ASSESSING CLIMATE CHANGE RISKS-TO AND RESILIENCE-OF INDIA'S SEAPORT INFRASTRUCTURE AND OPERATIONS

National Maritime Foundation

CDRI
Coalition for Disaster Resilient Infrastructure

Assessing Climate Change Risks-to and Resilience-of India's Seaport Infrastructure and Operations

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Table of Contents

Acronyms and Abbreviations

CDRI	–	Coalition for Disaster Resilient Infrastructure
CS	–	Cyclonic Storm
ESCS	–	Extremely Severe Cyclonic Storm
IMD	–	Indian Meteorological Department
IPCC	–	Intergovernmental Panel on Climate Change
JNPA	–	Jawaharlal Nehru Port Authority
Kmph	–	kilometers per hour
MbPA	–	Mumbai Port Authority
MIV-2030	–	Maritime India Vision 2030
MoES	–	Ministry of Earth Sciences
MoPSW	–	Ministry of Ports, Shipping and Waterways
MT	–	Million Tonnes
NMF	–	National Maritime Foundation
PPA	–	Paradip Port Authority
PPP	–	Public Private Partnership
RCP	–	Representative Concentration Pathway
RO-PAX	–	Roll On-Roll Off cum Passenger
SSP	–	Shared Socio-economic Pathway
VSCS	–	Very Severe Cyclonic Storm

Abstract

In the increasingly interconnected and interdependent contemporary world, trade forms a significant component of every major economy; for India, trade accounts for over one-third of the total economy. Around 95 percent of India's merchandise trade, by volume, travels through the sea in cargo ships. India has 12 major ports and over 200 non-major ports that facilitate this trade which is expected to continue to grow in the future. In 2021, the Ministry of Ports, Shipping and Waterways of the Government of India unveiled the *"Maritime India Vision 2030"* which outlines a growth model focussed on building world-class greenfield ports, creating 'smart ports', modernising existing ports, promoting port-led industrialisation and public-private partnerships. While this ambitious vision and the development projects identified under it are critical in facilitating India's transition from a "*Brown Economy*" to a "*Blue Economy*", they are being and will continue to be seriously impeded by the ever-growing impacts of anthropogenic climate change. In this context, this study aims to assess the threats posed by climate change in the form of more intense and frequent extreme weather events and sea-level rise to India's port infrastructure and operations. A climate-change-risk assessment framework and methodology were created which utilise a combination of available climatic data, field-based research, and expert-interviews with port officials to generate *"climate-risk profiles"* of Indian ports. The framework was tested and implemented through case studies of two of India's major ports, namely, the Mumbai Port Authority (on the west coast) and the Paradip Port Authority (on the east coast). Findings from the two ports were compared to bring out the differences and commonalities in the challenges facing individual ports. The study highlights the urgent need for devising comprehensive and dynamic climate-change adaptation strategies for individual ports and a concerted policy framework at the national level to ensure long-term security and sustainability of India's maritime trade sector.

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1 Introduction

To date, no Westphalian State has achieved the status of being acknowledged as a global hegemon without simultaneously being the world's primary maritime power. In recent years, India, too, has recognised the extraordinary potential of its maritime space which has led to a concerted push from all echelons of the government to expand and strengthen the maritime sectors of Indian economy. The Prime Minister of India, Shri Narendra Modi, at the Maritime India Summit in 2021, declared India's ambition of becoming a major *"Blue Economy"* in the world. In this regard, amongst Government of India's capstone publications documenting the country's developmental efforts, the "Maritime India Vision 2030" (MIV-2030) is arguably the most ambitious and comprehensive one, spelling out a whole slew of initiatives to promote national port-led development (MoPSW, 2021a). The ports and shipping sector, does indeed, comprise a major economic sector of the country. There are 12 major ports (under the Ministry of Ports, Shipping and Waterways) and over 200 non-major ports (under state governments or private administration) in India. Taken in aggregate, Indian ports handle around 95 per cent of Indian trade (imports and exports) by volume and 68 per cent by value (MoPSW, 2021b).

Formulated by the Ministry of Ports, Shipping and Waterways (MoPSW), MIV-2030 lists over 150 initiatives in the ports, shipping, and inland-waterways sub-sectors, which are expected to generate over USD 40 billion in investment, 2 million new jobs, double cargo-handling capacity, and accelerate the growth of India's maritime sector over this decade (MoPSW, 2021a). In the ports sub-sector, the *"creation of world-class greenfield ports, modernisation of existing ports, creation of 'smart ports', enhancement of land-connectivity, promotion of port-led industrialisation and public-private partnership (PPP)"* are outlined as the principal themes. While the push for capacity augmentation and modernisation is highly commendable, it is deeply disturbing that the MIV-2030 lays no explicit emphasis on *protecting* critical maritime-infrastructure assets against the ever-growing impacts of climate change.

Overwhelming scientific evidence clearly indicates that contemporary climate change, primarily caused by the increasing concentration of greenhouse gases in the atmosphere since the industrial revolution, has led to an increase in the frequency and intensity of hydrometeorological extreme events such as terrestrial and marine heatwaves, heavy rainfall events, and cyclonic storms (Raghavan et al, 2020). Climate change has also led to an increase in global mean sea level since the 20th century (Oppenheimer et al, 2019). All of these trends are expected to continue at accelerating rates in the future if global average temperature continues to rise unabated. These climate-change-induced changes pose direct and significant threats to India's holistic maritime security, as also that of every other coastal nation (Bajaj, 2020a; Bajaj 2020b; Bajaj & Honmane, 2020). Seaports, which are, more often than not, located in low-lying and high-risk coastal regions, are particularly susceptible and exposed to climate-related hazards.

In this regard, this study aims to highlight the current and projected impacts of climate change that continue to pose major risks to India's port infrastructure and operations. The study argues for the urgent need to develop comprehensive and dynamic climate change adaptation strategies, at the individual-port level as well as at the national-policy level, which are informed by rigorous climate-change risk-assessments. Section 2 discusses in greater detail the research problem and objectives of the study. Section 3 outlines the research methodology, which incorporated a combination of desk-based research and field research. Sub-section 3.1

describes the climate-change-risk assessment methodology that was created and implemented during the study. Section 4 presents and analyses the main findings from the case studies of three of India's major ports, namely, the Jawaharlal Nehru Port Authority, the Mumbai Port Authority, and the Paradip Port Authority. Section 5 discusses the enablers that contributed to the successful completion of the study, and identifies a few of the more impactful barriers that were identified in the context of devising and implementing climate-change adaptation strategies for Indian ports. Finally, Section 6 provides a conclusion and outlines a way forward.

1.1 Climate Change Threats to India's Coastal Regions

Coastal regions around the world are among the most ecologically diverse and socio-economically dynamic spaces. Primarily due to the close vicinity of the ocean and the access they provide to rich marine living and non-living resources, coastal regions generate substantial economic opportunities and are, therefore, densely populated. According to the 2011 Census, about 15.5 per cent of India's population, i.e., nearly 188 million people, live in coastal districts, while another 440 thousand live in India's island territories. These numbers are only expected to grow as these regions are experiencing remarkable urbanisation and development. Unfortunately, coastal areas in India, and around the world for that matter, are also amongst the most vulnerable to the impacts of climate change, because in addition to the impacts such as heatwaves, droughts, and extreme rainfall events, all of which are common to hinterland regions as well, coastal regions are increasingly experiencing sea-based threats such as far-more frequent and intense cyclonic storms and the long-term challenge of sea-level rise (Fuchs, 2010; Ranasinghe & Jongejan, 2018; Kulp, 2019).

Over the last 10 years, a total of 14 severe cyclonic storms either made landfall over India or affected the Indian peninsula. Eight of these impacted the country's eastern coast, including *Phailin* in 2013, *Hudhud* in 2014, *Ockhi* in 2017, *Titli* in 2018, *Matmo* in 2019, *Fani* in 2019, *Amphan* in 2020, and *Yaas* in 2021, while six, including *Gaja* in 2018, *Vayu* in 2019, *Kyarr* in 2019, *Maha* in 2019, *Nisarga* in 2020, and *Tauktae* in 2021, struck India's western coastline. These cyclones led to significant damage through the inundation of low-lying areas, destruction of public and private property, loss of livelihood, devastation of natural coastal ecosystems, disruption of fishing activities and land-based agriculture, erosion of beaches and embankments, and, disruption of electricity, road, rail and port access. Cyclone *Amphan* in 2020, for instance, was one of the costliest tropical cyclones recorded in the North Indian Ocean. According to some estimates, it caused losses worth approximately USD 13.6 billion (Medha, Mondal, Doloi, Islam & Bera, 2021), damaged more than 2.8 million homes, affected nearly 5 million people across India, Bangladesh, Myanmar, and Bhutan, and marked the largest displacement event of 2020, globally (IMDC, 2021). According to analysis published by the Indian Meteorological Department, long-term trends clearly suggest that the frequency of very severe cyclones, such as *Amphan*, has increased in both, the Bay of Bengal and the Arabian Sea (Mohapatra, Sharma, Devi, Kumar & Sabade, 2021). Climate-model-based projections show that this trend will continue in the future and the frequency and intensity tropical cyclones will increase throughout the course of this century, primarily driven by the relentless rise is sea-surface temperatures due to global warming (Knutson et al, 2020).

Insofar as extreme weather events are concerned, in addition to cyclonic storms, heatwaves, droughts, and heavy precipitation events are also burgeoning across India and are expected to continue to increase in the future. According to the 2020 report by the Ministry of Earth

Sciences of the Government of India entitled *"Assessment of Climate Change over the Indian Region"*, *"the frequency of summer (April-June) heat waves over India is projected to be 3 to 4 times higher by the end of the twenty-first century under the RCP 8.5 scenario, as compared to the 1976-2005 baseline period."* The report also noted that the duration and spatial extent of heat waves is also expected to increase over the course of this century. The landmark report additionally highlighted that in recent decades, India has experienced a shift towards more frequent dry spells as well as more intense wet spells during the summer monsoon season (Raghavan et al, 2020). This change is consistent with what is being observed globally in the patterns of extreme precipitation events; it is being driven by a fundamental scientific fact, which is that with every one-degree Celsius rise in temperature the ability of the atmosphere to hold water vapour increases by 7 per cent. The direct consequence of this is that dry periods become more intense because the air can now absorb more moisture before it reaches saturation and a corollary to this is that the wet periods also become more intense since there is now more water vapour in the atmosphere. There are of course other, more complex, factors that are contributing to the changing patterns of droughts and extreme rainfall events, such as the increase in aerosol pollution and changes in air and ocean circulation patterns, which affect the Indian monsoon as well.

Climate-change-induced sea-level rise poses another major threat to India's coastal regions as this would inundate low-lying areas, damage wetlands, erode shorelines, contribute to coastal flooding, and increase the flow of salt water into estuaries and nearby groundwater aquifers. According to the 2020 MoES report mentioned earlier, the rate of sea-level rise in the northern Indian Ocean accelerated from 1.4 mm/year during 1874-2004 to 3.3 mm/year during 1993-2017 (Raghavan et al, 2020). Data shows that the Indian Ocean — and the Bay of Bengal in particular — is experiencing a faster rate of sea-level rise than the global average. Much like the other impacts of climate change discussed above, sea-level rise, too, is expected to continue at accelerating rates, over the foreseeable future. As per the United Nations Intergovernmental Panel on Climate Change (IPCC) Working Group I Contribution to the Sixth Assessment Report, released in 2021, under the very high greenhouse gas emissions scenario (SSP 5-8.5), global mean sea level is projected to rise by 0.63-1.01 m by 2100, compared to the baseline of 1995-2014. The report also acknowledged that, *"global mean sea level rise above the likely range – approaching 2 m by 2100 and 5 m by 2150 … cannot be ruled out due to deep uncertainty in ice sheet processes"* (IPCC, 2021). Every fraction of a metre of sea-level rise will further exacerbate the impact of extreme weather events such as monsoonal floods, cyclonic storms, and storm surges. Together, these threats pose a monumental, long-term, and irreversible challenge to critical maritime infrastructure including the infrastructure and operations of Indian ports and, in turn, India's maritime trade and the national economy (Thakur, 2021).

2 Research Problem, Aim & Objectives

As discussed in Section 1, the MIV 2030, while ambitious in its vision to expand India's maritime trade sector by creation of world-class greenfield ports, smart ports, and modernisation of existing ports, puts no specific emphasis on enhancing resilience of the port ecosystem. It does not recognise the growing threats posed by the impacts of climate change which can significantly 'slow-down' port operations and reduce port efficiency causing economic losses worth crores of rupees to the country annually.

Admittedly, ports are trying to become *'green'* by reducing their emissions of greenhouse gases and other pollutants, primarily driven by the need to maintain international health and environmental standards to continue to attract international trade. MIV-2030 also encourages this through its targets of "port modernisation" and creation of "smart ports", which includes, for example, increasing the level of mechanisation in cargo handling procedures which is particularly useful in reducing pollution related to the handling of dry-bulk cargo (such as coal, iron ore, fertiliser, etc.). Further, the creation of smart ports will inevitably lead to an increased usage of renewable energy sources, including solar and wind, in order to make the port's energy supply more robust.

In other words, typically, when port authorities think of 'sustainability', their primary concern is on *"how the port is affecting the environment"* (i.e. through pollution of the air, water, and/ or land degradation) and not quite so much on *"how the environment might affect the port"* (i.e., through the increasing frequency and intensity of extreme-weather events and sea-level-rise due to climate change, see Section 1.1).

This glaring gap was the primary motivation for this study. It needs to be clarified that the authors do not assert that ports are not prepared for natural and/ or man-made disasters. Quite the contrary, in fact. Ports, almost invariably, have well-formulated disaster-management strategies including standard operating procedures during disasters such as tropical cyclones. However, none of the ports in India have a dedicated and comprehensive "climate-change adaptation" strategy that accounts for the changing behaviour of hydrometeorological disasters and the slow-moving yet high-impact and irreversible threat of sea level rise.

Accordingly, the study has the following four main objectives:

1. Create awareness about the impacts of climate change on the port and the need for climate-change adaptation in addition to climate-change mitigation.
2. Determine and classify the "degree of risk" posed by individual climate-change-related hazards to individual port infrastructure assets and operations, in order to inform "areas of priority" for individual ports.
3. Conduct a comparative risk analysis of India's major ports in order to inform policy makers in the Government of India of the most vulnerable ports.
4. Propose practical and implementable adaptation solutions, based on local-level capacities and limitations, that could be adopted to minimise the impact of these threats.

3 Methodology

The study was divided into two major phases: (a) Desk-research phase and (b) Field work and analysis phase. The desk-research phase was primarily devoted to a comprehensive literature-review to identify and assess current best practices with regard to climate-risk assessments of seaports and adaptation strategies that are being formulated or implemented by seaports internationally (Scott, McEvoy, Chettri, Basic & Mullet, 2013; Nursey-Bray et al, 2013; McIntosh & Becker, 2017; Asariotis, Benamara & Mohos-Naray, 2017; Esteban et al, 2020). Conclusions were then drawn for the Indian context and the steps that could and should be taken by Indian ports to move towards a more climate-resilient future. The findings have been published elsewhere (Bajaj & Youdon, 2021). The literature review reinforced the previous assertion that climate-change adaptation-planning in the context of seaports is at its embryonic stages even in the developed parts of the world (Becker, Innoue, Fischer & Schwegler, 2012; Becker, Ng, McEvoy & Mullet, 2018). It was realised that before any climate-change adaptation strategy could be devised for Indian ports, the first step would be to sensitise the port authorities and other stakeholders, at the local level, and policymakers at the national-level, regarding the current and projected threats posed by climate change in the near- to mid-term future (05-30 years). In this regard, a climate-risk assessment framework and methodology were generated, as described in greater detail below, for the second phase of the project.

The field work and analysis phase was dedicated to implementing the climate-risk assessment methodology that had been created in the first phase in respect of Indian ports, to provide a semi-quantitative understanding of the level-of-risk posed by climate change to individual infrastructure assets and operations. Three major ports were chosen for the field visits, based on a comparative "climate vulnerability" analysis of India's 12 major ports. Six indicators were utilised for the analysis to determine, (a) the amount of cargo handled by the ports, which would indicate their criticality to India's overall maritime trade, (b) the performance and efficiency of the ports, and (c) their potential vulnerability to the impacts of climate change such as increasingly frequent and more intense extreme-weather events and sea-level rise. The six indicators were: (i) climate vulnerability ranking of the port's district based on government data, (ii) annual cargo traffic volume, (iii) distribution of different types of cargo handled by the port, (iv) vessel turn-around time, (v) number of vessels visiting the port per year, and (vi) average berth productivity. The complete analysis will be published elsewhere. Based upon this preliminary analysis and taking into account ease of access, the Jawaharlal Nehru Port Authority (JNPA) on the West Coast of India was chosen for the pilot study. Due to its geographic proximity to the JNPA, the Mumbai Port Authority (MbPA) was also included for the pilot study. The Paradip Port Authority (PPA) was chosen for the second field study, as a representative port on the eastern coast of India, where the local environmental conditions and climate-change-related challenges are very different from those on the western coast.

3.1 Climate-Risk and Resilience Assessment Methodology for Indian Ports

Following the broad definition put forward by the United Nations Intergovernmental Panel on Climate Change (IPCC), climate risk was described as a combination of *'hazard'*, *'exposure'*, and *'vulnerability'* (IPCC, 2007). As alluded-to earlier, in the present context, the 'hazards' correspond to extreme environmental conditions that are becoming more frequent and more intense due to contemporary climate-change, such as sustained extreme temperatures (or heatwaves), extreme precipitation (that may lead to flooding), and tropical revolving storms (or cyclones). Another climate-change-induced hazard that is relevant for coastal regions and, in turn, for port infrastructure and operations is the rising sea level due to increasing ocean temperatures, coupled with the melting of mountain glaciers and land-based polar ice caps.

‘Exposure’ [to climate-related hazards] connotes the ways in which a port or its individual infrastructure assets and operations may or may not be affected by these hazards. The port’s ‘vulnerability’ could be then described as the *degree* to which the port or its individual assets and operations may be affected. Vulnerability can, in turn, be viewed as a function of *‘sensitivity’* and *‘adaptive capacity’*, where, sensitivity is a measure of the extent of damage that could potentially be caused by an extreme event or a climatic trend, while adaptive capacity is a measure of the extent to which this potential damage can be minimised by taking some timely and commensurate action during an extreme event or in response to a climatic trend.

Consistent with existing methodologies in the available literature, the climate-change-related risk to the selected port was estimated by assessing the exposure and vulnerability of individual port assets and their associated operations to climatic hazards. Five main hazards were selected that are expected to pose the most significant threats to ports: (1) Extreme Temperature; (2) Extreme Precipitation; (3) Cyclonic Storms (incorporating the IMD-defined-categories of *“Cyclonic Storm”*, *“Severe Cyclonic Storm”*, and *“Very Severe Cyclonic Storm”*, i.e., sustained wind speeds between 62 and 167 kilometres per hour [kmph]); (4) Extremely Severe Cyclonic Storms and higher (incorporating IMD-defined-categories of *“Extremely Severe Cyclonic Storm”* and *“Super Cyclonic Storm”*, i.e., sustained wind speeds higher that 168 kmph); and (5) Sea Level Rise. Port-assets were divided into three categories: *sea-side*, *port-side*, and *hinterland-side*. Included under the category of ‘Sea-side’ were assets/ operations such as the anchorage area, the navigation channel, breakwaters, tugboats, etc. Port-side assets included the cargo-handling infrastructure, cargo-storage areas, administrative buildings, etc. Hinterland-side assets included the infrastructure that connects the port to the city such as the railways, roads, power, and communication lines, etc. In order to determine the magnitude of climate risk posed to each asset and, in turn, to the port, a series of interviews were conducted with the port officials, including the Chairman and/ or Deputy Chairman and the Heads of Departments of the marine department, the traffic department, the mechanical and civil engineering department, the port planning and development department, and the

Figure 1: Images of the Research Team with the Jawaharlal Nehru Port authorities, during their field visit in December 2021.

environment-planning department. It is obvious that the organisational structure and the names/ designations of the departments/ individuals could and did vary across ports. Figures 1, 2, and 3 depict images of the authors conducting interviews/ discussions with the port authorities at JNPA, MbPA, and PPA, respectively, during their field visits.

Figure 2: Images of the Research Team conducting interviews/ discussions with the Mumbai Port authorities during their field visit in December 2021.

Figure 3: Image of the Research Team with the Paradip Port authorities, during their field visit in April 2022.

The interviews were conducted in a free-flowing but guided discussion-format, centred upon questions designed to ascertain the exposure and vulnerability of individual assets. While determining the exposure of an asset to a particular hazard was relatively straightforward, quantifying the vulnerability of the asset was much more nuanced and relied on multiple parameters. Factors such as the age and condition of the asset, its cost, the ease and cost of maintenance of the asset, the ability of the port to function efficiently without the asset, and the ability of the port to find an alternative or replacement to the asset, all contribute to the vulnerability. In the present context, the risk to the port arises from its dependency on proper functioning of its infrastructure assets and personnel to continue its operations at maximum efficiency. As shown in Table 1, the risk index ranges from one to five, corresponding to an increasing amount of time that port operations may be affected due to unavailability or unviability of the asset. Risk index value of 'one' corresponds to "No Risk", 'two' corresponds to "Low Risk", 'three' corresponds to "Moderate Risk" wherein port operations may be down for a few hours, 'four' corresponds to "High Risk" wherein port operations may be down for a few days, and 'five' corresponds to "Extreme Risk" wherein port operations may be down for more than a week. These factors were discussed during the interviews with the port authorities and the authorities were asked to assign a *"risk value"* to each individual asset based on the risk index described in Table 1.

To gather qualitative insights into the *resilience* of the port in the face of a high-impact extreme-weather event, the port authorities were asked to share their experiences and the port's response to an extremely severe cyclonic storm that had occurred in the recent past. In the case of the western coast ports (JNPA and MbPA), cyclone *Tauktae* (2021) was taken as the case study, while for the eastern coast (PPA), cyclone *Hudhud* (2014) was taken as the case study. The following questions were asked, in this regard:

(a) What was the impact of *Tauktae/ Hudhud* on the port infrastructure and operations?
(b) What was the economic impact on the port or the country, resulting from infrastructural damages, berthing charges, loss of working hours, vessel calls, etc.?
(c) What were the port's responses before and after *Tauktae/ Hudhud* made landfall?
(d) What was the impact on inland support infrastructure (roads, railways, etc.)? How much did that affect the port's operations?
(e) How long did it take for the port to return to normal functioning after *Tauktae/ Hudhud*?

Table 1: Climate Change Risk Scale.

Risk Value	Description
1	No Risk
2	Low Risk
3	Moderate Risk (Port operation down for hours)
4	High Risk (Port operation down for days)
5	Extreme Risk (Port operation down for weeks)
N/A	Not Applicable

4 Results and Discussion

As described in Section 4, a climate-risk assessment framework and methodology were created for ports as a first-step towards a climate-adaptation strategy for Indian ports. The framework was tested through a pilot study of the Jawaharlal Nehru Port Authority (JNPA) and the Mumbai Port Authority (MbPA). Commissioned for commercial purposes in 1989, the JNPA is located at the eastern end of Mumbai, on Sheva Island. In FY 2021-22, the JNPA handled around 64.81 million tonnes (MT) of cargo. In fact, JNPA handles more than half of the total container cargo handled by India's major ports and around 40 per cent of the country's total container cargo traffic. Currently, the port operates five container terminals, namely, the Jawaharlal Nehru Port Container Terminal (JNPCT), the Nhava Sheva International Container Terminal (NSICT), the Nhava Sheva International Gateway Terminal (NSGT), the Gateway Terminals India Pvt Ltd (GTIPL), and the newly commissioned Bharat Mumbai Container Terminals Pvt Ltd (BMCT). The port also has a shallow-water berth for general cargo and a liquid-cargo terminal, which is managed by a BPCL-IOCL consortium (JNPA, nd).

The Mumbai Port Authority is the second oldest port of India. It has been handling cargo for more than 150 years. The port is located within a natural deep-water harbour of about 400 sq km. The harbour itself is naturally protected by the mainland of Konkan to its east and the Island of Mumbai to its west, and the port, therefore, needs no artificial breakwaters. The port handles large quantities of dry-bulk cargo, break-bulk cargo, and liquid-bulk cargo. In 2021-22, the port handled a total of 53.32 MT of cargo. MbPA also concentrates greatly on tourism and water-transport related activities, supported by an International Cruise Terminal, a Domestic Cruise Terminal, a RO-PAX Terminal, and a marina. MbPA seeks to become a major cruise-ship destination within India (MbPA, nd). Notably, in the year 2021-22, of the country's 12 major ports, Mumbai Port reported the highest number of Vessel Calls (number of vessels a port attended-to within a voyage), with 5140 vessel-calls.

While the pilot field visit to JNPA was extremely insightful and allowed the authors an opportunity to sensitise the port authorities to the urgent need for climate change adaptation, the interviews and discussions with the authorities at the JNPA ended-up taking an unstructured form and were, therefore, limited to preliminary qualitative discussions regarding the potential impacts of climate-change-induced hazards on the infrastructure of the port, and steps that could be taken by the port authority to minimise these impacts. Discussions also concentrated on the efforts being made by the port to minimise its environmental footprint by minimising its interference with the surrounding natural ecosystems and by investing in renewable energy for power-generation. Unfortunately, due to limited time available for interactions with the JNPA personnel, the discussions could not be unambiguously converted to a "climate-risk profile" for the port as had been envisioned in the methodology. This was an important learning-experience for the authors, and one that led to important modifications in the way the interviews needed to be structured in order to best utilise the limited amount of time and yet produce maximum results. A new, streamlined and focused approach was then followed during the pilot study of Mumbai Port Authority (MbPA) which did, indeed, lead to the desired result of development of a climate-risk profile for the port, as shown in Table 2.

The second field study was conducted at the Paradip Port Authority (PPA), which is strategically situated between the Kolkata Port and the Visakhapatnam Port. The PPA is an artificial deep-water port located on the east coast of India in Jagatsinghpur district of Odisha state. It is protected by two rubble-mound breakwaters (the 538 m long North Breakwater, and the 1217 m long South Breakwater) and is connected to deep water by a dredged navigation-channel. In the year 2021-22, the PPA handled 114.5 MT of cargo traffic (second-highest amongst the major ports), which included various types of dry-bulk, liquid-bulk and breakbulk cargo (PPA, nd). The PPA handles the largest volume of dry-bulk cargo of all twelve of India's major ports, with thermal coal and coking coal being the main entities, largely due to the port's proximity to the Mahanadi coalfields. The port has two docks, the Eastern and the Central dock, which together incorporate three mechanised berths, seven general cargo conventional berths, two oil jetties, and three dedicated berths. In addition, the PPA has one RO-RO (Roll On-Roll Off) jetty and three Single Point Moorings (SPMs), which are owned by the Indian Oil Company Ltd (IOCL). The detailed climate-risk profile of the infrastructure assets of the PPA is provided in Table 3.

The climate-risk profiles produced for the MbPA and the PPA suggest that all three sections of the port ecosystem, viz., the sea-side, the port-side, and the hinterland side, are impacted by the different climate-change-induced hazards. As was expected, both the climate-risk profiles are broadly similar in terms of the relative level of risk posed by the individual climate hazards on individual infrastructure assets. However, the absolute risk values, as prescribed by the port authorities, do vary to some extent, which could be partially attributed to the different local-level geographical, environmental, and economic conditions and limitations.

The most apparent conclusion from both the risk profiles is that the highest level of risk (risk index value ranging from 3-5, corresponding to Moderate-to-Extreme risk, see Table 1), as perceived by the port authorities, is posed by cyclonic storms, specifically from Extremely Severe Cyclonic Storms or higher, i.e., when wind speeds are higher than 168 kmph. This assessment is supported by the first-hand experiences of the port authorities of such high-intensity cyclonic storms, such as Cyclone *Tauktae* at Mumbai Port, Cyclone *Nisarga* at JNPA, and Cyclone *Hudhud* at Paradip Port. Most of the infrastructure at these ports, including the cargo-handling equipment, cargo-storage areas, and administrative and residential buildings, are not designed to withstand sustained wind speeds of greater than 160 kmph.

Standard operating procedures dictate that during any cyclonic storm the port is to halt all operations, all vessels inside the port are asked to move outside to the anchorage area, all cargo-handling equipment is to be anchored and secured, cargo-storage facilities are to be secured appropriately (depending on the cargo type), and all staff members, except essential staff, are to be asked to vacate the port premises. This 'shut-down' period could last for a few hours to a couple of days, depending on the intensity and speed of the cyclonic storm.

Even after the emergency-preparedness protocols are followed and the infrastructure is secured, significant damage can and does accrue, particularly in the case of extremely severe cyclonic storms such as *Tauktae* and *Hudhud*, both of which recorded maximum sustained wind speeds of over 185 kmph and caused very heavy rainfall. Depending upon the extent of the damage caused, the recovery period after a major cyclone could vary from a few hours to several days, during which several segments of the port, or the entire port, may be forced to halt some or all operations. Port authorities reported that during cyclone *Tauktae*, one of the vessels in the anchorage area went adrift after losing its anchor and collided with one of the jetties, causing considerable damage that had to be repaired later at significant economic cost. During Cyclone *Hudhud*, the North Breakwater at Paradip Port suffered significant damage, which took several days to repair. While these repairs were going on, the port could not operate at all, since vessels could not safely enter and berth at the port.

Apart from cyclonic storms, extreme-precipitation events, such as heavy monsoon rains or cloud-burst events, also pose a risk to port operations (see Table 2 and 3). In sea-side operations, the primary cause for concern is low visibility during heavy rainfall and choppy waters if there are strong winds. In extreme cases, low visibility hampers the ability of pilot boats and tugs to bring a cargo ship from the anchorage area into the port. Such conditions might stop seaside operations, albeit for a few hours at most, if heavy rains continue to be experienced.

As far as port-side operations are concerned, barring extreme cases, heavy-rainfall events typically do not affect container cargo-handling equipment or storage areas, primarily because the cargo is secured within containers. Similarly, heavy rainfall does not affect liquid-bulk cargo operations because most of it is handled through pipelines. Heavy rainfall could, however, affect handling and storage facilities for dry-bulk cargo (such as coal, iron ore, limestone, etc.). In general, low visibility and flooding during heavy rainfall events typically affect port-side operations, for a few hours. Port authorities placed the risk posed by extreme-precipitation events in the 2-3 range, corresponding to Low-to-Moderate risk (see Table 1).

Heavy precipitation poses a greater risk to hinterland connections such as roadways, railways, power connections, communication lines, waste services, and staff-access to the port, due to flooding. This is a significant concern for the MbPA during the monsoon months, when urban flooding can cause slowdown of cargo moving out of the port via road or railway (see Table 2). This slowdown in public transportation would also affect the ability of the staff to reach the port.

Extreme-temperature events or heatwaves were rated as the lowest risk hazard with regard to their impact on hard infrastructure, which is negligible. The port authorities did however acknowledge that in extreme cases, heatwaves could affect work-efficiency and the health of the port staff. This is particularly relevant for dry-bulk cargo-handling facilities, where already-harsh working conditions can become intolerable during heatwaves. The health impacts of heatwaves have, of course, been widely reported in medical journals. The latest and best available science unequivocally states that heatwaves will become more common and more intense as global average temperature continues to rise. Tropical countries including India are particularly vulnerable to extreme heatwaves.

While port authorities at both, the MbPA and the PPA did recognise the potential threat posed by climate-change-induced sea-level-rise, the authors would argue that risk ratings for sea level rise may be underestimated (see Table 2 and 3). The port authorities noted that sea-level-rise might, in fact, bring some benefits for the port because an increase in sea level would increase the depth of the navigation channel of the port, which would reduce the dredging requirements for the port and allow larger vessels with greater draughts to enter the port. Dredging is a very expensive activity that is carried out frequently by ports in order to maintain the depth of their navigation channels. Clearly, any reduction in the frequency of dredging would be hugely beneficial to the port. However, there are many additional ways in which sea-level rise would adversely affect the port's infrastructure and operations. For instance, the jetties and associated cargo handling infrastructure on the jetty are designed at specific heights, which considers the vessel types that will be handled by the terminal. A change in sea-level, combined with tidal variations, would change the height of the freeboard of the ship relative to the jetty, which could affect cargo handling operations. In response to this, the port authorities pointed out that height of the freeboard of the ship can be altered through ballast water management. However, they admitted that if there were large variations in sea level, around or greater than 0.5 m, in the medium to long term future, this could affect port operations.

Most importantly, the authors argue that sea-level-rise poses a serious and irreversible threat to port infrastructure and operations due to permanent inundation of low-lying areas within the port and of low-lying areas in the city. Figures 4 and 5 depict, in red, the areas that are expected to be below tidal level by the year 2040, around Mumbai Port and Paradip port, respectively. The projections are based on the latest global climate model simulations (Climate Central, nd). Clearly, the projections suggest that large areas would be inundated by sea-level rise in the not-too-distant future. This would be further exacerbated by coastal flooding, including tidal flooding and monsoonal flooding, which are experienced on an annual basis. Moreover, several scientific studies in recent years have highlighted that there are physical processes that are contributing to the acceleration of the melting of the Greenland and Antarctic Ice Sheets which would, in turn, accelerate global mean sea-level rise. To name a few, these processes include a reduction of ice sheet surface albedo due to algal blooms, soot-particle depositions and a consequent increase in the number of meltwater lakes, encroachment of warm ocean water from under the Antarctic ice sheet that leads to the formation and destabilization of "ice cliffs", etc. These processes are not yet included in global climate models because they have only recently been discovered (Bajaj, 2019).

Table 2: Climate Change Risk-Assessment of Mumbai Port Authority. Refer to Table 1 for description of the Risk Scale. See text for detailed explanations of the factors contributing to the risk ratings.

Port Interface	**Asset/ Operation**	**Extreme Temperature**	**Extreme Precipitation**	**Cyclonic Storms**	**Extremely Severe Cyclonic Storms**	**Sea Level Rise**
Seaside	Access Channel	1	1	3	3	1
	Anchorage/ Waiting Area	1	2	3-4	3-5	1
	Navigation Assistance (Pilot/ Tugboat)	1	2	3-4	3-4	1
	Lock Gate/ Berthing Area	1	2	3-5	3-5	3-5
Portside	Crude Oil Jetties	1	1	4	4-5	4
	Crude Oil Loading Arm	1	1	3	4	2
	Oil Pipelines/ Valve Stations	1	1	2	2	1
	Office/ Admin Buildings (*Jawahar Dweep*)	1	1	1	1	1

	Break-bulk Jetties	1	2	3	4	2
	Cargo Transit/ Storage Areas	1	3	3	4	1
	Ship-repair Facilities	1	3	3	4	1
	Commercial Fishing Facilities	1	1	3	4	2
	Admin Staff and Workers	3	3	3	4	1
Hinterland Connections	Roadways	1	3	3-4	4	1
	Railways	1	3	3-4	4	1
	Power Connections	1	1	1	3	1
	Communica-tions	1	1	1	3	1
	Waste Services	1	1	2-3	4	1

Table 3: Climate Change Risk-Assessment of Paradip Port Authority. Refer to Table 1 for description of the Risk Scale. See text for detailed explanations of the factors contributing to the risk ratings.

Port Interface	**Asset/ Operation**	**Extreme Temperature**	**Extreme Precipitation**	**Cyclonic Storms**	**Extremely Severe Cyclonic Storms**	**Sea Level Rise**
Seaside	Breakwater North	1	1	3	3-4	2-3
	Breakwater South	1	1	3	3-4	2-3
	Access Channel	1	1	3	3	1
	Anchorage/ Waiting Area	1	1	2-3	3	2
	Navigation Assistance (Pilot/ Tugboat)	2	2	3	3-4	1
	SPMs	1	1	3	3-4	1
Portside	Coal Berth	2	2	3	3-4	1-2
	Coal Handling Facility	1	2	3	3-4	1
	Iron Ore Berth	1	2	3	3-4	1-2
	Iron Ore Handling Facility	1	2	3	3-4	1-2

	General Cargo Berth	1	2	3	3-4	1-2
	North Oil Jetty	2	2	3	3-4	2-3
	South Oil Jetty	2	2	3	3-4	2-3
	Fertilizer Berth	1-2	2	3	3-4	1-2
	Multi-Purpose Cargo Terminal	1	2	3	3-4	1-2
	Ro-Ro Jetty	1	1	3	3-4	1-2
	Mobile Cranes	1-2	1-2	2-3	3-4	1-2
	Clean Cargo Terminal	1	1-2	3	3-4	1-2
	Cargo Storage Facilities	1	1	2	2-3	1-2
	Ship Repair/ Dry Dock	1	1	2-3	3-4	2-3
	Office and Admin Buildings	2	2	2-3	2-3	1
	Staff and Workers	2-3	2	3	3-4	1
Hinterland Connections	Roadways	1-2	2-3	2-3	2-3	1
	Railways	1-2	1-2	2	2-3	1
	Power Connections	1	2	2	2	1
	Communica-tions	1	2	2-3	3-4	1
	Waste Services	1	2	2	3	1
	Staff Access	1-2	1-2	2	3	1

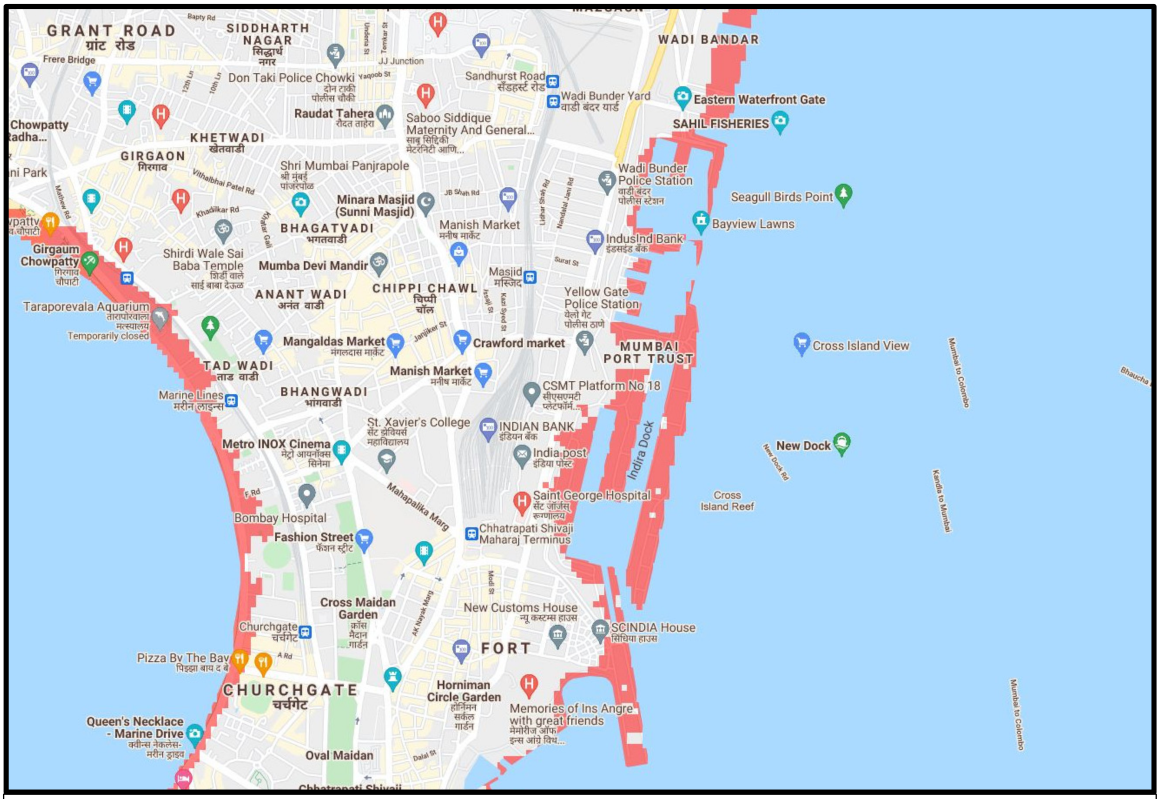

Figure 4: Map depicting sea level rise projection for the year 2040 under the current trajectory ("SSP3-7.0") around Mumbai Port Authority (shown as "Mumbai Port Trust" in the map). The red areas correspond to areas that are projected to be below tideline. Based on IPCC (2021). Source: Climate Central – Coastal Risk Screening Tool, https://coastal.climatecentral.org.

Clearly, managing these impacts of climate change on brownfield and greenfield projects will require extensive and long-term planning and coordination between all relevant stakeholders. Some of the potential adaptation measures were discussed with the port authorities during the field visits. Typically, these measures can be divided into two categories, *"hard measures"* and *"soft measures"*. Hard measures include infrastructural upgrades or additions, such as creation of protective infrastructure (seawalls/ dikes), upgrading breakwaters (construction material or dimensions), increasing the elevation of existing infrastructure, retrofitting or strengthening existing infrastructure, upgrading drainage systems, mechanising cargo handling facilities to minimise exposure, etc. In this context, *"nature-based solutions"* must also be considered that focus on the protection, conservation, and expansion of coastal and marine ecosystems, such as mangroves and seagrass, that act as natural protection against cyclonic storms, floods, and storm surges (Cheong et al, 2013). Of course, almost all the hard infrastructural measures involve hefty financial costs and careful analysis and planning to justify those costs. Soft measures, on the other hand, mainly require changes in policies or standard operating procedures, for instance, emergency response protocols, working protocols, training exercises, building codes, etc.

All potential adaptation measures must be analysed on a case-to-case basis and evaluated for their effectiveness, technological feasibility, and financial viability, in order to determine the ones most appropriate to a specific port. Arguably, a comprehensive adaptation strategy, particularly for a developing country such as India which has limited technological and financial capacity, would necessarily constitute a combination of "hard measures" and "soft measures". As alluded-to earlier, this would greatly depend on the local-level circumstances and limitations of a particular port. Much more research would be required to devise effective and practical adaptation strategies for individual ports, which was outside the scope of this study but will be addressed in subsequent ones.

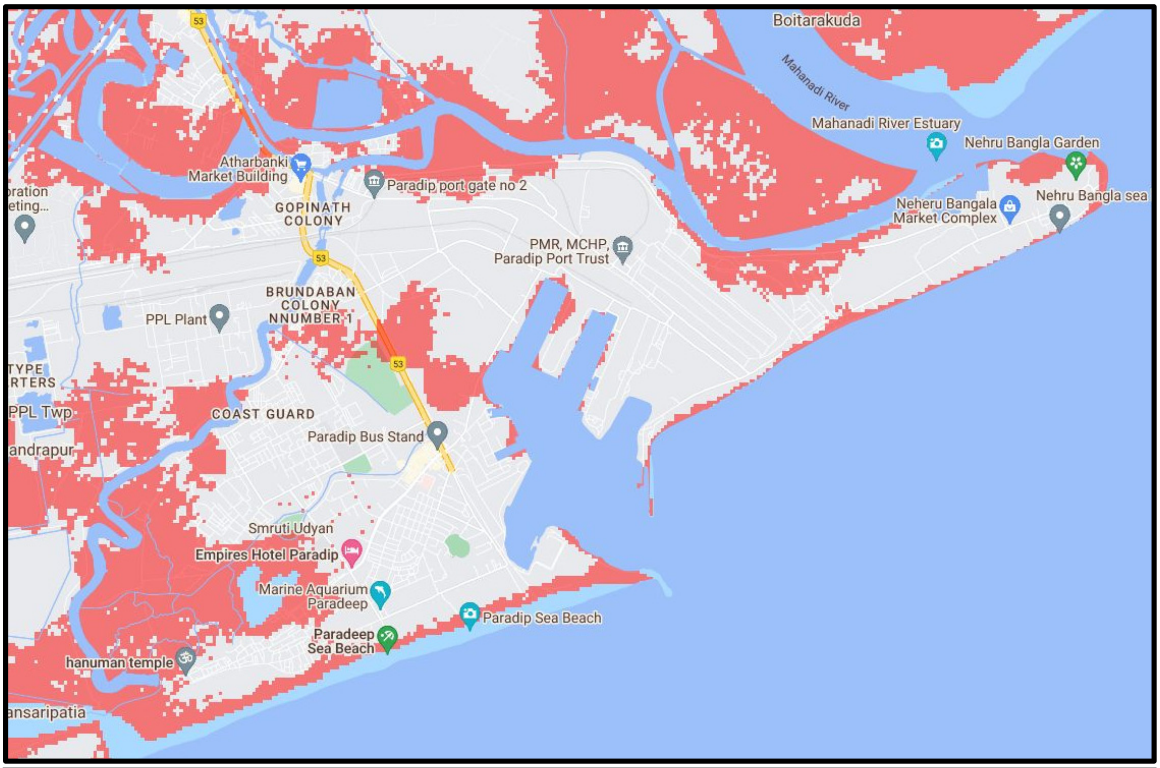

Figure 5: Map depicting sea level rise projection for the year 2040 under the current trajectory ("SSP3-7.0") around Paradip Port Authority (shown as "Paradip Port Trust" in the map). The red areas correspond to areas that are projected to be below tideline. Based on IPCC (2021). Source: Climate Central – Coastal Risk Screening Tool, https://coastal.climatecentral.org.

5 Enablers and Barriers

It is substantially evident, even at the global scale, that efforts focussed on climate-change adaptation are significantly lagging behind efforts focussed on climate-change mitigation. While climate-change mitigation through drastic cuts in greenhouse gas emissions must certainly take top priority so as to avoid some of the worst-case future-warming scenarios, we must also simultaneously protect and adapt our civilizations to the impacts of climate change that have already occurred or those that are projected to occur in the near future. This is even more important for a densely populated and fast-growing economy such as India and, within India, the coastal regions that are particularly vulnerable to climate change.

In this context, this study, which focussed on "Assessing Climate Change Risks-to and Resilience-of India's Seaport Infrastructure and Operations", which is a one-of-its-kind study in India, is but the first step towards developing a comprehensive climate change adaptation strategy for India's maritime trade and transport sector. The institutional support and patronage provided by the National Maritime Foundation (NMF) as the endorsing institute and the Coalition for Disaster Resilient Infrastructure (CDRI) Fellowship were crucial enablers of this research, particularly in facilitating the field visits to the JNPA, the MbPA, and the PPA, which were essential elements of the study.

While most of the stakeholders that were interviewed had personal anecdotes, and impressions based on those anecdotes, regarding the changes that have occurred in ocean conditions and weather patterns in recent years/ decades, there was a general lack of awareness about the current and projected impacts of climate change on coastal areas, in general, and ports in particular, based on the latest, widely-accepted scientific understanding. This sort of conviction, based solely on anecdotal evidence, invariably, leads to a biased and often incorrect understanding of the actual manner in which climate change may or may not affect a particular city or port. Arguably, the primary reason for this state of affairs is a dearth of easily accessible, local-level climate change projections for India and a lack of discussion-forums where these projections and their implications for critical maritime infrastructure could be discussed between climate scientists, port authorities, policy-shapers, and policy-makers. In this context, the discussions that took place during the field visits within this project were a critical and much-needed first step towards sensitising the port authorities.

For construction of greenfield infrastructure and major renovation activities of brownfield infrastructure, a port authority typically hires external consultants and construction companies to design and implement the projects based on the specifications provided by the port. Typically, the project-planning phase includes an analysis of past trends (up to 100 years) in respect of weather parameters and ocean conditions for the particular location, in order to determine the various design parameters of the marine infrastructure. However, it is no longer sufficient to consider past trends alone. Future projections of climate-change impacts must be built into the design parameters during the planning stages. This would require concerted efforts between the external agencies, local-climate modellers, and port authorities.

6 Conclusion and Way Forward

This study reflects a critical first step towards developing a comprehensive climate-adaptation and resilience strategy for India's maritime trade sector. As climate change continues unabated, its manifestations in the form of more intense and frequent extreme weather events and accelerating sea-level rise will continue to pose direct and serious threats to India's critical maritime infrastructure, including seaport infrastructure and operations. As discussed in Section 1, this enormous challenge remains largely unaddressed in the national policy framework, as also in the action plans of individual ports. In this context, the study aimed to highlight the urgent need for creating climate-adaptation plans at the individual port level as well as at the national level. The authors created a climate-risk assessment framework and methodology for Indian ports, based on existing international best practices. The framework included a perception-based study which relied on extensive interviews and discussions with relevant stakeholders (in this case, the port officials) to generate a semi-quantitative "climate-risk matrix" of the port's infrastructure assets and operations. Accordingly, the framework was tested and applied to generate climate-risk profiles of

Mumbai Port Authority and Paradip Port Authority in consultation with the respective port officials.

As discussed in detail in Section 4, the findings show that, according to the port officials interviewed, of the various climate-change-induced hazards, cyclonic storms pose the most serious threat to the port as they typically lead to operational downtimes ranging from a couple of days to over a week, depending on the strength of the cyclone. Extremely severe cyclonic storms with wind speeds greater than 168 km/hr have, in the past, caused significant infrastructural damage to the port, and since such extreme cyclones are expected to become more common in the future due to climate change, they will pose a major challenge for Indian ports. Extreme rainfall events, followed by extreme heatwaves, also pose threats to port infrastructure and operations, albeit to a lower degree than cyclonic storms. While the port authorities recognised the long-term threat from climate-change-induced sea level rise, the level of risk was not perceived to be very high. The authors argue that this may be an unaffordable underestimation, but one reason for this is the lack of robust, easily comprehensible local-level climate-model projections for sea-level rise, leading to the lack of appreciation of the interconnectedness between the port and the city, wherein if large swaths of the city are inundated, it will inevitably lead to knock-on effects on the port.

While there are some generic best practices that can be followed and infrastructural upgrades that can be made to begin to address the impacts of climate-change-related hazards, more in-depth research, along with concerted effort on the part of all stakeholders would be required if we are to devise effective and practical climate adaptation strategies for individual ports that account for local-level challenges and limitations. The authors believe that this study can and must act as a trigger for additional studies and inter-organisational collaboration on the subject. The natural extension of this study would be to expand the scope of the climate-risk assessments to a pan-India level and analyse as many major and non-major ports of India as possible. This would generate a holistic picture of the degree of risk posed by climate change to India's ports sector and maritime trade sector in general. A pan-India assessment would be highly relevant to the policymakers in the Ministry of Ports, Shipping and Waterways to generate appropriate policy guidelines at the national level. Additionally, as discussed in this report, individual ports must invest time and resources in collaboration with external agencies, most certainly including think-tanks and city authorities, to devise dynamic and holistic adaptation-strategies that can minimise the impacts of climate change on their infrastructure and operational efficiency. This should also involve the sharing of best practices from other ports in India and abroad some of which may well be at more advanced stages of their planning processes.

As India moves full steam ahead to achieve its goal of becoming a leading blue economy of the world, it must recognise and proactively address the ever-growing challenges from climate change, which otherwise have the potential to undo any progress that may be made by ambitious coastal-development projects. Effective climate-change adaptation would require long-term planning and the adoption of a holistic approach that accounts for the needs of all stakeholders. Therefore, we must start planning now to ensure a safe and resilient maritime economy.

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