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Towards a Comprehensive Climate Adaptation Framework for India's Port Infrastructure and Operations: Lessons from Global Best Practices

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Abstract

The ever-growing impacts of climate change such as extreme heat, more frequent heavy precipitation events, intensifying tropical revolving storms, and sea level rise continue to pose major threats to India's critical maritime infrastructure. As the country moves towards its ambition of becoming a leading Blue Economy of the world, a wide range of initiatives have been taken by the central and state governments to expand the maritime sector with a specific focus on the transport sector. However, there is little emphasis being paid on protecting the existing and planned seaport infrastructure against the deleterious impacts of climate change. None of the major ports in India have a dedicated climate action strategy and climate adaptation finds no mention in the policy documents pertaining to the maritime transport sector. In this context, this paper aims to highlight the need for a comprehensive, holistic and dynamic climate change adaptation strategy for India's port infrastructure including support infrastructure and supply chains. The adaptation strategy, at the individual ports' level and the national level, must be preceded by rigorous risk assessment studies to identify and prioritise the major challenges arising from climate change at the local level. The paper draws upon international best practices in climate risk assessments and adaptation measures to provide a way forward for Indian ports.

Keywords

Climate risk; climate adaptation; resilience; maritime sector; ports; shipping.

1. Introduction

Coastal areas around the world are among the most vulnerable geographical areas to climate change. In addition to the generic impacts such as rising temperatures, extreme heatwaves, erratic rainfall patterns, etc., that are common to all land areas, coastal areas are exposed to two more dramatic impacts of climate change: a) sea level rise and b) increasingly frequent and intense tropical revolving storms (Fuchs, 2010; Williams, 2013; Ranasingha & Jongejan, 2018; Kulp & Strauss, 2019). They are typically also densely populated, primarily due to the myriad economic opportunities that are afforded simply by being in the vicinity of the ocean and having access to the rich marine resources. Approximately 40 percent of the world's population lives within 100 kilometers (km) of the coast. Coastal zones around the world are also experiencing the fastest rates of urbanization and growth and undergoing remarkable socio-economic and environmental transformations in the process. As a result, even more people are moving to coastal areas from the hinterland to take advantage of the growth trends.

In recent years, India, recognizing the immense potential of its maritime space, has launched a slew of measures to expand and enhance the maritime sectors of the economy and facilitate the transition from a *'Brown Economy'* to a *'Blue Economy'*. The latest and most comprehensive development plan, in this regard, is the Maritime India Vision 2030 (MIV-2030), launched by the Prime Minister in March 2021 on the inaugural day of the Maritime India Summit 2021 (MoPSW, 2021). Under the aegis of the Ministry of Ports, Shipping and Waterways (MoPSW), the port-led development model outlined in the MIV-2030 is focused on building world-class greenfield ports, creating 'smart ports' and modernizing existing ports, reducing logistics by enhancing land-connectivity, promoting port-led industrialization and public-private partnerships. Over 150 initiatives have been identified so far under the 10-year plan which is expected to generate over INR 3 trillion in investment and 2 million new jobs. The plan also lays emphasis on building a *sustainable* and *green* maritime sector by increasing the use of renewable energy at ports, improving air quality at ports, reducing water consumption and improving health and safety standards. Notably, no explicit targets for reduction of greenhouse gas (GHG) emissions have been defined yet. Similarly, no mechanisms have been mentioned to calculate the life-cycle GHG emissions of the greenfield ports that will be constructed. Nonetheless, the commitment towards improving energy efficiency and increasing renewable energy usage in the vision document denotes a significant step towards a sustainable transition.

Even though the motivation for sustainability measures such as improving efficiency and using technology may be rooted in the economics, to save on fuel costs and time, they could, in principle, be considered a part of the climate change mitigation strategy. However, there are no plans in this port-led development model to adapt to the impacts of climate change that have already occurred or those that are projected to occur in the near- and long-term future. Currently, while almost all Indian ports have extensive 'Disaster Management Strategies' for natural disasters such as earthquakes, cyclones, floods, fires, etc., these disaster management strategies do not account for the ongoing changes that are occurring in the frequency, intensity, and behavior of these disasters due to climate change. None of the major Indian ports have a dedicated 'Climate Change Adaptation' strategy. This is, in fact, a common theme across most coastal States in the world, there is little emphasis on enhancing the resilience of the ports and shipping infrastructure and the critical supply chains to the impacts of climate change compared to the emphasis given to climate change mitigation by reducing carbon emissions from ports and shipping. As discussed in detail in the next section, everything from rising temperatures to flash floods to sea level rise and more frequent cyclones, will adversely impact port infrastructure and the personnel which could seriously hamper the ability of the ports to carry out their operations and meet their targets. This would, at best, result in frequent localized, short-term economic losses and, at worst, lead to increasing instances of shutdowns of one or more ports for weeks or even months causing crippling damage to the country's economy.

Currently, India has 12 major ports (see Figure 1), that are managed by the MoPSW of the central government, and 205 minor ports, that are managed by the state governments of the states in which the port is located (MoPSW, n.d.). India's maritime transport sector accounts for 95 percent of the country's total trade by volume corresponding to 70 percent of total trade by value. The absolute volume of trade is expected to continue to grow significantly under the MIV-2030, in fact, capacity augmentation for maritime trade is one of the core objectives of MIV-2030. Of course, trade forms a significant portion of the Indian economy. In 2020, India's trade-to-GDP ratio was 36.47 percent; at its highest point, in 2012, the trade-to-GDP ratio was 55.79 percent (Macrotrends, n.d.). In order to ensure the long-term security and sustainability of its maritime transport sector, India must make its ports 'future-ready' by making them 'climate-resilient'.

This paper aims to provide a comprehensive overview of the steps and guidelines that need to be followed to develop an exhaustive climate adaptation strategy for seaports in India, based on a discussion of international best practices. To set the context, Section 2.1 highlights the observed and projected impacts of climate change on Indian ports and the urgent need for an adaptation strategy. Of course, the first essential step towards climate adaptation and building climate resilience is a robust 'risk assessment' which must include a study of the climate hazards to a particular region and type of infrastructure, the ways in which the region and infrastructure are exposed to those hazards, and the degree of damage that could potentially be caused by those hazards. Section 2.2 discusses these elements and how they may be determined, through a review of risk assessment frameworks that have been utilised in recent years. Section 3 provides an overview of the current and proposed adaptation measures by ports around the world to enhance their resilience to the impacts of climate change. Section 4 provides a way forward for Indian ports and analyzes how these best practices can be molded-to and utilized-in the Indian context. Finally, the main conclusions of the paper are collated in Section 5.

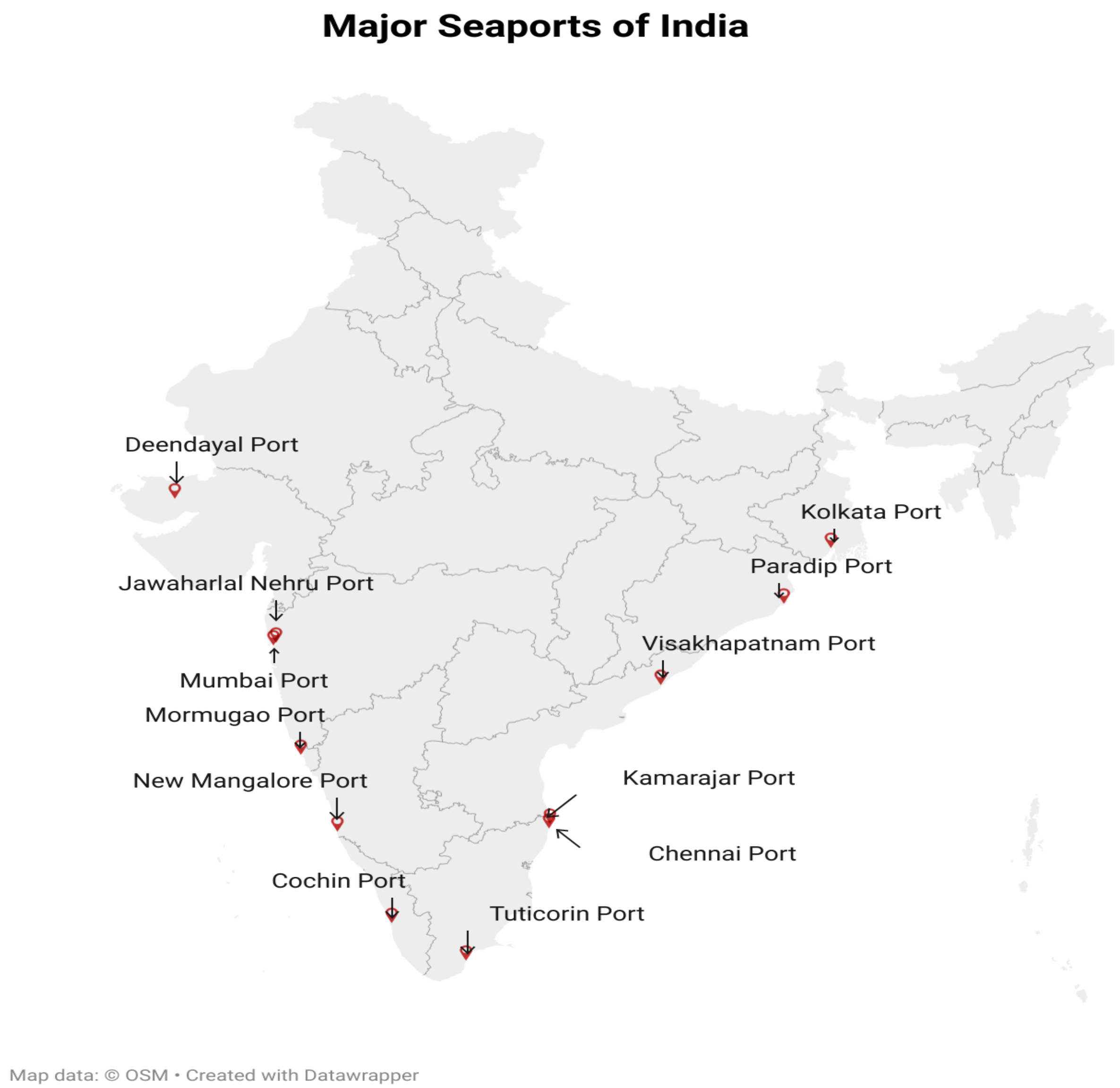

Figure 1: Location of India's 12 major seaports.

2. Literature review

2.1. Impact of climate change on Indian ports

Before assessing the impacts of climate change on ports, it is critical to realize that the influence and interlinkages of ports extend well beyond their physical location. The road and railway networks in the hinterland are just as important for port operations as the maritime shipping network. Industries, small businesses, and local communities, in far-away regions in the hinterland are dependent on the efficient functioning of the ports for their own operations. Several port infrastructure assets, including the support infrastructure and supply chains, and human personnel, are vulnerable to climate-change-induced events such as sea level rise and climate-change-altered events such as extreme precipitation, tropical revolving storms, storm surges, and heatwaves. Flooding due to extreme precipitation or after a cyclone could cause damage to radio and radar equipment, storage facilities, and inundate inland road and rail networks resulting in delay in operations. High speed winds during cyclones could affect loading/unloading crane operations and cause damage to communication and navigation equipment, in addition to generic damage to buildings and warehouses. In many cases, ports halt all operations during cyclonic storms, particularly during severe cyclonic storms, to minimize damage. However, with more frequent and intense cyclones being predicted in the Indian Ocean due to climate change, the average annual economic loss caused by direct infrastructure damage or due to operational downtime, will likely increase in the coming decades. Frequent and more extreme heatwaves and overall increase in high-temperature days could lead to significant increase in energy consumption of cold storage equipment and refrigerated containers, as also for air conditioning of office buildings. Additionally, sustained periods of extreme heat could lead to damage to road and rail infrastructure and affect the health and productivity of human personnel due to harsher working conditions.

In May 2021, when Cyclone *Tauktae* (which made landfall as an Extremely Severe Cyclonic Storm) hit the west coast of India, it caused significant disruptions in operations at the Jawaharlal Nehru Port Trust (JNPT) in Navi Mumbai in Maharashtra. The JNPT is one of the youngest ports and the top container port in India. The port has a 39.54 km long main harbor channel with a draught of 14 km. The container traffic at JNPT constitutes about 50 percent of total container traffic handled by all the Indian Major Ports (around 9 million TEUs) (JNPT, n.d.; Parliamentary Standing Committee on Transport, Tourism and Culture, 2018). Following standard protocols, the port took preventive measures by evacuating most port areas before *Tauktae* made landfall. Only the control rooms at the ports were kept active for monitoring purposes for three days (15 to 17 May 2021). Many vessels which were scheduled to route through the west coast were called off from berthing. JNPT has four dry port or dry dock sites in Wardha, Jalna, Nasik and Sangli that facilitate cargo aggregation in the hinterland away from the port; the roadblocks and cancellation of railway lines during the cyclone led to significant delays for shipping lines. Overall, suspending all the operations at the JNPT resulted in congestion at the port and severely affected the supply chain. Other non-major ports in the areas hit by *Tauktae* were affected even more badly and operations were suspended for several weeks (Shah, 2021). This setback, of course, added to the losses incurred due to the ongoing COVID-19 pandemic which had already caused a slow-down in port operations and disrupted supply chains due to labor shortages and *force majeure* during the global travel restrictions.

Additionally, more erratic and extreme monsoon rains and strong winds, due to climate change, are becoming an annual nuisance for the city of Mumbai and the state of Maharashtra, in general. Frequent, heavy monsoonal flooding also affects port operations. In 2020, during a record-setting monsoon season, Mumbai recorded a total rainfall of over 1,240 mm in the month of August, which was more than double the average rainfall of 585 mm for that month (Pinto, 2020). In the same month, three high-capacity cranes deployed at the JNPT collapsed due to heavy rains and strong winds. However, no injuries or casualties were reported since operations were already halted, and personnel evacuated due to bad weather (Nayak, 2020). The year before that, 2019 also broke several records for monsoon rainfall in Mumbai (Gupta, 2019). Such events are expected to become more common all along the West Coast as climate change continues unmitigated.

In October 2014, Cyclone *Hudhud* hit the coast near Visakhapatnam as an Extremely Severe Cyclonic Storm (ESCS) with a wind speed of 175 km/h, causing extensive damage to the city and its neighboring districts. *Hudhud* was one of the two strongest tropical cyclones of 2014 within the Bay of Bengal (Cheela et al, 2014). Over 250,000 people were affected, and the city of Visakhapatnam suffered billions in damages. Within a few hours of hitting the coast, the cyclone caused significant impacts on the Naval Dockyard, Vizag Steel Plant, Hindustan Petroleum Limited, and other critical assets. An estimated four hundred boats conducting fishing and related activities were damaged and seventy-two were sunk without trace; thirty-eight trains were cancelled on 12 October 2014 (PTI, 2014). Around 2,250 km of roads were damaged, and the total loss incurred by the local industries was estimated to be around INR 100 billion. The Indian Navy suffered economic losses of around INR 20 billion. The estimated damages faced by the Visakhapatnam Port Trust was around INR 3 billion (Singh, 2016). Several port services remained on hold even days after the cyclone. The damages to the road and railway infrastructure caused significant hindrance to the movement of trucks to the port, vital internet services remained unavailable, and consequent supply-chain disruptions posed considerable delays in providing essential services.

These are just a few of the recorded examples of the ways in climate-change-related events are adversely affecting the port infrastructure and operations in India. Unfortunately, the true extent of the damages caused by climatic events to Indian ports cannot be accurately estimated due to the lack of robust data collection, monitoring and reporting in the public domain. Lack of data records is, in fact, one of the major challenges in the efforts to analyse and create awareness about these impacts and the growing trends. According to the 2020 climate change assessment report of the Ministry of Earth Sciences of the Government of India, there has been a significant increase in the number of heavy precipitation events and severe cyclonic storms over India since 1950 (Krishnan et al, 2020). The climate-models-based projections suggest that frequency and intensity of these events are expected to continue to increase throughout the 21st century primarily driven by the warming of the atrmosphere and the ocean which is creating favorable conditions for heavy precipitation events and rapid intensification of tropical cyclones (Sarthi et al, 2014).

2.2. Dimensions of climate risk

The first and most critical step towards any climate adaptation strategy or policy is a comprehensive *'climate risk assessment'*. In the present context, the term *'climate risk'* corresponds to risks or threats, arising as a result of contemporary anthropogenic climate change, to human lives, livelihoods, infrastructure and operations, and natural ecosystems and resources. This definition becomes more and more specific as the scope is narrowed down either in terms of the stakeholders or the specific impacts of climate change or a specific timeline. The Fifth Assessment Report (AR5) of the UN IPCC, released in 2014, laid great emphasis on and attempted to quantify the concept of 'risk' which is crucial for making decisions with respect to managing the effects of climate change (IPCC, 2014). The report described the risk posed by climate change as a combination of *'hazard'*, *'vulnerability'*, and *'exposure'*. Wherein, *Hazard* corresponds to a singular event or a changing trend that could have an adverse impact, *Exposure* corresponds to the elements (people, infrastructure, livelihoods, ecosystems, etc.) that may be exposed to the adverse impacts of the aforementioned hazard(s), and *Vulnerability* corresponds to the degree to which the adverse impacts can cause damage and the lack of capacity to cope with those damages. Almost all climate risk assessment frameworks follow essentially the same general approach to measuring risk, however, they may use different terminologies and they may have different methods to quantify hazards, exposures, and vulnerabilities (Scott et al, 2013; Becker et al, 2018). While global scientific analyses, such as those published by the UN IPCC, provide a broad overview of the major threats arising from climate change at the global scale, what are more relevant for policy-making are the national and local level manifestations of these threats.

All three of these factors and the resultant climate risk vary widely across temporal and spatial scales and depend on a wide range of social, economic, demographic, geographic, cultural, institutional, political, and environmental parameters. These parameters are typically not easily quantifiable. Even if they are quantifiable, they may not be recorded frequently and accurately enough to provide robust insights. This makes rigorous, quantitative climate risk assessment an extremely challenging problem. The task becomes even more difficult when analyzing future climate risks, several decades or even a century into the future, where the number of possible scenarios-of and uncertainties-in climate hazards, exposures, and vulnerabilities, grow exponentially (Wilby et al, 2009; Dickson et al, 2012). Therefore, in many cases, climate risk assessments, instead, rely heavily upon the stakeholders' *'perceptions'* of risk that are typically recorded through a series of surveys/ interviews which are then transformed to a numerical index or to risk-categories to facilitate comparative analysis.

In the context of seaports, climate change risk assessments and adaptation planning are relatively novel areas of research. Most of the literature in the area has come out in the last one to two decades, a majority of that has emerged from the more developed parts of the world (Becker et al, 2012). In an attempt to fill the gaps in data and information availability for risk assessments and adaptation planning, Asariotis et al (2017), under the aegis of the United Nations Conference on Trade and Development (UNCTAD) secretariat, conducted a comprehensive online survey of stakeholders in the port-industry to understand the impacts of climate change and weather-related events on the ports around the world. A total of 44 ports (73 percent of which were located in developed countries), from 29 countries, participated in the survey which comprised questions related to the profile of the port, the history of climate and weather-related events that impacts the ports, the availability of information for a vulnerability assessment, and the level of preparedness. About 70 percent of the ports that participated reported that they had been impacted by climate- or weather-related events in the past, in terms of operations and delays, and some of them also experienced physical damage to infrastructure. A significant number of them indicated that future infrastructure investment plans would consider weather/climate-related factors, however, this result should be interpreted with the caveat that most of the ports that were surveyed were located in developed countries which are better equipped financially and better informed than the developing and least-developed countries. The survey also found that there is a significant lack of data availability in terms of local-level future projections of climatic changes and the port operational and infrastructure design parameters which would play a critical role in adaptation planning.

While the global-level studies/ surveys such as those conducted by UNCTAD provide critical insights into the broader issues and an international perspective, more nuanced risk assessment studies with national- and local-level details are necessary to inform adaptation decisions for individual ports. Nursey-Bray et al (2013), conducted a national-level climate vulnerability assessment of ports in Australia, through a systematic literature analysis and two stakeholder workshops. The authors followed the IPCC-prescribed definition of 'vulnerability' and focused on determining *"(1) real or potential [climate change] impacts on the system [the port ecosystem]; (2) the systems' ability to cope and adapt to these impacts; and (3) the extent to which coping capacity may be constrained by environmental or societal conditions."* The participants in the workshops comprised ports managers, workers and administrators within Australia's port-industry. The workshops were also supported by a survey questionnaire before and after the workshop to gather the participants opinions on how climate change has and will affect the ports. Based on the literature review, the broader impacts of climate change on ports were divided in five key areas: (1) Environmental impact, (2) Infrastructure, (3) Ports and people, (4) Occupational health and safety impacts, and (5) Supply chain impacts. The expert surveys were then used to assess the "the ability of the systems to cope and adapt to these impacts", and the constraints that may limit the ability to build adaptive capacity as seen by the port authorities. As one would expect, the study found that while all ports will indeed be affected by the impacts of climate change, the vulnerability varies significantly between the different sections of port infrastructure and operations. Importantly, the surveys revealed that most port authorities displayed high levels of confidence in their ability to adapt to the ongoing and projected changes. The authors called for a standardized national-level framework which can be applied to individual ports to assess the climate vulnerability of Australia's port infrastructure. The semi-quantitative yet robust methodology of the study provides a blueprint for researchers in other countries on how to break down climate vulnerability into its critical components and systematically evaluate it through perception surveys.

Port-specific case-studies have also been conducted in the recent past. To mention a few, Stenek et al (2011), published a comprehensive climate-risk assessment report, including financial impacts estimates and suggested adaptive measures for the Terminal *Maritimo Muelles el Bosque* (MEB) in Colombia. The authors categorized the impacts across a wide range of operational, financial, reputational, legal, environmental and social categories and across different future climate change scenarios. The study was accomplished through a combination of desk-research and modelling, and discussions with the port authorities, local government and climate change experts. The study also laid great emphasis on the interdependencies between the port operations and hinterland industrial activities and local businesses. Following a similar methodology, Cox et al (2013), conducted a climate risk assessment for the Avatiu port in the Cook Islands. Building upon previous studies the authors took specific steps to address the interconnectedness of port operations with the broader city infrastructure and included multiple stakeholders for a more holistic assessment. Messner et al (2013), used the port of San Diego as a case study to understand the impacts of climate change, sea level rise in particular, on ports and provided an evaluation framework for risk and vulnerability; Chettri et al (2013), also studied the impacts of sea level rise on port infrastructure and operations using Port Kembla in New South Wales as the case-study. All of the aforementioned vulnerability/ risk assessment studies utilize some combination of 'desk-research' and 'expert interviews/ surveys' or 'stakeholder workshops'. The ratio of this combination may vary significantly depending on accessibility of data and port personnel. As discussed later in Section 5, expert interviews/ surveys become particularly relevant for developing countries, such as India, where robust, long-term data records may not be available.

It is important to remember that at the national or regional level all the ports taken together form the larger maritime transport network of a country. By corollary, it is also true that some ports may be more critical to the broader maritime sector than the others. Arguing for a holistic, multi-port approach to climate risk assessment and adaptation planning, McIntosh and Becker (2017) stated that *"At the single port scale, decision makers such as port managers may consider the uninterrupted functioning of their port the number one priority. But, at the multi-port (regional or* *national) scale, policy-makers will need to prioritize competing port climate-adaptation needs in order to maximize the efficiency of limited physical and financial resources and maximize the resilience of marine transportation system as a whole."* Towards this end, the authors highlighted the lack of multi-port assessment studies and provided a critical review of the few indicator-based multi-port vulnerability assessments that have been published in recent years. The 'indicators' used in such studies typically include quantifiable, observable quantities, for instance, projected sea level rise, storm surge level, value of port assets, port efficiency measures such as turnaround time, etc., that can collectively be used to determine the vulnerability or risk of the system. One of the limitations of indicator-based assessments at multi-port level is the fact that the indicators need to be generic enough that they can be applied to all ports under consideration. While this may allow for a comparative analysis to be conducted which would generate a relative ranking of the ports according to their risk level, it limits of the scope of the indicators which may lead to an incomplete assessment of the risk. Nonetheless, a standardized approach to multi-port assessment would be highly relevant for India, since India has 12 major and over 200 non-major ports, and more ports are being planned under the central government's long-term development plans. Considering the limited financial and technological capacity of the country, it would have to prioritize the more vulnerable ports in the adaptation plans which would require a comparative multi-port assessment.

3. State-of-the-art in climate adaptation measures for seaports

With growing literature and increased awareness of the ways in which climate change impacts will affect coastal regions, coastal state/ city planners are increasingly acknowledging the need for implementing adaptive measures to minimize damages to infrastructure. However, in the port industry very few ports globally have actually taken appropriate adaptive measures (Becker et al, 2018). Some studies have noted that this could partly be attributed to the difference in timeframes of port planning activities, which typically ranges between 5-15 years and the timeframes in which climate change impacts play out which could be over multiple decades, particularly in the case of sea level rise (Becker et al, 2012; Scott et al, 2013). This myopic approach to infrastructure planning is, of course, a hinderance to climate adaptation planning in all sectors and at all levels of governments. In almost all cases, the critical maritime transport infrastructure has a lifetime of many decades and therefore their planning and maintenance processes must ensure resilience to medium- and long-term threats arising from climate change.

A wide range of adaptation measures for seaports have been proposed, analyzed, and some have been implemented, in recent years. Adaptation measures could range from 'soft measures' such as changes in standard operating procedures, adaptation policies, emergency preparedness exercises, generating more accurate local-level climate projections, etc., to 'hard measures' which include infrastructural changes such as building seawalls/ storm surge barriers, expanding the dimensions of breakwaters, upgrading drainage systems, increasing elevation of infrastructure, etc., and everything in between. In this context, the city of Rotterdam in Netherlands provides an example of a holistic approach. The city set up the "Rotterdam Climate Proof (RCP)" programme, as part of the broader "Rotterdam Climate Initiative" of 2008, which aims to make Rotterdam resilient to climate change by 2025 while simultaneously generating opportunities to make the city more attractive (Rotterdam Climate Proof, 2010). The RCP is focused on five major aspects- flood management, accessibility, adaptive building, the urban water system and the urban climate. The RCP has laid specific emphasis on knowledge sharing, creating awareness, and promoting innovation in science and technology. The city founded the "Connecting Delta Cities" knowledge network, in 2009, as a part of its initiatives under the C40 climate leadership group. Some of the members of the knowledge network include Tokyo, Jakarta, Hong Kong, New York, New Orleans, London, Ho Chi Minh City, Melbourne, and Copenhagen. In 2021, the Port of Rotterdam Authority and the Municipality of Rotterdam jointly launched the "Flood Management Adaptation Strategy Programme" to protect the port and associated industries from the impacts of climate change including sea level rise, storm surges and increased likelihood of tidal flooding (Port of Rotterdam, 2021).

The Port Authority of New York and New Jersey (PANYNJ) had integrated climate change mitigation and adaptation into their environmental sustainability policy in 2008 which recognized safety, resilience and environmental sustainability as its primary objectives. In 2009, the PANYNJ Engineering Department released the Climate Resilience Design Guidelines that demand climate risk factors to be incorporated into the design and construction of ports' buildings and other infrastructure. The design guidelines were further updated in 2015 and again in 2018 (PANYNJ, 2018a). The Port Authority completed the climate risk assessment focusing on flood-related risks across all port facilities in 2020. The follow-up multi-year programme was initiated in 2021 focusing on applying rigorous, engineering-based assessment techniques at the local level. Notably, the PANYNJ was the first public transportation agency in the USA that promulgated carbon emissions reduction targets to align themselves with the goals of the 2015 Paris Climate Agreement. It made commitments to reduce its carbon emissions by 35 percent by 2030 and by 80 percent by 2050 (PANYNJ, 2018b).

The city of Kaohsiung in ROC (Taiwan) which hosts the Port of Kaohsiung, ROC's largest international port, is highly vulnerable to the impacts of climate change including rising temperatures and frequent bouts of extreme weather events. In response to these growing threats, a number of measures have been taken by the city to enhance the resilience of its physical and social infrastructure, including large-scale restoration of wetlands to protect its coastline, upgrades to water management and drainage systems to mitigating urban flooding, construction of energy efficient 'green buildings', among others (Urban Climate Adaptation, 2019; Lai, 2012). Notably, the Port of Kaohsiung received the 2021 World Ports Sustainability Program (WPSP) award for Resilient Physical Infrastructure. In Australia, several ports have undertaken extensive climate risk assessment studies in recent years and incorporated measures to mitigate socio-economic damages from the impacts of climate change. For instance, the Port of Melbourne adopted corporate climate change policy in 2007, a climate change action strategy in 2009 and became a signatory to the World Ports' Climate Declaration (Ng et al, 2013). Other ports in Western Australia, Northern Territory and New South Wales have taken adaptive measures against flooding from cyclonic storms and sea level rise (Scott et al, 2013).

The city of Jakarta in Indonesia is one of the largest coastal megacities in the world which is also considered to be one of the most vulnerable cities to coastal flooding, large parts of the city are already below sea level. Studies have shown that the primary cause for increasing flooding events in Jakarta is land subsidence being caused mainly by unsustainable and unmanaged extraction of groundwater for various industrial and domestic purposes (Ng et al, 2012; Chaussard et al, 2013). The extent and frequency of coastal flooding will be worsened by accelerating sea level rise in the coming decades. According to model-based projections, the potential flood area extent is estimated to increase by 110.5 sq km by 2050 relative to 2000 levels (Takagi et al 2016a). The simulations also indicated that the rate of flood area expansion during the 2025-2050 would be 3.4 times faster than that in the 2000-2025 period.

The ports of Jakarta are severely affected frequently by tidal floods and storm surges. The Sunda Kelpa port is the oldest port in Jakarta spanning 52 hectares of land area. Some estimates suggest that the port is currently experiencing 5-10 cm of land subsidence per year, over the last two decades. According to port authorities, around 20 percent of the annual income is spent on adaptation measures including protective dikes and raising the elevation of port infrastructure which is being done in a section-by-section manner (Esteban et al, 2020). Similarly, the Pelabuhan Perikanan Samudera Nizam Zaham port which is the largest fishing port in Indonesia is experiencing 7-12 cm of subsidence annually. Consequently, the port elevation was raised in 2002 and then again in 2012 by +1.4 m. The Muara Angke port was also raised three times, in 2006, 2011 and 2014, by 40-50 cm each time using sheet piles (Esteban el al, 2020). Other studies have argued that the protective dikes that have been built are themselves vulnerable to sea level rise and increased frequency and intensity of tropical storms (Takagi et al, 2016b). Moreover, measures such as increasing the elevation of port infrastructure are akin to "band-aid solutions", and very expensive ones at that, which focus on short-term adaptation rather than increasing long-term resilience of the infrastructure.

4. Molding to the Indian circumstances

As alluded to before in Section 1, India has initiated a number of measures in recent years to expand its maritime transport sector and the broader Blue Economy. There is one thing that is common across all of these initiatives, that is the overwhelming emphasis on capacity augmentation and modernization. While that is commendable and necessary for economic growth, it is crucial to acknowledge and prepare-for current and projected threats arising from the impacts of climate change which may otherwise derail the ambitious expansion plans. There is an urgent need for a holistic and dynamic climate change adaptation strategy to ensure the protection and continued operation of the existing and planned port infrastructure. Clearly, this adaptation strategy will have to be based on a series of risk assessment studies at the national-, state- and local-levels. In this regard, the amount of literature in India is relatively sparse. For the first time in 2020, a comprehensive ‘climate change assessment report’ for India was published by the Ministry of Earth Sciences (MoES) (Krishnan et al, 2020). This much-needed report highlighted the observed and future projections of temperature, precipitation, sea level, extreme weather events and the Indian monsoon system, among other parameters, over the Indian region. In 2021, the Department of Science and Technology of the Government of India published a report entitled, *“Climate Vulnerability Assessment for Adaptation Planning in India Using a Common Framework”*, which mapped all-India state-level and district-level vulnerability to climate change (DST GoI, 2021). However, the report provided an incomplete picture because it was solely focused on determining vulnerability based on an analysis of the current state of infrastructure and state- and national-level policies. The report did not account for the current and projected evolution of climate-change related *‘hazards’* and the level of *‘exposure’* of the districts and states, which are necessary for quantifying *‘risk’*. The authors acknowledged this caveat and mentioned that additional studies will be conducted on these aspects in the future.

This lack of robust and reliable long-term data records and analyses of climate variables and local-level climate projections poses a major hurdle towards a quantitative climate risk assessment of ports in India. As discussed in Section 3, this limitation is often remediated, at least partially, by conducting interviews and workshops with domain experts and stakeholders to collect qualitative information-on and perceptions-of risk to infrastructure and operations. Insofar as adaptation measures are concerned, India would have to work within the national financial and technological limitations which may preclude the possibility of adopting the cost-intensive hard infrastructure solutions that have been adopted by the more developed cities/ countries, such as Rotterdam, some of which were discussed in Section 4. Consequently, India would have to utilize a creative combination of hard- and soft-measures, in other words, a combination of capacity building (that is the generation of material wherewithal) and capability enhancement (that is enhancing the human ability to manage the impacts), to build resilience against climate change.

Considering the national circumstances described above, the following interventions are recommended for policy makers in India at the national- and state-level governments to enhance the resilience of the country’s port infrastructure:

a) Conduct comprehensive climate risk assessments of India’s major and non-major brownfield ports, including asset- or area-specific details, in consultation with all relevant stakeholders including climate scientists, engineers, port authorities, local government officials, industry members, local businesses, and local community members including the fisherfolk. This could be incorporated as an actionable under the ‘port-modernisation’ goal of the Maritime India Vision 2030 (MIV-2030) to ensure security and continued functioning of existing ports. Additionally, preemptive climate risk assessments and adaptation planning for the current and projected impacts of climate change should be mandated for all greenfield projects proposed under MIV-2030.

b) A standardised framework is needed which can be applied to all ports to produce a comparative analysis of climate risk, which could then be compiled into a national-level assessment of the broader maritime transport sector of the country. This would allow the central and state governments, private entities, and port management authorities to identify the most vulnerable ports and the most vulnerable sections or assets within individual ports which should be prioritised for adaptation actions.

c) As discussed in Section 4, climate change adaptation measures for ports could include ‘hard measures’ or ‘soft measures’ or a combination of the two. Due to limited financial resources in India, hard measures (which may include creation of protective infrastructure or retrofitting or relocating existing infrastructure) would require cost-benefit analyses to be conducted to identify the most viable options. Nature-based protective solutions such as creation of coastal dunes, conservation and plantation of mangrove forests, etc., should be seriously considered, in combination with the man-made protective infrastructure, which would provide cost-effective ways to reduce the impacts of floods and storm surges. The protection and conservation of such ecosystems would also provide additional ecological and socio-economic benefits for coastal regions. Conservation efforts are already being pursued by some of the coastal states in India; these efforts could be integrated with port planning and development to maximise the benefits.

d) Since ports form integral components of the city, state, and country's economy, and are inextricably linked with hinterland activities, there is a need for greater cooperation at these levels to generate a cohesive adaptation strategy. For instance, the resilience (or the lack of resilience) of hinterland road and railway networks, energy infrastructure, fisheries infrastructure, and other industries, against climate-change-induced hazards would have direct consequeces for port operations and efficiency. Therefore, city-wide or state-wide adaptation strategies that address the broader socio-economic systems would have to be developed accordingly. The examples of New York and New Jersey in the USA and Kaohsiung City in ROC discussed in Section 4 provide insights into combined port and city climate adaptation strategies that have been attempted.

e) Importantly, the adaptation strategy must account for the dynamic nature of climate change. The impacts of climate change are expected to continue to grow at an accelerating rate even in the more optimistic future scenarios. Moreover, there are new phenomena that are being discovered constantly that challenge our past predictions, especially with regard to sea-level rise and the intensification of extreme weather events. Therefore, the adaptation measures cannot be short-sighted, one-time efforts but should leave room for further changes and updates as we learn more about these natural processes and their interactions with human activities. This is also important because protective measures that involve construction of hard-infrastructure such as seawalls, breakwaters or support structures to increase the elevation of port infrastructure are capital- and time-intensive and, therefore, require careful planning to ensure long term sustainability. Along the same lines, it is necessary to put in place mechanisms for monitoring and evaluation of the adopted measures and re-assess the risks at regular intervals, every five to ten years. Devising and implementing a holistic and dynamic climate adaptation strategy for seaports will not only ensure a secure and sustainable maritime transport sector but also facilitate India's ambitions of becoming a leading Blue Economy of the world.

f) Finally, it must be recognised that some regions may be beyond adaptation and would be completely inundated by sea level rise in the coming decades. In India, this is particularly relevant for the Bay of Bengal region and the Sundarbans delta in particular which is experiencing a much faster rate of sea level rise than the global average due to a combination of geographical and anthropogenic factors. The ports in such regions would have to be systematically decommisioned or relocated to other regions. Therefore, planned retreat should also be considered as an adaptation action that may become increasingly necessary in the future.

5. Conclusion

As global warming continues unabated, the knock-on effects of rising atmospheric and oceanic temperatures such as more frequent and intense extreme weather events (heatwaves, heavy precipitation and tropical cyclones) and accelerating sea level rise pose major threats to coastal regions around the planet. For the maritime trade sector, these climatic changes will have direct impacts on the port infrastructure and the ability of the ports to maintain maximum operational efficiency. As discussed in detail in the paper, in India, more frequent extreme weather events are already affecting port operations which lead to downtime ranging from a few hours to several days. Collectively, these operational downtimes can add-up to major economic losses for the country. In the coming decades, climate-change-induced sea level rise will significantly worsen the impact of cyclonic storms and tidal flooding and will emerge as an irreversible threat to the port infrastructure. Adapting brownfield ports to sea level rise may require significant modifications to the existing infrastructure (such as raising elevation) or building protective infrastructure such as breakwaters or storm surge barriers, all of which will require long-term planning and huge financial costs.

While India has taken several measures in recent years to expand its maritime sector, there are no national- or local-level strategies to protect the port infrastructure and operations against the growing impacts of climate change. A stark example of this is the lack of emphasis on climate change adaptation in the Maritime India Vision 2030 which is the guiding document from the Ministry of Ports, Shipping and Waterways for the maritime trade sector for the next decade. In this context, this paper highlights the need for a holistic and dynamic climate change adaptation strategy for India's port ecosystems and provides recommendations for a way forward based on a comprehensive literature review of international best practices. The adaptation strategy must be built upon rigorous and comprehensive climate risk assessments of the ports and interdependent supply chains to determine the internal and external vulnerabilities to the impacts of climate change. A standardized national-level risk assessment framework would be critical to conduct a comparative vulnerability analysis of India's major and non-major ports to identify the most vulnerable ports which may require priority action from the central government (in the case of major ports) or respective state governments (in the case of non-major ports).

Moreover, considering the dependencies of the port on the broader city activities and vice versa, the adaptation strategy must take an integrated approach and incorporate the needs and limitations of all stakeholders including the city authorities, industries, local communities and businesses. As discussed in the paper, the ideal adaptation strategy should be based on a combination of infrastructure-level and operational-level solutions which considers not only capacity-building but also capability-enhancement measures. Devising and implementing a holistic and dynamic climate adaptation strategy for seaports will not only ensure a secure and sustainable maritime transport sector but also facilitate India's ambitions of becoming a leading Blue Economy of the world.

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