# Act Now or Pay Later: The Costs of Climate Inaction for Ports and Shipping

March 2022


***Prepared by***

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# Executive Summary

Global seaborne trade has grown enormously in the last 25 years, now accounting for roughly 80% of the total volume of global trade each year. Global trade will likely continue to grow in the future, as will the volume of goods transported by sea.

At the same time, the shipping industry is under growing threat from climate change. Projected increases in global temperatures are expected to cause or intensify several climate-related hazards that can pose considerable physical risks to the shipping and port industries. Most significantly, these hazards include:

- Sea level rise
- Severe tropical storms
- Inland flooding
- Drought
- Extreme heat events

To shed light on future climate impacts to the shipping industry, this report explores two key questions:

- **In what ways does climate change impact the shipping and port industries?**
- **How large will the economic effects of climate change be on the shipping and port industries if actions are not taken to reduce emissions?**

This report summarizes existing evidence and estimates of the impacts and costs of climate-related hazards, as well as expands on these findings to provide new estimates of the potential global costs of climate change for shipping and ports.

Without further action to reduce emissions, climate change impacts could cost the shipping industry an additional US$ 25 billion every year by 2100. To put these estimates into context, total operating profits for the global container shipping industry averaged less than US$ 20 billion per year during 2018-2020. It's also important to note that data on this topic is sparse and these estimates of added costs only reflect port damages and disruptions, meaning future costs overall could be far higher than estimated here.

The potentially high costs underscore the importance of strategies for preventing climate change, particularly by reducing greenhouse gas (GHG) emissions from the shipping sector itself. Powered by carbon-intensive bunker fuels, the shipping industry currently accounts for roughly 20% of global emissions from the transportation sector.

The findings from this report should encourage governments and shipping leaders to act now to reduce emissions and avoid the worst impacts – or pay later.

### ES-1 IN WHAT WAYS DOES CLIMATE CHANGE IMPACT THE SHIPPING AND PORT INDUSTRIES?

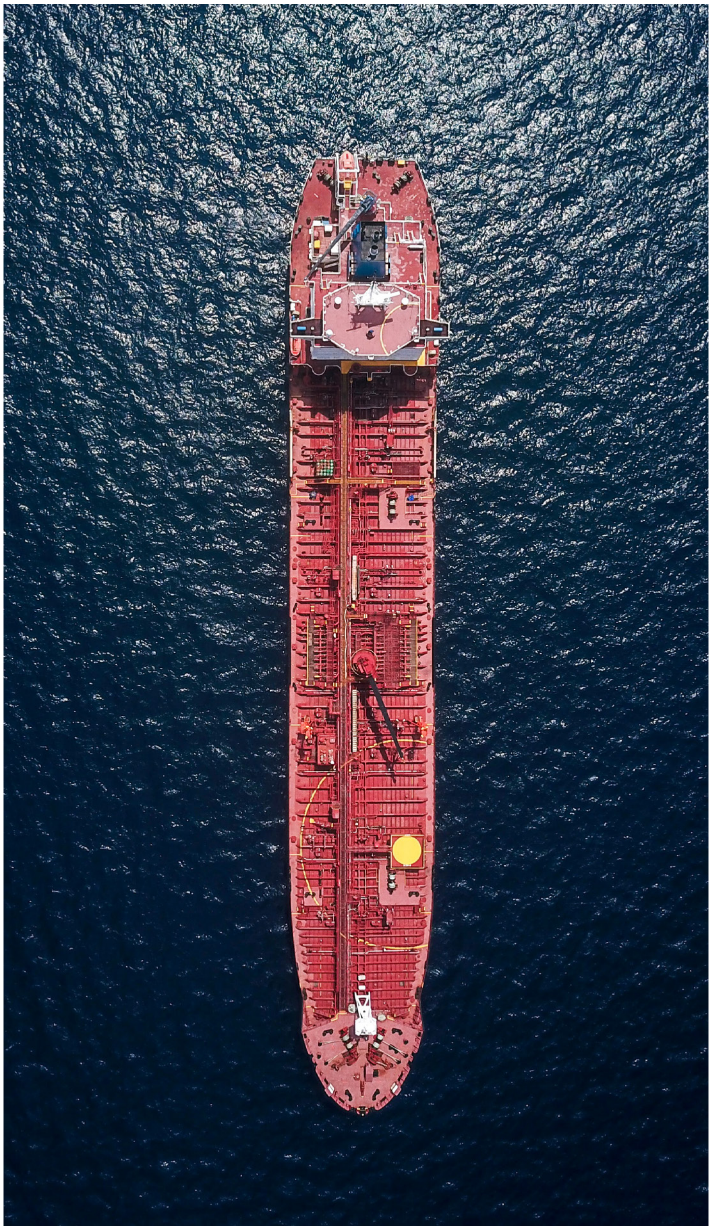
The report starts by taking stock of a growing body of research focused on climate-related impacts to shipping and ports, highlighting examples of how much different types of climate hazards have cost around the world.

#### Impacts from Sea Level Rise and Tropical Storms

Climate change is likely to cause global sea levels to rise and increase the intensity of tropical cyclones through increased wind speeds, wave heights, and rainfall intensity. Below are several examples of how storm-related losses have impacted the shipping industry and seaports in recent years, as well as results from analyses grappling with this question.

##### *Losses from Damages to Port Infrastructure*

- Damage estimates to US ports from previous hurricanes range from US$ 46 million for Hurricane Florence in 2018



to about US$ 2.2 billion for Hurricane Katrina in 2005.

- One study looks at the Hurricane Katrina damages to the Port of Mobile in Alabama. If sea level and storm surge had been as high as some 2100 projections, the study estimates that the millions of dollars in damage would have been 5.5 times larger.

### *Losses from Disruptions to Port Operations*

- Economic loss estimates due to previous storm-related disruptions range from US$ 10 million at the Port of Shanghai, caused by a 2-day disruption due to Typhoon Haikui in 2012, to US$ 65 million at the Port of Dalian, caused by a 5-day disruption due to Typhoon Lekima in 2019.
- An analysis of storm-related disruptions across 74 ports in 12 countries found that an additional meter in storm surge height or 10 meters per second in wind speed is associated with a 2-day average increase in the duration of disruption.

### *Losses from Vessel Incidents at Sea*

- Weather-related conditions were responsible for at least 20% of the roughly 400 total vessel losses that occurred worldwide from 2015-2019.
- Total vessel loss incidents over these five years have resulted in the death at sea of 142 crew members, many due to extreme weather events.

### *Adapting to Avoid Losses*

- For ships at sea, stronger storms will require adaptation through re-routing, which increases delays and operating costs. For a containership consuming 150 tons of fuel per day, each additional day at sea can cost roughly US$ 75,000.
- Most research on port adaptation costs has focused on elevation approaches, with unit costs ranging from US$ 30 million to over US$ 200 million per km2 of port area.

## Impacts from Inland Flooding and Droughts

Changing inland precipitation patterns, including increased risks of flooding and drought, can have indirect impacts on the maritime sector through supply chain effects.

- Record water levels on the Mississippi River in 2019 disrupted this key transport network for exporting US agricultural goods, causing losses valued at almost US$ 1 billion.
- In the same year, severe drought in the Panama Canal region required limits on through traffic that have been estimated to cost global shipping between US$ 230 million and US$ 370 million.

## Impacts from Rising Temperatures and Extreme Heat Events

Extreme heat can cause substantial damage to shipping vessels and port infrastructure, as well as disrupts port operations.


- Impacts on port infrastructure include stress on cooling systems and metal port structures, such as container handling cranes and warehouses.
- In 2009, heatwaves in Australia shut down sections of the Port of Melbourne for 3 days, resulting in productivity losses due to work stoppages.

### Impacts due to Climate Change's Effect on Global Economic Activity

Global maritime trade activity is strongly connected with the health of the global economy. Slower global economic growth due to climate change is therefore likely to constrain the growth of maritime trade; however, estimates of these climate impacts on global trade and maritime shipping are generally lacking.

## ES-2 HOW LARGE WILL THE ECONOMIC EFFECTS OF CLIMATE CHANGE BE ON THE SHIPPING AND PORT INDUSTRIES IF ACTIONS ARE NOT TAKEN TO REDUCE EMISSIONS?

Building on the existing evidence and findings, it is possible draw additional conclusions about some of the potential future economic impacts of climate change on the maritime shipping and port industries.

Estimating the economic costs of climate change requires analyzing projections of future temperature changes and the resulting hazards. To the extent possible, this report uses model-based scientific projections of these hazards, which are based on commonly used Representative Concentration Pathway (RCP) scenarios and assumptions. These scenarios range from the "worst-case" RCP8.5 scenario, which assumes no action on emissions, to the "best-case" RCP2.6 scenario, which assumes the most ambitious action to limit future emissions.

### Costs of Storm-Related Port Damages and Disruptions

The report examines and approximates these future costs for ports and shipping by first considering scenarios in which no adaptation measures are taken to protect ports against rising seas and stronger storms.

The analysis includes two types of impacts caused by a combination of sea level rise and stronger storms:

(1) storm damages to port infrastructure and

(2) storm-related port disruptions. Disruption costs include:

a. the economic losses incurred by ports, shippers, and carriers due to full or partial port closures and

b. costs to shipping customers due to resulting shipping delays.

As shown in **Table ES-1**, costs were estimated for two selected years – 2050 and 2100 – assuming a worst-case climate change scenario (RCP8.5).

Under current conditions, global average annual storm damages to ports are estimated at roughly US$ 3 billion. By 2100, the additional annual damages and port disruption costs are projected to be up to US$ 25.3 billion.

**Table ES-1. Projected Costs of Sea Level Rise and Stronger Storms for Ports and Shipping in Future Years (US$ billions/year)**

| | 2050 | 2100 |
|---|---|---|
| Increased Annual Storm Damage to Ports | 1.8 - 7.1 | 4.5 - 17.7 |
| Increased Annual Port Disruption Costs | 1.1 - 2.7 | 3.1 - 7.6 |
| **Total** | **2.9 - 9.8** | **7.6 - 25.3** |

## Port Adaptation Costs

Next, the report estimates the costs of adapting ports to avoid the previously described damages and disruptions, focusing on port elevation as the adaptation approach. Using the same combination of sea level rise and storm surge height assumptions for the RCP8.5 scenarios, the analysis estimates the cost of elevating all current port areas globally by the same total amount.

As shown in **Table ES-2**, the current global investment cost required to protect all ports against the increase in sea level rise and storm surge expected by 2100 is estimated to be up to US$ 205 billion. On an annualized basis (assuming a 3% interest rate and 80-year repayment period) these costs range from US$ 4 - 6.8 billion per year.

**Table ES-2. Port Adaptation Costs Against Projected Sea Level Rise and Larger Storm Surge for Selected Future Years**

| | 2050 | 2100 |
|---|---|---|
| **Investment Cost (US$ billion in 2021)** | 121 - 176 | 151 - 205 |
| **Annualized Cost (US$ billion/year 2021-2100)** | 4.0 - 5.8 | 5.0 - 6.8 |

As an example, when the estimation approach is applied specifically to the Port of Los Angeles, annual costs to elevate the port against sea level rise projections for 2100 (RCP8.5) are expected to be roughly US$ 100 million per year. These annual expenses would represent roughly one-third of the port's net available revenue in 2020.

## Loss in Future Maritime Trade due to Climate Change Impacts on the Global Economy

In addition to direct impacts from climate hazards, the shipping and port industries are likely to be indirectly affected by climate change through its negative impacts on the global economy. Under the baseline scenario without climate change, total trade volume is projected to grow from 11.5 billion tons in 2020 to almost 120 billion tons in 2100 (assuming trade continues to grow by 3% per year). The analysis estimates that maritime trade volume in 2100 under the worst case scenario will be between 5.3 – 11.8 billion tons lower than it would be without climate change.

## ES-3 CONCLUSIONS

The analysis offers several key findings and implications, including:

- First, climate change is likely to impose billions of dollars in additional costs each year – unless significant mitigation and/or adaptation steps are taken. Added costs in 2050 are likely to double by the end of the 21st century.
- Second, the estimated costs likely understate future costs to shipping and ports for several reasons. Cost estimates are for existing port infrastructure and operations; therefore, they do not capture costs linked to future growth in the size and number of ports or in global trade volume. Additionally, they do not include cost estimates for "soft" adaptation measures, like port defense or retreat strategies, or for re-routing costs for shipping.
- Third, more detailed analyses are necessary to fully assess the potential cost savings from port adaptation. Although the annualized cost estimates for port elevation are lower in dollar terms than the estimated increase in damage and disruption costs for future years, these values are not directly comparable, for reasons discussed in the report.

The cost estimates developed for this report are merely a starting point for understanding how much climate change is going to cost shipping and ports stakeholders. It's clear that actions now to reduce emissions can help avoid the worst impacts and ensure a safer, stronger shipping industry around the world.

# 1. Introduction

The global maritime shipping and port industries have experienced impressive growth in the last 20 years. Containerized trade in particular has expanded significantly, increasing from around 60 million 20-foot equivalent units (TEUs)[2] shipped in 2000 to over 140 million in 2020.[3] Over the same period, the total volume of international maritime trade has almost doubled to more than 11 billion tons per year.[3] Seaborne trade now accounts for roughly 80% of the total volume of global trade each year and 70% of its total value.[4]

Due to this growth, the shipping industry has also become a large emitter of greenhouse gases (GHGs) that contribute to climate change. It currently accounts for roughly 20% of global emissions from the transportation sector.[5] The size of these emissions is due not only to the volume of goods transported each year by sea, but more importantly because shipping relies on energy from relatively emissions-intensive "bunker fuels."[6]

Through these GHG emissions, the maritime shipping industry is contributing to changes in global climate that will ultimately harm itself. To shed light on these effects, this report addresses two main questions to support policy makers and the shipping industry in addressing climate change:

- In what ways will climate change impact the shipping and port industries?
- How large will the economic effects of climate change be on the shipping and port industries if actions are not taken to control emissions?

In addition to summarizing existing evidence and estimates of climate impacts and costs, the study expands on these findings to provide new estimates of the potential global costs of climate change for shipping and ports. The findings from this review and analysis underscore the great importance of substantially reducing emissions for the maritime shipping sector's own economic benefit, security, and sustainability.

# 2. Projected Climate Change and Hazards Affecting Shipping and Ports

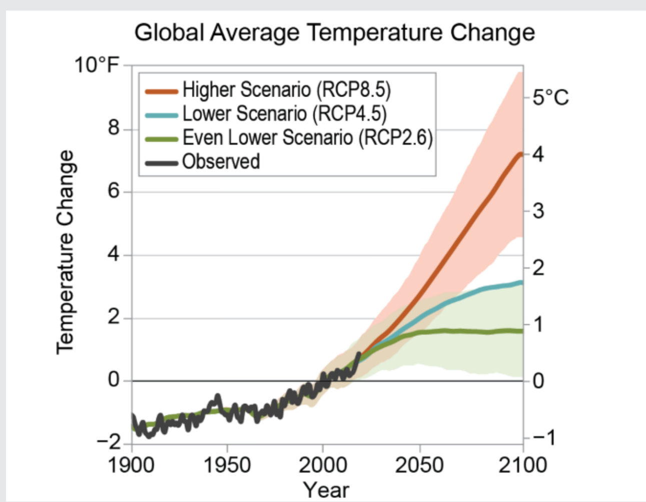
How the global climate changes in coming decades will depend critically on the future trajectory and types of GHGs released into the atmosphere. To address the inherent uncertainty in these future global emissions, climate scientists have developed a set of scenarios, known as Representative Concentration Pathways (RCPs). Each scenario is based on different assumptions about changes in annual GHG emissions from 2000 to 2100.

The RCP scenarios range from the "best-case" RCP2.6 scenario, which assumes aggressive action to limit future emissions, to the "worst-case" RCP8.5 scenario, which assumes little action on emissions. RCP4.5 is one of the main scenarios used to represent intermediate conditions, with future emissions between the best- and worst-case scenarios.[7]

Using these scenarios, estimates of future changes in average global temperatures are shown in **Figure 1**:

- Under the RCP8.5 scenario (shown in red), temperatures are projected to increase by roughly 2°C by midcentury and by 4°C by 2100, relative to average temperature in 2000.
- Under the RCP4.5 scenario (blue), which assumes that global carbon emissions peak around 2050, temperatures would continue to rise through the end of the century and reach levels about 2°C higher than in 2000.

**Figure 1. Observed and Projected Global Average Temperature Change[8]**



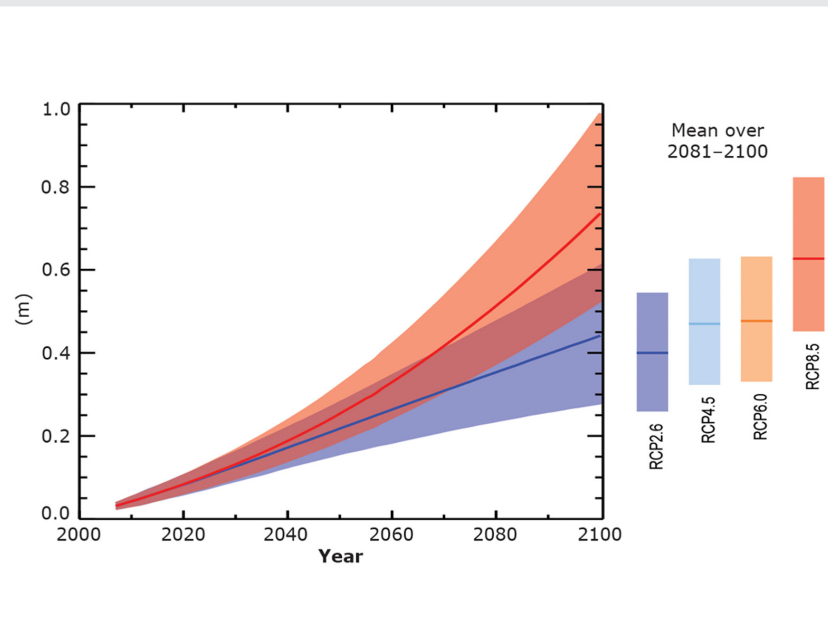
- Under the RCP2.6 scenario (green), temperatures would stabilize at roughly 1°C above 2000 levels.
- Shaded areas in the figure represent uncertainty ranges for future temperatures under the RCP8.5 and RCP2.6 scenarios.

The figure also shows how historical temperatures have risen since 1900. Given this observed change, the projected temperature increases for each scenario are between 0.5 and 1-degree C higher if compared to 1900 rather than 2000 levels.

Warming will likely also create or exacerbate several types of climate hazards that are detrimental to maritime ports and the shipping industry. Climate hazards are climate-influenced natural processes, conditions, or events that can directly harm human health, natural resources, and the economy.

For ports and the shipping industry, the two most significant and directly impactful hazards are likely to be sea level rise and higher intensity cyclones. Climate change will likely also worsen other hazards such as extreme heat, inland flooding, and drought, which can have both direct and indirect harmful impacts on the shipping industry.

**Figure 2.** **Projected Change in Global Average Sea Level**[11]




## Sea level rise

As global temperatures rise, land-based ice melts at a faster pace, which can raise sea levels around the world.[9] Rising ocean temperatures will also cause the volume of water to expand, which further contributes to sea level rise. Due to these factors, global average sea level has already risen by about 0.2 m since 1900, and it is projected to increase at an even faster rate in the future.[10] As shown in **Figure 2**, by the end of the century, global average sea level is expected to be more than 0.8 m higher than the 1985–2005 period under the RCP8.5 worst case scenario. Under the RCP4.5 intermediate warming scenario, an increase of almost 0.6 m by 2100 is projected.

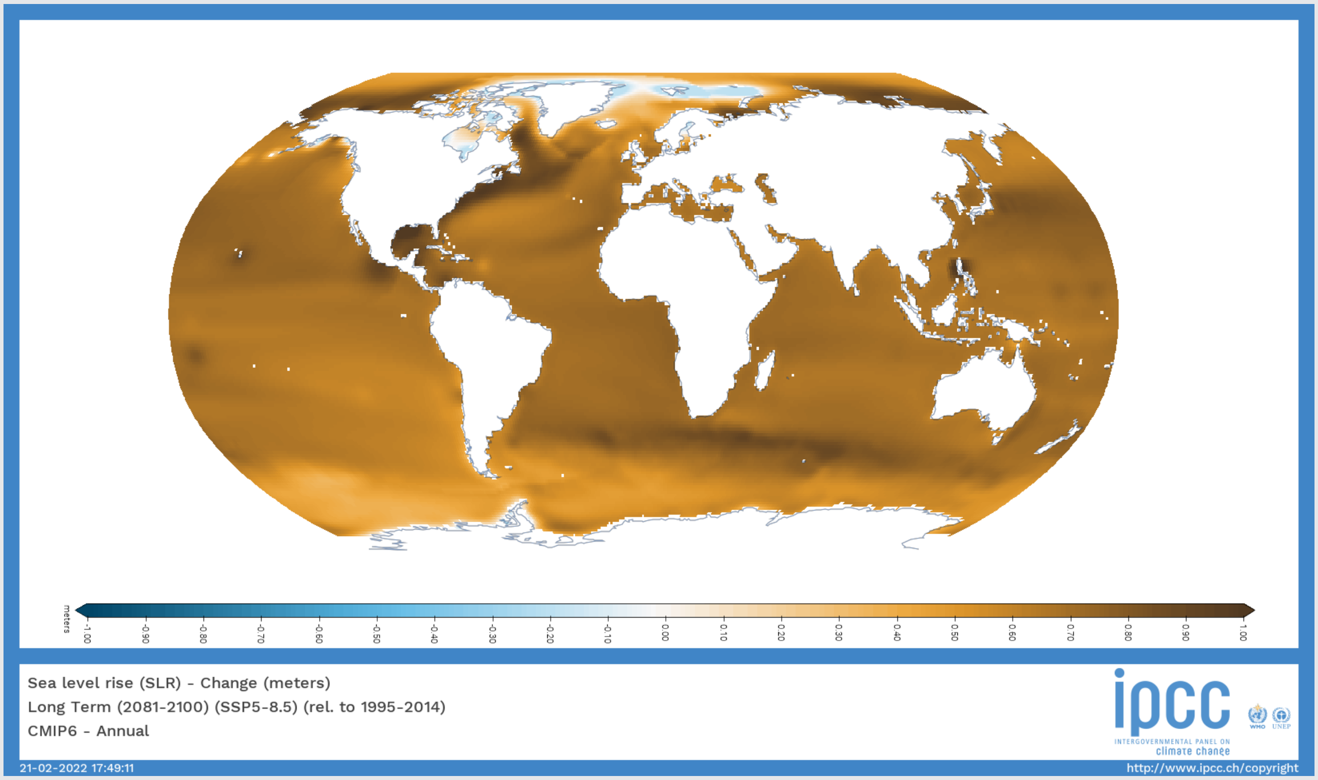
Future sea level rise is also projected to vary significantly across the globe. According to the most recent compilation of climate model results being prepared for the next International Panel on Climate Change (IPCC) assessment report (AR6), sea levels are projected to increase over this century by as much as 1 m in some regions under a high-emissions scenario,[12] especially in the northwestern Atlantic Ocean and parts of the Arctic Ocean (**Figure 3**). In other regions, the rise in sea levels is projected to be less than 0.2 m and may even decline. It is noteworthy that the estimates shown in **Figure 3** represent an average across many climate models, but there is considerable variation across these models in the projected spatial pattern of sea level rise.

As sea levels continue to rise, increasingly large areas in and around ports will be at risk of permanent inundation or periodic tidal flooding. In many coastal areas these risks are compounded by land subsidence (i.e., the gradual sinking of land surface). This process, which can occur naturally or because of human activities such as groundwater pumping, further contributes to coastal inundation. Higher seas will also make many port structures, facilities and operations, and the shipping vessels they are serving more vulnerable to waves, storm surge, and flooding from coastal storms.

## Increases in storm intensity

Warming temperatures are projected to increase the intensity of tropical cyclones,

**Figure 3.** **Spatial Pattern of End-of-Century Sea Level Rise Projections across the Globe**[13]




which include hurricanes, typhoons, and tropical storms. In particular, rising average sea surface temperatures—which are projected to increase by about 3°C globally from 2000 to 2100 under the RCP8.5 scenario—are likely to cause increases in cyclone wind speeds, rainfall, and wave height.[14] Climate studies predict that cyclone wind speeds can rise by roughly 4% for each 1° increase in sea surface temperature.[15] Increasing storm intensity will also likely lead to higher storm surge heights in coastal areas; however, these changes are more difficult to predict and depend on local factors such as coastline geography.[16]

Climate change is also expected to contribute to stronger extratropical storms (e.g., "nor'easters"), and there is evidence that the most severe tropical cyclones—that is, Category 4 and 5 storms, with sustained winds of 210 km/h or more—could become more frequent.[17]

More severe storms will increase hazards for coastal ports and maritime shipping in several ways. Higher storm surge from incoming waves will add to ports' growing flood risks caused by sea level rise. Higher winds and stronger wave action will worsen the risk of damages to port infrastructure and further disrupt port operations. For shipping operations, stronger winds and waves will further threaten the safety of crews and increase risks of vessel and cargo losses.

### Extreme heat

In addition to causing increases in average temperature, climate change is expected to increase the length, frequency, and intensity of heat waves in most of the world.[18] Days that are considered abnormally hot by today's standards will likely become more common. According to IPCC projections, extreme heat days (i.e., those that currently happen on average once per decade) may occur roughly 4 times more often in 2050 under the RCP8.5 scenario. By 2100 they could occur about 10 times more often.[19]

Extreme heat is a potential hazard for seaports and shipping because of the physical damage it can cause to infrastructure and equipment. Heat can also create unsafe working conditions for port workers and shipping crews, decrease productivity, and disrupt operations in port and at sea.

### Inland flooding and drought

Climate change is projected to cause an increase in precipitation extremes. These extremes include more frequent heavy precipitation events, as well as more droughts. One-day rainfall levels that currently occur at most once every 20 years are projected to increase in frequency to once every 5 to 15 years by 2100, depending on climate scenario and region. When these extreme events occur, they often lead to inland flooding of rivers, streams, and other waterbodies. Dry spells, which can reduce flows in inland waterways used for navigation, are also expected to increase in frequency and duration across much of the world, including southern and central Europe and the Mediterranean region, central North America, Central America, and southern Africa.[19]

As inland floods reach coastal areas, they can create severe hazards for downstream seaports, especially when they coincide with floods caused by coastal storms. Both inland flooding and droughts are also likely to cause indirect harm to maritime ports and shipping by disrupting the inland supply chains that are critical to these industries.

The following sections of this report describe in more detail the available evidence about how the previously described climate hazards are likely to impact maritime ports and shipping in the coming decades.

## 3. Impacts from More Severe Storms and Sea Level Rise

The largest impacts and costs for the maritime industry from climate change will almost certainly be due to the combined effects of sea level rise and more intense tropical cyclones and other storms. As described in more detail in the following sections, these climate hazards will:

- Damage seaport infrastructure and shipping vessels
- Disrupt port operations and shipping routes
- Require costly adaptation measures.

### 3.1 STORM DAMAGES TO PORT INFRASTRUCTURE

As climate change is projected to increase the intensity of tropical cyclones through stronger winds, extreme waves, and more rainfall, seaports across the globe will be increasingly at risk for storm-related damage, especially in areas already vulnerable. These risks will be exacerbated by higher sea levels, and the magnitude of damages will grow as port areas and infrastructure continue to expand.

Port damages from previous storm events provide a useful baseline for understanding potential risks and damages in the future. **Figure 4** shows the location of roughly 3,700 ports worldwide in relation to the tracks of tropical storms (shown

**Figure 4.** **Map of Ports Worldwide in Relation to Historical Tropical Storm Tracks**[22]

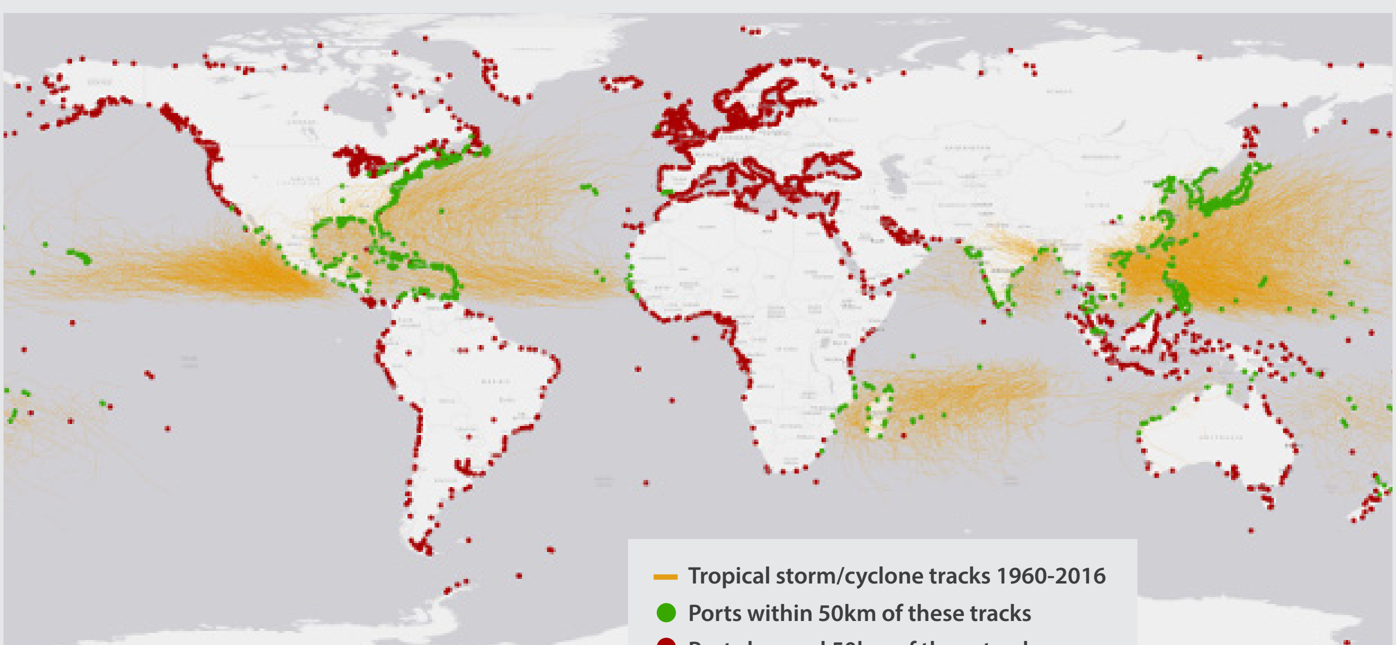


**Table 1. Reported Examples of Port Damages from Tropical Cyclones**

| STORM (YEAR) | STORM CATEGORY AT LANDFALL[a] | COUNTRY (AFFECTED REGION OR PORT) | DAMAGE ESTIMATE (2020 US$) OR DESCRIPTION |
|---|---|---|---|
| **Hurricane Katrina (2005)** | 5 | U.S. (Louisiana, Mississippi, Alabama) | US$2.2 billion damages to ports in Louisiana, $133 million to three ports in Mississippi (Bienville, Gulfport, and Pascagoula), and $40 million to the Port of Mobile in Alabama |
| **Hurricane Ike (2008)** | 2 | U.S. (Texas) | US$2.9 billion in damages to ports, waterways, and coastlines in Texas[24] |
| **Hurricane Sandy (2012)** | 1 | U.S. (Port of New York/ New Jersey) | US$147 million in damage[25] |
| **Hurricane Florence (2018)** | 1 | U.S. (North Carolina) | US$46 million in damage to the ports of Wilmington and Morehead City[26] |
| **Hurricane Maria (2019)** | 4 | U.S. (Puerto Rico) | US$911 million in damages to the Port of San Juan and other ports in Puerto Rico[27] |
| **Typhoon Maemi (2003)** | 2 | South Korea (Port of Busan) | Damage to 11 quay cranes and flooded the port's container yards |
| **Gujarat Cyclone (1998)** | 3 | India (Kandla Port) | Damage to port infrastructure and facilities, including 14 jetties, as well as to ships and cargo in the port |

[a] Categorized according to the Saffir-Simpson scale (https://www.nhc.noaa.gov/aboutsshws.php), which is based on maximum sustained (1-minute) winds of 119–153 km/h (Category 1), 154–177 km/h (Category 2), 178–208 km/h (Category 3), 209–251 km/h (Category 4), and above 251 km/h (Category 5).

in yellow) from 1960 to 2016.[20] Roughly a third of these ports (shown as green dots) are within 50 km of areas that have experienced at least one of these tropical storms or hurricanes. The range of damages experienced by ports in these events varies substantially, but roughly 130 ports in recent decades have been severely impacted by tropical cyclones.[21]

**Table 1** offers examples and estimates of cyclone-related damages to port infrastructure from the last 25 years. Monetary estimates of these damages, based on the estimated costs of repairing storm-related infrastructure damages, are primarily available for ports in the United States.

The most damaging storm for U.S. port infrastructure in recent decades was Hurricane Katrina, which made landfall in Louisiana on the U.S. Gulf Coast in August 2005, but impacted ports and coastal communities from Florida to Texas. A Category 5 hurricane with maximum sustained winds of 280 km/h, Katrina is estimated to have caused US$2.2 billion in damages to ports in Louisiana,[22] US$133 million to three ports in Mississippi (Bienville, Gulfport, and Pascagoula),[23] and US$40 million to the Port of Mobile in Alabama.[24] Other storms that caused significant port damages in the United States include Hurricanes Sandy, Ike, Maria, and Florence.

Few monetary estimates of port damages from coastal storms are available for other countries; nevertheless, severe

damages have been recorded in several ways. For example, Typhoon Maemi, which was a Category 2 storm when it hit the Port of Busan in 2003, damaged several cranes and flooded the port's container yards.[25] In 1998, the Gujarat Cyclone hit the Kandla Port in India. This Category 3 storm caused extensive damage to port infrastructure and facilities, as well as to ships and cargo.[25]

As illustrated by these examples and confirmed by other larger-scale studies, many ports are at high risk of storm damage. In East Asia alone, one study identified 12 major ports, with a combined annual throughput of more than 160 million TEUs (roughly 20% of the global total), that are highly exposed to cyclone hazards.[25] Based on a global-scale analysis, another study concluded that over 40 ports in the Caribbean are currently at particularly high risk.[30]

As the global climate changes, the number of ports that are at high risk of damage from coastal storms is expected to increase significantly, particularly in East Asia. When analyzing risks in 2100 based on the RCP8.5 scenario, one study of global port risks concluded that almost 290 ports (14% of all coastal ports[29]) will likely be at very-to-extremely high risk, with over 30% of them located in Indonesia, the Philippines, the United States, and Japan.[30] Even ports in Europe that are currently considered well protected against high intensity storms—like in Rotterdam, Amsterdam, and Hamburg—are expected to need upgrades for their flooding defense systems to address from future sea level rise.[32]

Although no known studies have developed global or regional estimates of how climate change is expected to increase the magnitude of storm damages to ports, a few studies have estimated significantly higher damages due to higher sea levels for specific ports and storm events:

1) Port of Mobile, United States: An analysis of the impacts of Hurricane Katrina on the Port of Mobile on the U.S. Gulf Coast concluded that the millions of dollars in damage that occurred in 2005 would likely have been 5.5 larger if sea levels were 1.21 meters higher.[33]

2) Port Rotterdam, Netherlands: A similar analysis for the Port of Rotterdam estimated damages for specific storm events under alternative future sea level rise scenarios.[34] The study estimates that a 100-year (i.e., 1% annual probability) storm under current condition would cause US$75 million in damages. However, with sea level rise of 0.6 m, the damages from the same storm would increase by a factor of 1.6. With sea level rise of 1.3 m, the damages would increase by a factor of over 8. For a 1,000-year (0.1% probability) storm causing US$112 million in damages, the multipliers for the same two sea level rise scenarios would be 2.4 and 14, respectively.

Although these two studies offer important insights into the magnifying effect of future sea level rise on storm damages to ports, they do not account for potential increases in the frequency of these storms. In other words, these studies may underestimate the full effect of climate change on storm-related damages.

### 3.2 DISRUPTIONS TO PORT OPERATIONS

In addition to causing greater and more frequent physical damages to seaports, climate change will likely increasingly interfere with ports' ability to operate. Larger storms coupled with sea level rise will increase the likelihood, size, and duration of port closures and reduce the efficiency and capacity of ports to process ships and cargo. These disruptions will take an increasingly large economic toll, not only on the port sector, but on the shipping industry and broader supply chains as well.

Tropical cyclones are already a major driver of costly port disruptions globally. High waves and strong winds and currents prevent operations, such as berthing maneuvers and loading and unloading of goods, from being carried out safely.[35] Additionally, damage to port infrastructure requires recovery and repairs that further limit port operations.

Ports play a key role in global supply chain networks, so any disruption to port operations in one location can spillover to other ports and the rest of the global supply chain.[20] The significant vulnerability of ports and maritime shipping networks to supply chain disruptions has been underscored by recent events, including the 6-day closure of the Suez Canal due to the grounding of the Ever Given containership[36] and the global-scale port backups and skyrocketing freight rates that have occurred due to COVID-related supply chain breakdowns.

A recent global analysis of port disruptions due to tropical cyclones from 2011 to 2019 found that when interruptions of port operations occur, the median duration is 6 days, and roughly half of the events led to complete shutdowns of port operations. The analysis, based on 141 incidences of disruptions across 74 ports in 12 countries, also examined how the duration of the port disruption was related to the severity of the event. It found that an increment of 1 m in storm surge height or 10 m/s in wind speed was associated with an average of a 2-day increase in the duration of the port disruption.[37]

In all cases studied, multiple ports were affected by the same storms. Given the interconnectivity of port networks, they found that even short-term delays in one port can cause lengthy disruptions to the broader logistics network, resulting in large-scale consequences for supply chains. During short-term interruptions, they observed very little substitution of shipping traffic between ports, meaning that the inoperability of one port was likely to cause broader delays for container traffic, at least in the short term.[37]

**Table 2** provides examples and estimates of cyclone-related port disruptions from the last 20 years. Monetary estimates of economic losses due to disruptions, which have been estimated for a small number of these cases, are also listed.

Ships waiting for entry to Port of Singapore

## East Asia

Ports in East Asia have been particularly vulnerable to storm-related disruptions due to the high frequency of cyclones (i.e., typhoons) in the region. One of the most significant disruption examples occurred as a result of Typhoon Maemi in 2003. The Port of Busan in South Korea, which was among the 10 most active ports in the world, was left inoperable for 91 days due to the storm.[37]

There are also multiple examples of typhoons causing significant economic losses for ports in China:

- In 2019, Typhoon Lekima in Wenzhou caused the port and inland water network to become inoperable for 45 days. Since that storm, the Port of Wenzhou has still not resumed its predisaster level of daily vessel activity, demonstrating the lasting economic impact of reduced port operations due to storm events.[37]
- For the Port of Dalian, a 5-day closure due to Typhoon Lekima resulted in a US$65 million loss in port income.[38]
- In 2016, Typhoon Nida caused port disruptions lasting 7 days, which for the Port of Shenzhen resulted in an estimated 20% decrease in income for that month.[38]

One recent study of economic losses from port disruptions in China due to extreme wind events uses evidence from previous storms to estimate expected annual losses across several ports.[39] Using data on port disruptions at eight major terminals in the ports of Shanghai and Nimbo from 2006 to 2013, the study developed a model to estimate damages for selected events. For example, it estimated that disruptions caused by extreme wind from Typhoon Haikui in 2012 created economic losses to the affected ports, shippers, and carriers totaling US$24 million and US$10 million for Shanghai and Nimbo, respectively. The study also estimated that average annual losses from extreme-wind-related disruptions at the three ports of Shanghai, Nimbo, and Shenzhen total roughly US$53 million, US$19 million, and US$11 million per year, respectively.

## United States

Ports in the United States have experienced significant downtimes because of hurricanes. In 2005, Hurricane Katrina closed the Port of New Orleans, Louisiana for 15 days. The nearby Port of Gulfport, Louisiana was closed for an entire month and required a coordinated federal, state, and local government effort to avoid a much longer shutdown. Farther east along the Gulf Coast, the Port of Mobile, Alabama, was also strongly affected by the hurricane's storm surge, and it required almost two weeks to remove mud and debris to become operational.[24]

In 2016, Hurricane Sandy caused the complete shutdown of the Port of New York and New Jersey for over 8 days, and it shut down the Red Hook Container Terminal within this port for 9 days.[22] Because the container operation experienced more physical damage and received lower emergency response prioritization than some other port operations, it took longer for it to resume normal operations. This terminal closure was particularly problematic because the disruption

**Table 2.** **Reported Examples of Port Disruptions and Associated Losses from Tropical Cyclones**

| YEAR | TROPICAL CYCLONE | STORM CATEGORY AT LANDFALL | COUNTRY | PORT | DURATION (DAYS) | ECONOMIC LOSS (US$) |
|---|---|---|---|---|---|---|
| 2003 | Typhoon Maemi | 2 | Korea | Port of Busan | 91 | not available (n/a) |
| 2005 | Hurricane Katrina | 5 | U.S. | Port of Gulfport | 30 | n/a |
| | | | | Port of Mobile | 15 | n/a |
| | | | | Port of New Orleans | 15 | n/a |
| | | | | Port of South Louisiana | 5 | n/a |
| 2011 | Cyclone Yasi | 5 | Australia | Port of Brisbane | 10 | US$52 million |
| 2012 | Hurricane Sandy | 1 | U.S. | Port of New York and New Jersey | 9 | n/a |
| | Typhoon Haikui | 1 | China | Port of Shanghai | 3 | US$10 million |
| | | | | Port of Nimbo | 3 | US$24 million |
| 2014 | Tropical Cyclone Christine | 4 | Australia | Port Walcott | 7 | n/a |
| 2015 | Tropical Cyclone Marcia | 3 | Australia | Port Townsville | 5 | |
| 2016 | Typhoon Nida | 1 | China | Port of Shenzhen | 7 | n/a |
| 2017 | Hurricane Harvey | 4 | U.S. | Calhoun Port Authority | 9 | n/a |
| | | | | Port Arthur and Port Beaumont | 8 | n/a |
| | | | | Port of Corpus Christi | 7 | n/a |
| | | | | Freeport | 6 | n/a |
| 2019 | Tropical Cyclone Veronica | 1 | Australia | Port Walcott | 7 | n/a |
| | Typhoon Lekima | 2 | China | Port of Wenzhou | 45 | n/a |
| | | | | Port of Dalian | 5 | US$65 million |

of container traffic occurred at the start of a busy holiday shopping season. The economic burden of the closure affected not only the port operation, but also local businesses, consumers, other stakeholders, and shipping firms that depend economically on the port system. [40]

### Australia

Extreme weather events have also had severe impacts on port operations in Australia.[41] In 2007, Port Hedland was hit by four cyclones, which closed the port to all vessels for 6 days.[41] In 2011, Cyclone Yasi closed the Port of Brisbane for 10 days, resulting in US$56 million in losses and decreasing the annual port throughput by 6.4%.[42]

### Vietnam

There is broad consensus in the scientific literature that the number, severity, and economic costs of port disruptions due to tropical cyclones will steadily increase in the future due to climate change. However, there are relatively few quantitative estimates of the projected economic losses. One exception is a study focused on ports in Vietnam, which concluded that, by 2085, the projected future increase in tropical cyclone activity due to climate change would increase annual port downtime by at least 60% compared to current levels. It estimates that these closures would result in a loss of US$700–US$1,600 million in gross domestic product (GDP) growth for Vietnam. The authors of that study note that their model is conservative and provides a lower-end estimate of the possible consequences of increased tropical cyclone activity.[43]

### Europe

In Europe, several studies have examined how sea level rise from climate change is likely to cause additional disruptions to port operations.[30] For example, analyses of ports in the Catalan region of Spain predict a general reduction of operability in all ports over the next century due to sea level rise associated with climate change under an RCP8.5 scenario.[35] For commercial berths specifically, 26% are estimated to become inoperable by 2070, and the percentage of inoperability then accelerates to reach 100% of berths by 2100. [35]

Other analyses have concluded that the increase in climate-related risk to European and Mediterranean port operations will be primarily due to the increase in coastal flooding and wave overtopping of breakwaters caused by sea level rise. Disruptions in the operations of even a few European ports can have significant spillover effects on other ports.[32] For example, although Mediterranean ports are less likely than many other European ports to be directly affected by sea level rise, they will experience considerable indirect impacts on their operations due to disruptions in the Northern European ports to which they are logistically connected. [32]

## 3.3 SHIPPING LOSSES AT SEA

The expected growing intensity of storms resulting from climate change will likely also increase the losses incurred by shipping vessels while in transit between ports. These weather-related losses, already significant for the shipping industry, take several forms.

Between 2015 and 2019, there have been almost 400 incidents worldwide resulting in total vessel losses and at least 20% of these were due to weather-related conditions. Many occurred in the South China, Indochina, Indonesia, and Philippines maritime region, in large part because this region experiences relatively high levels of ship traffic each year, and it is relatively prone to bad weather compared to other shipping areas. For example, Typhoon Damrey in 2017 was an important factor in six total losses that year.[44]

Total vessel loss incidents during this period have also resulted in the death at sea of 142 crew members, many due to extreme weather events. For instance, 33 of these deaths occurred in 2015 when the El Faro cargo ship sank in a Category 4 hurricane in the Bahamas.[45]

In addition to contributing to the loss of vessels and crew, extreme weather events are also responsible for hundreds of container losses at sea each year, as well as onboard damages to containers.[46] In the shipping industry, these container losses and damages are among the most frequent generators of insurance claims.

The loss of vessels or containers at sea also presents significant environmental hazards, along with costly cleanup and liability obligations for the ship owners. For example, the containership MSC Zoe lost at least 350 containers in heavy weather off the North Sea coast of Germany and the Netherlands in 2019. Toxic substances in some of the containers became a major source of environmental concern and contributed to a salvage operation of roughly US$40 million.[47] In the same year, a 200 m long car carrier, the Golden Ray, capsized and grounded in an environmentally-sensitive area off the coast of Georgia in the United States. This total vessel loss generated environmental cleanup and shipwreck removal costs of at least US$788 million for its owner and insurer.[48]

Despite these costs and losses at sea due to extreme weather events and the high likelihood that storms will continue to increase in intensity, projections of how these costs will rise because of climate change are generally lacking in the scientific literature. This uncertainty makes it especially difficult for the shipping industry to adequately anticipate and prepare for future impacts.

### 3.4 COSTS OF ADAPTING TO STRONGER STORMS AND SEA LEVEL RISE

Faced with these increasing climate-related threats and impacts, ports may be able to pass on damage costs to insurers in the short term, but insurance companies are likely to increase premiums or deny coverage if ports do not act to limit their exposure.[49] Fortunately, there are several strategies the maritime industry can use to protect ports and vessels and limit damages; however, these climate change adaptation strategies can also entail significant costs.

For ships at sea, the increased severity of extreme weather events will primarily require adaptation in how they select and alter their routes. To avoid or minimize losses at sea due to storms, many ocean vessels take steps to anticipate the tracks of hazardous storms and adjust their planned routes accordingly (e.g., using weather-routing services). Although rerouting reduces the risk of large storm-related losses, it can impose significant costs through shipment delays and increasing fuel and other vessel operating costs.[50] For example, for a containership that consumes an average of 150 tons of fuel per day, each additional day can cost an extra US$75,000 in fuel costs alone.[51] Entire supply chains may also be disrupted in the process. Moreover, the additional fuels used for rerouting creates even more climate-warming GHG emissions. As storms become stronger due to climate change, the extent and costs of these avoidance measures are certain to increase.

For ports that are vulnerable to the effects of stronger storms/sea level rise, adaptation approaches can be organized into two main categories:

- "Soft" adaptation strategies involve administrative and decision-making aspects of planning for climate change impacts, such as land use management, financial incentives, evacuation schemes, and institutional changes.[52, 53]
- "Hard" strategies, in contrast, involve structural changes to ports. The three main hard strategy approaches can be described as elevate, defend, and retreat.[54, 55]

To select the appropriate adaptation strategy, ports must account for local conditions, port configurations, and costs, as well as the specific climate threats confronting them, whether pertaining to sea level rise or storm surges. Most likely, ports will need to adopt a combination of these strategies.

The following sections describe the main features of each port adaptation approach and summarize available evidence regarding their expected costs, ranging from port-level to global estimates of costs.

#### Soft adaptation

Soft strategies aim to reduce decision-making uncertainty in planning for climate change impacts. They involve institutional, governance, and planning mechanisms of ports in response to climate change. These measures generally require fewer resources and capital than hard strategies, so they provide a good starting point for ports to reduce climate risks before deciding to implement hard adaptation. Soft strategies include financial instruments, decision-making support tools, port construction standards and regulations, and increased funding for adaptation and risk management, which help ports manage climate-related risks, reduce vulnerability, and increase resilience to an uncertain future.[52]

The costs of implementing soft adaptation strategies reflect a port's administrative costs related to insurance, regulations, budget reallocation, and the design of new documents.[54] While the literature does not provide quantified cost estimates, soft strategies are described as relatively inexpensive compared to the high fixed costs and upfront investments required for hard adaptation interventions.[52] As such, soft adaptation works best as a first step in the climate change adaptation process or as a supplemental mechanism to support other adaptation strategies. For soft strategies to contribute to port climate change adaptation, ports must also incorporate other strategies and multiple stakeholders into the adaptation process.

### Hard adaptation

**Elevate**. This strategy typically involves raising the port surfaces and infrastructure using fill materials and reconstructing facilities at a higher elevation. It includes raising piers, as well as yard areas, roads, and warehouses. In some instance bridges may need to be elevated to ensure adequate clearance for vessels. In the context of climate change adaptation, elevation is primarily used to address sea level rise; however, it is also often being used, particularly in Asia, to address land subsidence in port areas.

Global port adaptation cost estimates focusing on elevation as a strategy to address sea level rise have been developed by at least one study.[56] The estimates range from US$9–US$21 billion in current investment costs to address sea level rise projected to occur by 2050 to US$14–US$75 billion in costs to address projections for 2100. These estimates account for the range of global sea level rise projections linked to the best-case and worst-case (i.e., RCP2.6 and RCP8.5) climate change scenarios. Importantly, they only include adaptation costs for port areas existing in 2010 (almost 1,400 km$^2$), and they are based on average per unit cost estimates of US$30.3 million per square kilometer for each meter in elevation.[56] The authors note that these estimates are "almost certainly on the low side" due to the omission of defensive infrastructure to protect port facilities in their calculations.[57] **Table 3** compares the unit elevation cost assumptions used in this global study with estimates used in the regional and local studies described in the next paragraphs.

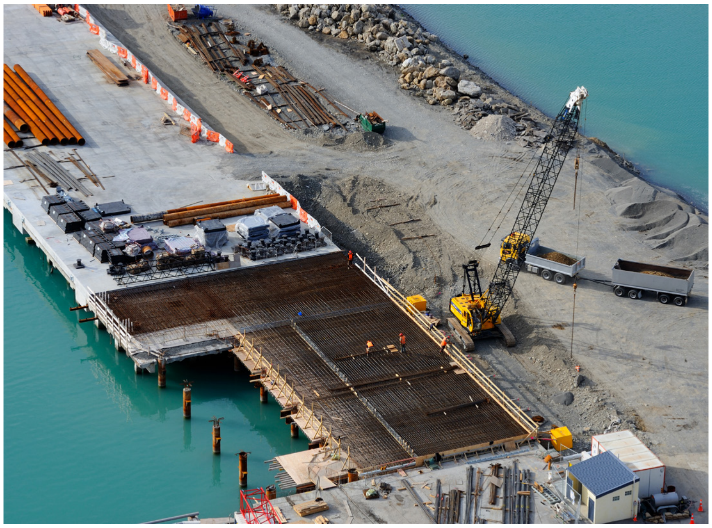
Other analyses have used similar approaches to estimate port elevation costs at a regional or country level. Two studies in particular have developed adaptation cost estimates for U.S. ports. The first study estimated that it would cost, at minimum, US$71–US$101 billion to elevate all existing commercial coastal ports in the United States (covering a total area of over 400 km$^2$) to address the combination of sea level rise projected by 2070 (assumed to be 0.68 m for all ports, based on scenarios that are different from the RCPs but correspond most closely with RCP8.5) and increased storm surges (ranging from 0 m for West Coast ports to 0.85 m for the Gulf Coast).[58] These estimates, which include not only the costs of dredging and filling but also reconstruction of some port infrastructure, are based on average unit cost estimates of US$145–US$239 million per square kilometer.[62]

Using the same modeling framework, a second study estimated that it would cost US$64–US$88 billion to elevate 100 U.S. ports (covering an area of almost 310 km$^2$) by 2 m.[63] These total cost estimates are derived from average unit cost estimates for a 2 m elevation increase and retrofit of US$170–US$232 million per square kilometer.

Both of these U.S. studies emphasize that there are many costs associated with the elevation strategy that are not included in these estimates, such as environmental compliance and permitting, demolition costs, utilities infrastructure, erosion control, and connecting rail infrastructure, among

**Table 3.** **Unit Cost (US$ per Km$^2$) Estimates Used in Port Elevation Studies**

| STUDY | STUDY AREA | ELEVATION (M) | UNIT COST PER Km$^2$ |
|---|---|---|---|
| **Hanson & Nichols**[56] | Global | 1 | US$30.3 million |
| **Hippe et al.**[58] | U.S. | 0.68–1.53 | US$145–US$239 million |
| **Becker et al.**[59] | U.S. | 2 | US$170–US$232 million |
| **McCarron**[60] | Asia Pacific (53 ports) | 1.6–2.3 | US$31–US$49 million |
| **Esteban et al.**[61] | Japan and Indonesia | 1 | US$80–US$4,000 million |



others. The authors note that environmental compliance costs alone would "contribute significantly to the final price tag."[59]

The modeling framework used in these studies also relies on several simplifying assumptions that underestimate total costs. For example, it is assumed that there exists enough fill in the local area that dredged material would not need to be trucked in. However, some ports might lack enough fill to elevate the port area by 2 m, and the associated costs to truck in fill material would drive up costs considerably.[58]

A few studies estimating port elevation costs have been conducted for other parts of the world. Asian ports are a particular concern due to their high vulnerability to both sea level rise and storm events. One study predicts that Asia alone will account for 47% of resource demand for climate adaptation construction materials.[54]

For 53 of the largest ports in the Asia Pacific region, it has also been estimated that the costs of elevating port infrastructure to address sea level rise ranging from 1.6 to 2.3 m would be US$32–US$51 billion.[60] The total port area included in this analysis was 1,033 km$^2$; therefore, the average cost per square kilometer ranged from US$31 million to US$49 million depending on the amount of elevation. Across the 53 ports, average costs also varied by a factor of almost five due to differences in material and labor costs and in the number of buildings and warehouses, which are more costly to elevate.

Other estimates of average unit costs for elevating ports are reported in a study of Japanese and Indonesian ports, which uses evidence from existing projects designed to address land subsidence.[64] These unit costs range from US$80 million to US$4 billion per square kilometer for a 1 m elevation increase; however, the larger values include the costs of raising existing pier pilings designed as earthquake countermeasures.

Notably, the unit cost of elevating ports increases as a function of sea level rise, so it is reasonable to assume that these costs will increase even more after 2100.[59] For example, one analysis of elevation costs finds that it is only possible to elevate certain ports by 1 m before a wholesale redesign is required. Any subsequent elevation would be 10 to 100 times more expensive than the initial cost.[61]

In the end, it is a consistent theme across the literature that the cost estimates provided are conservative and do not encapsulate the full financial burden of adapting global ports to climate change. As one study concludes, port adaptation costs present a "significant burden," and it would be far better to pursue aggressive mitigation strategies to avoid suffering expensive adaptation costs.[61]

**Defend**. Like port elevation, port defense methods are considered "hard" adaptation strategies.[52] They include dikes, seawalls, floodgates, breakwaters, and drainage systems, among others.[65] While the elevation strategy specifically addresses global sea level rise, port defense systems target increases in storm surge that are caused by the combined effect of strong storms and sea level rise. Constructing some of these defense infrastructures for ports can be very resource intensive, requiring major upfront investments. For example, constructing the Maeslantkering storm surge barrier in the Netherlands, which was completed in 1997 and protects the Dutch Port of Rotterdam, cost around US$890 million.[66]

Although no studies to our knowledge have produced global cost estimates for these defensive port adaptation strategies against climate change, several studies have estimated costs for individual ports and groups of ports. An analysis of five main ports in Israel estimated total adaptation costs ranging from US$224 million to US$407 million for protection against sea level rise of 0.5 and 1 m, respectively (i.e., broadly similar to the range predicted by the RCP8.5 scenario for 2100[67]).[68] The main adaptation strategy analyzed in this study was raising sea front breakwaters that extend for more than 8 km.

Another analysis of adaptation costs examined 47 seaports along the Catalan coast; however, only two of these ports are large commercial harbors (Barcelona and Tarragona).[69] To protect these ports from sea level rise affecting the surge height of storms with a 50-year return period (i.e., annual probability of 2%), it estimated adaptation costs ranging from US$14 million to US$14.3 million for sea level rise by 2050, under the RCP4.5 and RCP8.5 scenarios respectively. This range increases to US$15.7 million to US$16.8 million for sea level rise by 2100. These cost estimates are relatively small, in part because they are based on an adaptation approach that only includes raising the height of 1 m-wide crown walls located on top of existing breakwater barriers.

In addition to their construction costs, there are other concerns with defensive adaptation strategies, including environmental impacts and operational delays to shipping carriers. For instance, the construction of dikes and coastal armoring is known to disrupt the surrounding marine environment, which can then also cause further problems to port infrastructure, including from erosion and sea surface salinity.[70] Defenses against storm surges can also restrict the movement of ships in and out of ports, therefore adversely affecting their operational efficiency.[37]

**Retreat.** The retreat strategy involves relocating ports away from impact zones and towards higher elevations that are better protected from future sea level rise and storm surges.[71] Particularly if future sea levels reach high-end predictions for 2100 and beyond (i.e., greater than 2 m above current levels), many ports may need to be abandoned entirely.[72] Although to our knowledge no existing studies have developed cost estimates for port relocation at a regional or global level, if widely used, this adaptation approach would certainly require many billions of dollars in investments.[72]

Although construction costs for building a new port at a higher elevation are generally less than elevating an existing port,[60] the total costs of port relocation can be relatively high compared to other adaptation approaches when accounting for land costs and economic impacts on local communities. Particularly in fast-growing coastal areas, acquiring land for new port facilities can be difficult and prohibitively expensive. Moreover, port relocation is often the least popular adaptation option among local stakeholders. When looking into local attitudes about port relocation, a survey of port stakeholders found that 92% of locals would rather build "stronger and bigger dikes" than move port operations.[64] However, the study notes that, despite the costs and other drawbacks of port relocation, other alternatives may lead to even greater negative consequences (e.g., if defense measures fail to withstand higher sea levels and storm surges). Therefore, port relocation cannot be ruled out as a potential adaptation approach.

## 4. Impacts from Inland Flooding and Droughts

In addition to increasing the intensity of ocean and coastal storms, climate change is expected to alter inland precipitation patterns. As periods of both high and low rainfall are likely to become more common and intense around the globe, so may the occurrence of inland flooding and droughts. Although their impacts on ports and shipping are less direct than tropical cyclones, these growing climate hazards can impose sizable costs on the maritime industry.

Mississippi River flooding in Davenport, Iowa in 2019

Like coastal cyclones, extreme inland precipitation can cause significant flood damage to seaports and lengthy disruptions to port operations. In 2015 the second largest

Indian container port (in Chennai) was severely damaged by flooding from inland areas, leaving the marine terminals only partially operational. In South America, extreme rainfall in 2008 caused flooding and landslides, which led to the closure of one of the most important ports in Brazil (in Paranagua). The losses resulting from this closure were estimated to be roughly US$420 million.[20]

Perhaps even more importantly, inland flooding can cause supply chain interruptions with severe spillover consequences for the maritime sector. This type of severe impact was starkly demonstrated by the record water levels on the Mississippi River in 2019. The river and its tributaries form a critical transport network for exporting U.S. agricultural and other goods. However, over a four-month period in 2019, more than 6 million tons of grains, with a total value of almost US$1 billion, could not be shipped due to barge traffic interruptions.[73] Other examples of supply chain disruptions from inland flooding include the previously mentioned 2015 flood in Chennai, India, where damaged roads and suspended rail service temporarily crippled commercial traffic through the port[74] and flooding of inland coal mines in Queensland, Australia, in 2011, which reduced exports through Port Gladstone by about 40 million tons.[20]

On the other precipitation extreme, droughts can also lead to costly interruptions in commercial traffic linked to the affected inland areas. Nowhere has this been more evident than in the context of the Panama Canal. With an average throughput of 34 ships per day, the canal is an essential connector for maritime traffic. It handles roughly 4% of global trade each year, amounting to more than 400 million tons of cargo transported between the Pacific and Atlantic Oceans. In 2019, however, the canal area experienced a rainfall deficit of over 25%. Additional water losses occurred due to higher-than-normal temperatures and evaporation in Gatun Lake, which is on a main tributary to the canal.[75] The Panama Canal Authority (PCA) was forced to place limits on the size of shipments through its locks, resulting in roughly US$15 million in lost revenue that year.[76]

To further address drought conditions and water shortage, in 2020 the PCA added a water surcharge of US$10,000 per transit for vessels over 300 feet (91.4 m) and US$2,500 to US$5,000 for smaller vessels. The International Chamber of Shipping estimates that this surcharge could cost global shipping US$230–US$370 million per year.[77]

As inland flood and drought events become more extreme with climate change, the indirect costs on the maritime industry, such as those described above, will almost certainly grow. However, numerical estimates of the size of these future costs are currently lacking in the scientific literature.

## 5. Other Impacts from Rising Temperatures and Extreme Heat Events

Higher global temperatures and more extreme heat events can have a range of negative impacts on ports and shipping.

Like flooding, winds, and heavy rains, extreme heat can cause substantial damage to shipping vessels and port infrastructure and can hamper shipping and port operations. Extreme heat creates risks to port infrastructure, including excessive power demand for cooling systems, accelerated deterioration rates of terminal services, and excessive stress on metal port structures, such as container handling cranes and warehouses.[78] Warmer water temperatures may also increase corrosion of port infrastructure due to changes in ocean acidity.[79] Consequently, increasing heat-related damage to ports is expected to reduce the lifetime of port infrastructure and thus increase overall maintenance costs.[79]

Extreme heat also impacts port operations because it limits the ability of port staff to work outdoors safely, especially when the temperature exceeds 40°C.[80] For example, in 2009, heatwaves in Australia caused melting of wharf tarmac and downed sections of the Port of Melbourne for 3 days, resulting in significant productivity losses due to work stoppages.[20]

Rising temperatures may also negatively affect important maritime shipping routes through the Great Lakes–St. Lawrence Seaway System on the U.S. and Canada border. Roughly 150 million tons of cargo move through the system each year.[81] Historically, water levels in the system have fluctuated in multiyear cycles; however, the range of these fluctuations has been growing recently. Evaporation caused by warm temperatures in the early 2010s put downward pressure on lake levels, such that in 2013 lake levels in some areas reached record lows. In contrast, heavy rains in recent years have had the opposite effect and pushed levels closer to historic highs.[82] Periods with low lake levels can be particularly problematic for shipping activity because they lead to restrictions on vessel drafts and cargo size. One study estimated that declines in future Great Lake levels due to climate change could increase vessel operating costs by 5–22%.[83]

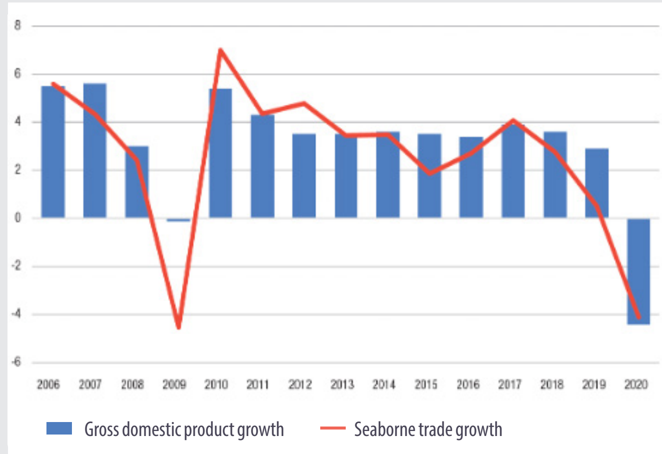
One potential benefit of warmer global temperatures on shipping that has received attention is the opening of arctic sea routes due to the gradual retreat of summer sea ice in the region. The Northern Sea Route (NSR) along the northern coast of Russia has attracted the most attention because it could shorten transport between Europe and Asia (compared to the Suez Canal route) and facilitate access to natural resource markets from Russia. Despite growing interest, annual transport volumes have to date not exceeded 1.3 million tons (roughly 1% of annual volume of Suez transits), and year-round transport through this route will most likely only become feasible well into the next century.[84, 85]

Even though the potential for arctic shipping may be improving, the NSR will continue to face several barriers in the coming decades. These barriers include ever-present ice hazards for shipping vessels, uncertainty caused by year-to-year variation in weather and ice patterns, the need for icebreakers during parts of the year, physical limits on vessel size for shorter routes, and relatively high costs of rescue and salvage operations due to remote locations and difficult weather. Many of these conditions also contribute to relatively high insurance costs for the shipping sector and increased risk of environmentally damaging shipping incidents. Similar challenges are confronting the development and use of the Northwest Passage along the coast of Canada and Alaska, which is primarily seen as a potential future alternative to the Panama Canal route.

## 6. Impacts Due to Changes in Global Economic Activity

As forcefully demonstrated by the recent COVID-19 pandemic, and before that the financial crisis of 2009, global maritime trade activity is strongly connected with the health of the worldwide economy. As shown in **Figure 5**, a more than 4% decline in global GDP in 2020 was accompanied by a similar decline in seaborne trade.

**Figure 5. Comparison of Annual Growth Rates for Global GDP and Seaborne Trade (2006–2020)[86]**




Over the short and long term, climate change is similarly expected to put significant downward pressure on global economic growth, which will have damaging ripple effects on global trade and maritime shipping. For example, a recent analysis released by the International Monetary Fund (IMF) concludes that rising global temperatures will reduce future growth in global per capita GDP. The study estimates that by 2100, per capita GDP under the RCP8.5 scenario will be 4.4–10% lower than it would have been without climate change.[87] The range of estimated GDP impacts depends on how well economies are able to adapt to climate change and lessen its impacts. These findings are consistent with a previous IMF study that estimated per capita GDP for a typical low-income country would be 9% lower in 2100 under a worst case scenario (compared to no climate change).[88]

Studies directly analyzing the impact of climate change on global trade activity have also concluded that climate damages will likely substantially hamper future growth in trade flows. Although published estimates of the size of these future impacts are lacking, projections indicate that agricultural trade flows between countries will be particularly affected.[89]

## 7. Projecting Future Costs of Climate Change to Shipping and Ports

It is important to consider what the evidence from existing studies implies about the effects of future climate change on the maritime shipping and port industries. In this section, we build on and extrapolate from the existing findings to estimate potential future impacts and costs. We focus on impacts related to sea level rise and increased storm intensity, as well as the broader impacts of warming temperatures through their effects on global economic activity and trade.

We begin by examining how large future impacts could be if no significant adaptation measures are taken to protect ports against rising seas and stronger storms. We then estimate port adaptation costs that may be needed to combat the effects of climate change. We also estimate potential losses in future maritime trade volumes due to projected downward effects of climate change on future growth in the global economy. In all cases, we estimate future impacts under a worst case (RCP8.5) climate change scenario.

It is important to emphasize that the cost estimates developed in this section are based on limited data and in many cases require strong assumptions, which are laid out in the discussion. Given these limitations, the objective is to examine what the available evidence suggests about future costs for the shipping and port industries, but the resulting estimates must be interpreted as preliminary approximations. The intention is for these estimates to inform decisions and policies related to GHG emissions and climate adaptation, and to lay the groundwork for further studies of climate change impacts on the maritime sector such that more accurate estimates may be developed.

### Increased Storm Damages to Ports

What are the implications of sea level rise and storm intensity projections for future hurricane damages to ports, if significant adaptation does not occur? As described in Section 3.1, monetary estimates of port damages from previous storms are primarily available for the United States. The estimates previously summarized in **Table 1** (page 12) indicate that, over the 15-year period from 2005 to 2019, total port damages from five major hurricanes totaled over US$5 billion. When adjusted for price inflation, the total over the period amounted to roughly US$6.4 billion in assessed damages (in 2020 dollars). In other words, hurricane damages to U.S. ports have averaged almost US$430 million per year in recent years.

Given the lack of storm-related damage estimates for ports in other part of the world, we can only roughly approximate annual global damages using the U.S. evidence. In other words, an annual damage estimate for U.S. ports can be scaled to ports worldwide, if we assume that annual damages are directly proportional to the geographic area of the affected ports (i.e., average annual damages per square kilometer are the same in the United States as in the rest of the world). This scaling assumption is likely to overestimate global damages primarily because the average risk of exposure to cyclones is relatively high for U.S. ports compared to all ports and the value and repair costs for U.S. port infrastructure is likely higher than the global average.[22] To correct for the second source of overestimation, we assume that the average damage per square kilometer in half the world's port area is about 60% lower than in the United States due to lower average construction costs (for port repairs) in lower income countries.[90] Because the global port area is roughly 10 times larger than the U.S. port area alone,[91] the implied average annual damage estimate for ports globally is approximately US$3 billion per year.

Using this current annual damage estimate as a baseline, we estimate increases in storm damages due to climate change for two future 15-year periods—centered around 2050 and 2100—under the RCP8.5 climate change scenario. To represent sea level rise in each case, we apply IPCC average global projections for the RCP8.5 scenario, which range from 0.27 m in 2050 to 0.84 m in 2100.[92] To represent increase in storm surge, we apply and rescale an estimate for U.S. ports.[84] The resulting increase in storm inundation levels from the combined effect of sea level rise and higher storm surge ranges from 0.55 m in 2050 to 1.60 m in 2100. Details on the methods used to develop these estimates are provided in Appendix A.

To estimate increases in storm damages for the selected climate change scenario and years, we apply damage scaling factors adapted from two port-specific case studies. We use the range of scaling factors derived from the two studies to specify a range of cost estimates. Details on the methods used to develop these estimates are also provided in Appendix A.

We estimate that, by midcentury, global average annual storm damages to ports will increase, relative to current levels, by US$1.8–US$7.1 billion under RCP8.5. By the end of the century, the additional annual damages are projected to be US$4.5–US$17.7 billion (**Table 4**).

To put these damage estimates into context, global net earnings for the container port industry were roughly US$25 billion in 2019.[93] Therefore, these estimated increases in annual storm damages due to climate change represent as much as 70% of current (in 2019) annual net earnings for the container port sector.

**Table 4. Estimated Increase in Annual Storm Damages to Ports Due to Global Sea Level Rise and Higher Storm Surges (US$billions)**

| YEAR[a] | 2050 | 2100 |
|---|---|---|
| SEA LEVEL RISE (M) | 0.27 | 0.84 |
| INCREASED STORM SURGE HEIGHT (M) | 0.38 | 0.76 |
| Increased global storm damage | US$1.8 - US$7.1 | US$4.5 - US$17.7 |

[a]year represents mid-point of 15-year period over which storm damages are averaged

### Increased Costs of Storm-related Port Disruptions

In addition to damaging port infrastructure, tropical cyclones also routinely disrupt and delay port operations around the world. If sea levels rise and storms become stronger as expected in the future due to climate change, the magnitude and costs of these disruptions are expected to grow.

To gauge the magnitude of these impacts, again assuming no significant adaptation to current port infrastructure, we apply evidence from existing studies to first approximate current annual costs from storm-related port disruptions. Based on a global study of storm-related port shutdowns and delays[37] and separate estimates of the average economic costs of port disruptions (which vary across the port studies from US$89 to US$179 per TEU per day),[39] we estimate that ports, shippers, and carriers currently incur annual costs of US$1.3–US$2.4 billion per year due to storm disruptions.

In addition, based on an economic study analyzing the benefits of faster shipping deliveries, which estimates that each additional day in transit imposes costs equivalent to a price increase of 0.6–2.1%,[94] we estimate that, globally, consumers of shipping services incur annual losses of roughly US$0.5–US$1.8 billion due to delays caused by these disruptions.

Using these two ranges of estimated disruption costs to define lower and upper bounds, we calculate how much larger these costs would be with the projected higher sea levels and storm surge, as well as stronger winds. We include the same projections of sea level rise and increase in storm surge height that we used to estimate increased damages to port infrastructure (see **Table 3**). For each year and scenario, we also added projections of increased wind speed. Details on the sources and methods used are provided in Appendix A.

As shown in **Table 5**, by 2050 the annual economic losses to ports, shippers, and carriers due to storm-related disruptions may be US$0.8–US$1.6 billion higher under the RCP8.5 scenario than they would be without climate change. By 2100, these additional losses are projected to be US$1.9–US$3.7 billion per year.

By 2050 the annual economic costs to shipping customers due shipping delays are projected to increase by US$0.3–US$1.1 billion under RCP8.5. These added annual costs may reach US$1.1–US$3.9 billion by 2100.

Therefore, by 2100, climate change under the RCP8.5 scenario is projected to increase the total annual costs due to storm-related port disruptions by US$3.1–US$7.6 billion. To put these cost estimates into context, total operating profits for the global container shipping industry averaged less than US$20 billion per year during 2018–2020,[95] and as previously mentioned, global net earnings for the container port industry were roughly US$25 billion in 2019.

**Table 5.** **Estimated Increase in the Annual Costs of Port Disruptions Due to Sea Level Rise and Stronger Storms (US$billions)**

| YEAR | 2050 | 2100 |
|---|---|---|
| SEA LEVEL RISE (M) | 0.27 | 0.84 |
| INCREASED STORM SURGE HEIGHT (M) | 0.38 | 0.76 |
| INCREASED PEAK WIND SPEED (M/S) | 3.0 | 6.0 |
| Ports, shippers, and carriers | US$0.8 - US$1.6 | US$1.9 - US$3.7 |
| Consumers of shipping services | US$0.3 - US$1.1 | US$1.1 - US$3.9 |
| Total added costs | US$1.1 - US$2.7 | US$3.1 - US$7.6 |

### Costs of Port Adaptation to Climate Change

To avoid or reduce the previously described damages and costs associated with climate change, ports can take various measures to protect against sea level rise and stronger storms (as described in Section 3.4). Although at least one study has estimated the global costs of adaptation using port elevation strategies,[56] their estimates are based on unit costs (US$ per km2) that do not vary across the world and are relatively low compared to other regional or port-specific studies. For example, a study of U.S. port adaptation,[58] which includes the costs of dredging, filling, and reconstruction of some port infrastructure, applies unit cost assumptions that are significantly higher.

Therefore, in this section, we re-estimate the global port adaptation estimates[56] using the unit cost assumptions.[58] In other words, for the current 1,364 km$^2$ in total global port area (as reported in the first study), we estimate the total investment that would be required to elevate ports to protect against higher sea levels and storm surges projected for future years (2050 and 2100).

To roughly account for differences in unit (US$/km$^2$) elevation costs between ports in higher and lower income countries, we make a simple adjustment to the U.S.-based estimates[58] using comparative estimates of average construction costs around the world.[89] These comparative estimates across 100 major urban areas indicate that average construction costs in the least expensive 50 cities (including for example port cities in China, India, and Africa) are about 60% less than in those the top 50. Therefore, for half the global port area (682 km$^2$) we applied U.S. elevation cost estimates that were reduced by 60%.

We estimate that elevating all ports (in the near term) to protect against the combination of sea level rise and increased storm surge height projected for 2050 under RCP8.5 would require investments totaling US$121–US$176 billion. For 2100 projections, these costs increase to US$151–US$205 billion (**Table 6**). The range of estimates, which are labeled as lower and upper bounds in **Table 6**, are based on the range of reported unit cost estimates for different model-based assumptions.

**Table 6.** **Estimated Port Adaptation (Elevation) Costs Against Sea Level Rise and Increased Storm Surge**

| YEAR | 2050 | 2100 |
|---|---|---|
| ELEVATION (M) | 0.27 | 0.84 |
| INCREASED STORM SURGE HEIGHT (M) | 0.38 | 0.76 |
| Average unit cost (US$ per square km) | US$89 - US$129 | US$111 - US$150 |
| Investment cost (US$ billions) | US$121 - US$176 | US$151 - US$205 |
| Annualized cost (US$ billions/ year)[a] | US$4.0 - US$5.8 | US$5.0 - US$6.8 |

[a] assuming 80 year life and 3% discount rate

When these investment costs are annualized (i.e., amortized) using an assumed 80-year lifespan[96] and a 3% discount rate, the range is US$4–US$5.8 billion per year to protect against the combination of sea level rise and increased storm surge height projected for 2050. For protections against these projected hazards in 2100, the annualized costs increase to US$5–US$6.8 billion per year.

To put these estimates into context, we can focus on the implied adaptation costs for a single port—the Port of Los Angeles (California)—and compare them to the port's reported annual net revenues in 2020. For the 17.4 km$^2$ port area, the estimated adaptation investment for a 0.84m elevation (i.e., RCP8.5 sea level rise in 2100[97])–is between US$2.3 billion and US$3.3 billion. This translates to between US$78 million and US$111 million per year. According to the port's financial reports,[98] these annual expenses would represent 31–44% of the port's net available revenue (i.e., total revenue minus operating expenses) in 2020.

## Loss in Future Maritime Trade due to Climate Change Impacts on the Global Economy

To estimate how climate change will affect global maritime trade through its effect on global economic activity, we can directly apply existing estimates of the relationship between climate change and global GDP growth (as discussed in Section 6). However, we also need to specify the size of the relationship between economic growth and maritime trade. As previously shown in **Figure 5**, the annual growth in seaborne trade tracks very closely to growth in the global economy over the last 15 years. Moreover, both global GDP and maritime trade have on average grown by close to 3% per year since 1970.[99] Despite this evidence, there remains uncertainty about the size of this effect, in part because the relationship between GDP and trade can go in both directions.[100] Economic growth stimulates demand for globally traded goods, but relaxing trade restrictions also promotes economic growth. Acknowledging this uncertainty, for this analysis we make the simplifying assumption that decreases in future economic growth due to climate change will result in equivalent declines in trade volume (i.e., each one percentage point decrease in economic growth over the long term will be matched by an equivalent reduction in maritime trade growth).

**Table 7** reports estimates of these future declines in maritime trade due to the macro-economic effects of climate change. Global GDP in 2100 may be 4–10% lower under the RCP8.5 climate scenarios (compared to a baseline scenario without climate change). This range depends on different assumptions made in the study about how quickly economies adapt to climate change, with more adaptation resulting in less of an economic decline. Under the baseline scenario without climate change, total trade volume is projected grow from 11.5 billion tons in 2020 to almost 120 billion tons in 2100 (assuming trade continues to grow by 3% per year). However, under climate change scenarios and assuming trade is reduced by the same percentage as global GDP, maritime trade volume is predicted to be 5.3–11.8 billion tons lower than the baseline in 2100.

**Table 7.** **Estimated Loss in Global Maritime Trade Volume Due to Climate-Induced Reductions in Global GDP**

| CLIMATE CHANGE SCENARIO | 2021 | 2050 | 2100 |
|---|---|---|---|
| | Projected Annual Trade Volume (billion tons) | | |
| Baseline (No Climate Change) | 11.5 | 27.1 | 118.8 |
| RCP8.5 | | 26.1 - 27.1 | 107.0 - 113.5 |
| | Reduction in Annual Trade Volume from Baseline | | |
| RCP8.5 | | 0.4 - 1.0 | 5.3 - 11.8 |

# 8. Conclusions

The existing literature provides many useful findings and insights for understanding climate-related impacts to shipping and ports. Nevertheless, large gaps and uncertainties remain about how fast future temperatures will rise and how large the resulting climate hazards and impacts on the maritime industry will be.

Unfortunately, the uncertainties created by a changing climate impose their own burdens on the shipping and port sectors. An unpredictable and variable climate makes it increasingly difficult for decision makers within the industries to anticipate, plan, and invest for the future.

Therefore, a principal aim of this report is to address these uncertainties and fill some of these knowledge gaps by building on and extrapolating from the current literature. To inform private- and public-sector decision making, it estimates the economic costs of selected climate change hazards for the shipping and port industries.

Developing these cost estimates with readily available data has in many cases required strong assumptions, which are explained in detail and supported in Section 7 and Appendix A. Given these limitations, the resulting estimates must be interpreted as preliminary approximations with uncertainties that are only partly captured by the lower and upper bound ranges reported in the results tables.

Recognizing these limitations, the analysis offers several key findings and implications.

**First, the combination of projected sea level rise and more severe storms by 2050 is likely to impose billions of dollars in additional storm-related port damages and disruption costs each year unless significant mitigation/adaptation steps are taken.** Moreover, these added costs in 2050 are likely to double by the end of the 21st century.

**Second, although the estimated costs are significant, they understate future costs to shipping and ports for several reasons:**

- They only estimate costs for existing port infrastructure and operations; therefore, they do not capture costs linked to future growth in the size and number of ports or in global trade volume.
- Many potential costs associated with stronger storms/sea level rise are not included in these estimates, such as shipping losses at sea, increased rerouting (shipping adaptation) costs, and potential increases in clean-up, liability and environmental compliance costs associated with weather-related shipping incidents.
- They do not include potential damages or costs associated with other climate hazards, such as inland flooding, droughts, and extreme heat.
- The port disruption estimates do not account for delays and costs that are imposed on other ports through supply chain effects. As the global-scale supply chain disruptions caused by the COVID pandemic have demonstrated, these ripple effects through shipping and port networks (regardless of their cause) can have significant global economic consequences.

**Third, although the annualized cost estimates for port elevation are lower in dollar terms than the estimated increase in damage and disruption costs for future years, these values are not directly comparable.** Importantly, this difference in value does not necessarily mean that investing in port adaptation will significantly lower the costs associated with climate change. The annualized adaptation cost estimates represent constant repeated payments that would start in the near term and continue for many years. In contrast, the additional annual damage and disruption costs would be small in the short term and grow incrementally to the values reported for 2050 and 2100. More detailed analyses, comparing future trajectories of these different cost categories, will be needed to more fully assess the potential cost-saving benefits of adaptation.

**Fourth, the port elevation cost estimates developed for this report understate total adaptation costs, because (1) they are only estimated for existing ports and (2) they do not include cost estimates for "soft" adaptation measures, for port defense or retreat strategies, or for rerouting costs for shipping.** Port elevation costs may also be higher than reported if the scale of materials required for filling port areas puts a strain on locally available supplies and drives up costs.

**Fifth, the cost estimates developed for this report can be refined and expanded in several ways through additional data collection and research.** More estimates of storm-related port damages from past events outside the United States are needed to improve estimates of future global damage. Similarly, more complete country- and port-level data on the area, infrastructure, and throughput of existing ports would greatly enhance all the cost estimates. More detailed simulations of how disruptions at individual ports affect delays at other ports will help improve estimates of future storm disruption costs. Studies of how larger and more intense storms at sea affect ship rerouting costs are also needed to better quantify the climate adaptation costs faced by the shipping industry.

Finally, the potentially high costs of climate hazards and climate uncertainties for the shipping and port industries—and the even higher estimated costs of adaptation—underscore the importance of strategies for preventing climate change. Most importantly, they emphasize the need to significantly reduce GHG emissions resulting from combustion of fossil fuels.

# Appendix A. Methods and Assumptions for Cost Analysis

This appendix provides technical details about the methods and assumptions used in specific components of the analysis estimating economic costs of climate change for the shipping and port industries.

### Assumptions for Specifying Increase in Storm Surge Height Under Selected Climate Change Scenarios

To specify increases in storm surge height due to stronger storms for RCP8.5 and for future years (2050 and 2100), we extrapolated from a U.S. average estimate for 100-year storms.[58] This study reports surge height increases for U.S. ports in 2070 that vary from 0 m on the West Coast to 0.85 m on the Gulf Coast. The average across the United States (weighted by port area) is 0.54 m. Although the RCP scenario assumptions for these estimates was not specified, we assigned them to RCP8.5 because their sea level rise estimates for 2070 corresponded most closely with RCP8.5. Assuming the increase in storm surge would occur linearly over time from 2000 to 2100, we developed scaled estimates for 2050 (0.38 m) and 2100 (0.76 m).

### Assumptions for Scaling Port-Storm Damages in Relation to Increases in Storm Inundation Height

Future increases in storm damage to ports, due to the combined effect of sea level rise and increase in storm surge height, were approximated by scaling baseline (i.e., current) damage estimates with results from two port-specific case studies. The multiplying effect of higher water levels on port damages depends on several port-specific characteristics, including the topography and configuration of port facilities. As a simplifying assumption, we use the results from two ports to represent the lower and upper range of this effect.

One case study, conducted for the Port of Rotterdam, estimated a damage increase factor (multiplier) of 1.57 for storm damages if sea level rises by 0.6 m.[34] This implies an average damage multiplier of 2.6 per 1 m rise in water levels, which we use as a lower bound estimate for scaling damages.

The other case study, for the Port of Mobile in the United States, estimated that damages from Hurricane Katrina in 2005 would have increased by a factor of 5.5 if relative sea levels had been 1.21 m higher.[33] This implies an average damage multiplier of 4.5 per 1 m rise in water levels, which we use as an upper bound estimate.

### Technical Approach for Estimating Climate Change Impacts on the Costs of Storm-related Port Disruptions

To estimate how economic losses from storm-related port disruptions are likely to increase due to the sea level rise and stronger storms, we applied the following analytical steps.

First, we estimated an average economic loss per TEU per day of port disruption, based on results reported in the literature.[39] This study used data from 2006–2013 to estimate the economic losses of disruptions (i.e., port closures) due to extreme weather at two major container ports in China—Ningbo and Shanghai—including losses to the affected ports, as well as to shippers and carriers. For the two ports, the estimated average annual total losses were 109 million and 292.6 million Chinese Yuan (RMB), respectively. Dividing these estimates by average annual disruption days and throughput at the ports implies average losses per TEU per disruption day of 507.3 and 969.3 RMB, respectively. Converting to U.S. dollars and adjusting for inflation provides estimates of average disruption losses of US$89–US$179/TEU/day.

Second, we estimated an annual number of port disruption or delay days and number of affected TEUs under current climate conditions. We began with data on global port disruptions caused by natural disasters, which were compiled using vessel tracking data.[37] We focused on the reported data for 53 container ports that were potentially affected by at least one of eight tropical cyclones (including hurricanes and typhoons) in 2019. For each port-storm event (N=61), they report estimates of the number of full shutdown days, as well as partial shutdown (i.e., reduction and recovery) days, including 25 port-storm events that involved neither type of disruption. For all selected 2019 port-storm events combined, there was an average of 1.02 full shutdown days and 3.74 partial shutdown days. For each port, we also acquired estimates of their annual throughput (in TEUs per year) and, dividing by 365, estimated their average daily throughput (TEUs/day). Average daily throughput for selected container port-storm events was 12,705 TEUs per day.

Third, we estimated total economic losses for ports, shippers, and carriers due to storm-related disruptions at the selected container ports in 2019. For this calculation, we multiplied the number of disruption days for each port-storm event by (1) the average daily throughput at the affected port and (2) the previously reported estimates of average disruption losses per TEU per day. We also assumed that each partial shutdown day has the same effect on economic losses as half of a full shutdown day. Because the available data[37] only cover half of 2019, we also multiplied the losses across port-storm events by a factor of 2. The resulting estimates of disruption losses to the affected container ports, shippers, and carriers in 2019 are US$231–US$442 million.

Fourth, because container cargo only accounted for roughly 18% of maritime trade (by loaded weight) in 2019,[3] we approximated storm-related disruption losses for all cargo ports and shipping by multiplying the container trade loss estimates by a factor of 5.5. The resulting estimates of disruption losses for all ports and shipping in 2019 are US$1.27–US$2.43 billion.

Fifth, in addition to port disruption costs that are borne by the ports and shipping sectors, we estimated losses to consumers of global shipping services due to associated delays in delivery. For this estimation, we relied on findings from an analysis of the demand for different modes of delivery that concluded that each additional day in transit imposed implicit costs equivalent to a price increase of 0.6–2.1%.[94] For maritime shipping prices in 2019, we focused on freight rates for container shipments and assumed an average baseline price of US$900 per TEU, based on the range of reported market rates.[3] Then, for each port-storm event included in the earlier data,[37] we estimated an expected total number of TEU delay days during and after each disruption event. Using the average daily TEU throughput at the affected ports we first estimated the number of "stranded" (i.e., unprocessed at the port) TEUs at the end of each day during the disruption period. For partial shutdown days, we assumed that cargo was processed in the port at half the average daily rate. We also estimated delays after each disruption, assuming ports operate at full capacity after the disruption until any backlog in TEUs is cleared. For this, we assumed that the average daily throughput at other times corresponds with an average port capacity utilization rate of 70%.[101] Finally, to estimate total consumer losses associated with each port-storm event, we multiplied the total estimated number of TEU delay days by the average freight rate (US$900) and the price adjustment (0.6–2.1%).

Summing across port-storm events, the resulting estimate of disruption losses to consumers due to container port delays in 2019 are US$90–US$318 million. Assuming consumers of noncontainer shipping services incur similar costs due to delays, we again used a factor of 5.5 to extrapolate these findings to all shipping services. The resulting estimates of consumer losses due to all shipping service delays from storm-related port disruptions in 2019 are US$0.5–US$1.8 billion.

Sixth, we estimated the number of additional storm-related disruption days that would occur with the higher sea levels and stronger storms that are projected to occur due to climate change. For this step, we relied again on estimates that found that each additional 1 m in storm surge height increased total port disruption days (full and partial combined) by an average of roughly 2 days.[37] Assuming that each meter of sea level rise, by raising the baseline level for storm surge, would contribute to a 1 m increment in storm surge, this finding implies, for example, that global sea level rise ranging from 0.23 m (RCP4.5 in 2050) to 0.84 m (RCP8.5 in 2100) would increase port disruption days due to storm surge from tropical cyclones by 0.5–1.7 days on average.

It is also estimated that each 10 m/s increase in hurricane peak wind speed would result in 1.3–1.9 additional port disruption days.[15] Assuming that (1) each additional degree of surface ocean temperature can increase wind speeds by 4%[16] and (2) average baseline hurricane wind speed is 50 m/s, it follows that ocean temperature increases of 1°C (RCP4.5 2050 and 2100), 2°C (RCP8.5 2050) and 3°C (RCP 8.5 2100) can lead to wind speed increases of 2, 4, and 6 m/s respectively, resulting in additional port disruptions of 0.3–1 day.

Finally, we estimated how much economic losses from storm-related port disruptions would increase with the amount of sea level rise and storm strengthening that are projected to occur due to climate change. To do this, we added the estimates of additional disruption days from the previous step to each of the port-storm events in the Verschuur et al. database,[37] and we recalculated losses to ports, shippers, carriers. and consumers using the same steps described above for 2019 conditions. Then we estimated the difference in total costs between these estimates and the baseline estimates reported above.

# Endnotes

[1] For comparison purposes, all monetary estimates reported in this document are expressed in 2020 US dollars (US$) using, as needed, currency exchange rates and the U.S. Consumer Price Index.

[2] TEUs are the most commonly used standardized unit for quantifying container shipping volumes. Twenty feet (6.1 m) refers to the horizontal length of a standard container.

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# **Act Now or Pay Later:**
## The Costs of Climate Inaction for Ports and Shipping

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