cost of additional working capital and storage space needed, similar to the semiconductor example above.

Rare earth miners can also adapt in other ways, for example, by using different leaching products and processes that decrease the risk of landslides or moving leach holes away from the steepest slopes. We estimate these measures could increase COGS by less than 5 percent.

Other adaptation measures could slightly decrease the output of the mines: one option would be to select sites in areas with a lower concentration of mines in order to diversify risk, even if these mines have marginally lower potential. For example, Yunnan and Hunan have less than 2 mines today, while there are more than 54 mines in Jiangxi. Finally, if extreme rainfall is expected, miners could extract the leach in the most mature leach holes ahead of schedule. This would limit destruction of work in progress inventory when the rainfall turns mines to mud. All adaptation measures mentioned could be implemented in the short term and would eliminate about 50 to 80 percent of risk for rare earth miners, according to our estimates.

There is significant potential for industries to adapt and strengthen supply chains in the face of growing climate risks

Supply chains and the infrastructure that supports them are designed for a stable climate. As hazards evolve, it will be necessary to increase investment in adaptation, possibly at the expense of efficiency.

Risk diagnostics should be a major consideration for many players. To successfully increase climate resilience, supply chain managers should first identify which of their suppliers (and their suppliers' suppliers, and so on) are critical for business continuity, and what level of climate hazard these suppliers face. Based on this information, an assessment can be made of where the largest risks lie in the supply chain from climate-related hazards. This is a non-trivial task: the many possible permutations and layers in supply chains, the interdependencies of supply and demand and the vast optionality of different adaptation measures at different points all create significant complexity. Investments in digital analytics to understand data-driven simulations of alternate adaptation and risk scenarios may be beneficial. No-regret moves include: identifying and prioritizing key risks, having adequate insurance coverage, setting up a war room and practicing simulations, and closer collaboration between suppliers and buyers. While any individual action is insufficient to eliminate the supply disruption risk entirely, a combination of adaptive actions can limit the risk significantly.

We find significant potential for many industries to adapt in the next decade, and indeed this is already underway in some areas, including from public authorities, suppliers in high-hazard locations, and customers in downstream sectors. For example, a leading global manufacturing conglomerate has increased stocks of critical inputs and has entered contingency plan agreements with suppliers to ensure they get allocation of available supplies following a disaster.[39] A global agricultural business is diversifying its raw material sourcing across different geographies and its industrial activities across crops, to reduce the impact of local crop failures (for example, from unusual local weather conditions).

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[38] Nawshad Haque et al., "Rare earth elements: Overview of mining, mineralogy, uses, sustainability and environmental impact," *Resources,* October 2014, Volume 3, Number 4.

[39] *Weathering the storm: Building business resilience to climate change,* Center for Climate and Energy Solutions, July 2013.

Broader adaptation measures we identify include:

- **Protecting supply chain assets:** For rare earth metals, this may include selecting leaching chemicals that degrade the structural stability of the soil as little as possible; putting lids on treatment ponds; limiting the slope around leach holes where possible; and extracting leach from near-mature leach holes in advance of major rainfalls. For semiconductors, this may include strengthening the inner shell around the clean rooms where critical manufacturing equipment and WIP inventory are kept; elevating the facility to stay above likely flood levels; or designing the facility so the most critical equipment is on the higher floors. Approaches to protecting assets should be considered as early as possible in the asset lifecycle, as tightening design standards will be cheaper than hardening assets after they are constructed in most cases.

- **Redesigning supply chain operations:** Working to improve the extreme weather preparedness of suppliers could help by encouraging suppliers to keep reserve capacity of critical supplies on-site, increase flexibility of production so it can continue even through a minor asset damage, or hold a war chest to be able to invest quickly to repair damages after a natural disaster. Downstream players can increase the safety stock of critical inputs to ensure their production continues even if the supply chain is interrupted. In addition, it is helpful to keep an overview of all relevant inventory in the entire supply chain, as there may be additional inventory at supplier sites or in transit.

- **Reducing exposure by creating alternatives:** By avoiding co-locating with a large share of suppliers or helping specialized suppliers select plant locations with low climate hazard, risk could be reduced. Finding ways to invest in spare production capacity to be able to ramp up if one supplier is disrupted is another option. Where possible, companies could source commoditized, generic parts and avoid at-risk materials or products. An option includes increasing modularity in product design to make it possible to replace parts with near substitutes without implications for other parts.

- **Allocating risk by using financial and contractual mechanisms:** Suppliers should consider hedging commodity price extreme risks to limit the impact of price volatility, engaging in long-term fixed-price contracts with resilient commodity suppliers to prevent price flareups in a disaster, and investing in insurance to help recoup repair costs.

- **Shoring up supply chain infrastructure:** Supply chains are also heavily exposed to infrastructure risk. Actions that can be taken to adapt include investment in understanding granular local hazards and infrastructure vulnerabilities to help businesses and communities adapt; organizing public-private partnerships to foster collaboration on climate change adaptation for exposed infrastructure; investing in infrastructure hardening to increase resistance to extreme weather; developing urban drainage solutions to limit future flood levels; and investing in early warning systems to alert the public when there is imminent risk of extreme weather events.

Not all actions will make sense for each supply chain category, as there often is a trade-off between efficiency and resilience. For example, dual-sourcing may not make sense if economies of scale are too large, as often is the case in pharmaceuticals or aerospace. Building safety stock may be too costly if holding costs are high (for example, airplane fuselage), inventory depreciation is high (for example, in semiconductors due to rapid innovation lifecycles) or if there already is a supply backlog meaning building inventory would limit current sales. There are "win-wins," however—some actions that increase resiliency can also increase efficiency or product quality. For instance, increasing modularity can make it easier to innovate and improve product design, because the design of each part is less constrained by the other parts. For downstream players, this could also help provide broader diversification opportunities across different suppliers and help reduce procurement costs. Similarly, closer collaboration with suppliers of single-sourced inputs can both enable resilience and offer opportunities for co-innovation through co-investing in asset hardening measures.

Industry 4.0 technologies could help support companies in achieving resilience as well as efficiency; for example, through improving transparency in supply chains, and in some cases, potentially changing the economics of production.

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