ARE
ASIA RESEARCH
& ENGAGEMENT

Climate Costs for Asia Pacific Ports

March 2018

Ben McCarron

ben.mccarron
@asiareengage.com

Commissioned by

HSBC

Sustainable Investment Consultants

We integrate sustainability and governance considerations into risk processes for investors, banks, and companies. Clients benefit from a network of partners and researchers across Asia that provide analysis of the financial relevance of these issues. ARE also represents GRESB in Asia ex-Japan, which provides sustainability benchmarks for investors in real estate and infrastructure.

Authors: Benjamin McCarron, Andrea Giunti, and Serena Tan CFA
Research: Jeehee Moon
Design: Shibao Pek

Commissioned by

HSBC

Foreword

Climate change is one of the foremost challenges of our times. Atmospheric concentrations of greenhouse gases rise with each passing year, bringing with them a trend of continuous temperature records – 2017 was the warmest year ever (in the absence of El Niño). It was also a year in which the importance of addressing climate change became even clearer. Extreme events such as floods, storms, and wildfires caused physical and social devastation across many parts of the world – the severity of many of these events was magnified by climate change.

Much more effort is required to close the emissions gap – the gap between our emissions trajectory today and the necessary pathway to put us on track to limit temperature rises to within (or well below) 2°C by century end. With almost every country having joined the Paris Agreement, their next task is to implement their climate pledges – which not only include reducing emissions, but also preparing for the consequences of climate change by building up physical (and social) resilience.

In their Fifth Assessment Report, the scientists of the Intergovernmental Panel on Climate Change (IPCC) provide details of the possible impacts across Asia – these include extreme weather, rising sea-levels, higher storm surges and damage to infrastructure. As we progress through this century, the urgency to act grows more apparent – the IPCC clearly states that waiting is not an option: “Adaptation and mitigation choices in the near-term will affect the risks of climate change throughout the 21st century.”

China’s Belt and Road Initiative aims to increase infrastructure investment and promote cross-border trade on land – the ‘belt’ that connects China, Central Asia, Russia and Europe – and by sea, the ‘road’ that links China to South-East Asia, India and Africa. This initiative highlights the importance of sea-ports and the surrounding trade links. Just as important as building the correct links is ensuring that they stand the test of time. Embedding resilience to climate change within these structures is paramount.

The suggested steps in this study by ARE offer sea-ports a place to begin as they prepare themselves for a warmer future along the Belt and Road. This report is designed to start conversations – amongst those who use and finance sea-ports in Asia – by asking the first question: “Are you ready for climate change?”

Wai-Shin Chan, CFA
Global Head, HSBC’s Climate Change Centre of Excellence

March 2018

Contents

Climate Costs for Asia Pacific Ports

- **Climate change is leading to rising sea levels and greater storm intensity, creating risks for coastal infrastructure, including the ports across Asia Pacific that underpin global trade flows**
- **Financial backers for new infrastructure, such as projects related to the Belt and Road Initiative, should ensure that projects have built climate projections into asset development and long-term capital plans to avoid facing such costs in the future**
- **We estimate a potential cost of between US$31 billion and US$49 billion to protect and elevate 53 of the region's largest port areas to adapt to climate related risks**

Asian ports: critical for global trade, vulnerable to climate risk

Trade accounted for 58% of Global GDP in 2015[1] with global seaborne trade volumes exceeding 10 billion tons.[2] The ports in Asia are particularly important for the global economy, occupying nine of the top 10 spots in terms of capacity. Climate change raises long-term risks to such coastal infrastructure from rising sea levels and increased storm intensity.

Port adaptation could cost US$31 billion to US$49 billion

This report is designed to raise awareness of climate change related risks to port infrastructure in Asia, quantifying the potential costs to rebuild and adapt ports to climate change. The first-order approximation of US$31 billion to US$49 billion to rehabilitate 53 of Asia's largest ports serves to bring about discussion with the various stakeholders such as port authorities, port owners and financiers, and governments.

Table 1 shows cost estimates for the 10 largest ports by capacity. Although they are in eighth and tenth place for capacity, the South Korean ports of Gwangyang and Busan have the highest and third highest cost estimates from this list. This is due to the presence of larger warehouse areas and relatively higher construction costs in Korea compared to China. Japan has relatively smaller ports, which do not feature in this list. The full cost breakdown for the ports is included in Table 4 in the section on findings.

1 World Bank (https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS)
2 UNCTAD, *Review of Maritime Transport 2016*

Table 1: Potential adaptation costs of top ten Asian ports by capacity

Port Area	Market	Capacity (mt)*	Cost to adapt - Low case (US$ million)	Cost to adapt - High case (US$ million)
Shanghai	CH	647	378	613
Singapore	SG	576	1,081	1,293
Qingdao	CH	476	509	1,006
Guangzhou	CH	475	430	739
Port Hedland	AU	453	132	151
Ningbo	CH	449	323	467
Tianjin	CH	440	680	1,525
Busan	SK	348	940	1,488
Dalian	CH	321	322	447
Guangyang	SK	272	1,614	3,564
TOTAL		**4,457**	**6,409**	**11,293**

** Note that different measures are used to assess port capacities (metric tons, revenue tons, and freight tons)*
Source: ARE cost estimates, capacity from American Association of Port Authorities

Recommendations

We hope asset owners, governments and financiers will accelerate dialogue on climate change effects

We undertook this study to contextualise the costs for protecting Asia Pacific ports from future climate realities. The objective is to encourage port owners and operators and the banks and investors that finance them to factor the long-term implications of climate change into decision making for their port development plans.

Suggested steps include:

- Develop scenarios and projections relating to climate parameters including sea level, storm intensity/surges, wind speeds, and temperature variability
- Evaluate safety margins for current infrastructure, including current height of the yards above sea levels
- Ensure that further upgrades factor changes in parameters across intended project design life, applying risk-based thinking
- The design of new port assets should take into consideration climate change and its impact on sea level and storm surges
- Where near terms costs prohibit adaptation, ensure that infrastructure can be upgraded in future
- Engage with local and state government to coordinate approaches to managing the physical effects of the changing climate

This report focuses on the steps that are rational for port operators to take on their own. In many cases, the physical issues will be relevant to many economic activities along the neighbouring coastline. Consequently, governments, both local and national, will need to think about broader solutions and about rational ways to share costs among the different parties that need enhanced coastal defence and flood protections. We hope that the cost projections provided in this report, which are based on first order assumptions, spur and support decision making through providing context for at least for one major asset class. We welcome further discussion with key decision makers.

Chapter 1: Findings

In this report, we provide an estimate of the capital cost to elevate 53 of the largest Asia Pacific ports to climatic conditions expected between 2070 and 2100. We provide findings on three levels: the overall estimate by modelling scenario (Table 2); the geographic breakdown (Table 3); and the estimates for each port (Table 1 shows the top 10 ports by capacity and Table 4 provides detail on all the ports).

1.1 Cost estimate range

It is not much more expensive to adapt to an aggressive climate scenario than a moderate one

We modelled costs for two climate scenarios using two sets of engineering assumptions. The climate change scenarios are based on modelled greenhouse gas concentration trajectories RCP 4.5 and RCP 8.5 with further assumptions for sea level height and storm intensity (see the climate modelling section). Climate scenario 1 corresponds to an increased sea level height of 1.6m and Climate scenario 2 corresponds to a 2.3m elevation. As fixed costs are high, the more aggressive climate scenario resulted in only 4-5% higher adaptation costs.

Costs are more sensitive to engineering assumptions than climate scenarios

We provide two sets of engineering assumptions, A and B. These assume respectively that only 10% and 30% of the building and warehouse areas will be elevated. We inserted these limits as elevating or rebuilding large areas becomes impractical and costly. The engineering assumptions resulted in a wider estimate range with the high-cost assumptions leading to total cost estimates more than 50% higher than the low-cost assumptions.

We use Climate scenario 1 with Engineering assumptions A as our low case and Climate scenario 2 with Engineering assumptions B as our high case. These sets of assumptions produce a low case cost of around US$30.9 billion and a high case cost of around US$49.4 billion to adapt 53 of Asia Pacific's largest ports to changing climate conditions.

Table 2: Adaptation cost estimates for varying sets of assumptions (US$ billion)

	Climate scenario 1	Climate scenario 2
Engineering assumptions A	30.9	32.3
Engineering assumptions B	47.4	49.4

Source: ARE

Early planning makes economic sense

These estimates highlight the additional costs required to adapt ports to the climate change scenarios. In general, it will be considerably cheaper to build a port with a greater height than to elevate it later.

Ports in developed countries are far more expensive to adapt

The models show a wide range of costs. The high case assumptions show Indonesia's Cilacap as the cheapest port to adapt for climate change at US$65 million, while Japan's Kitakyushu is the most expensive at US$4.9 billion. The detailed cost estimates are shown in Table 4.

The cost estimates can also be compared to costs to build a new port. Yangshan Port, a port in Shanghai, cost US$18 billion to build, according to a *New York Times* article. The estimated high case port adaptation cost of US$613 million represents 3.4% of the construction cost.

On the other hand, Singapore is currently building phase 1 of the Tuas terminal at a projected cost of US$1.8 billion. The estimated high case costs of US$1.3 billion to adapt the port is equivalent to 19% of the full new Tuas terminal costs.[3] In practice, the port may not face these costs in future for physical and regulatory reasons. First, Singapore does not suffer from intense storms in the same way as other ports. Perhaps more importantly the Singapore government has already shown awareness of the challenge of rising sea levels, for instance in raising the height requirements for reclaimed land as early as 2011.

1.2 Geographic splits

Mainland China ports account for the largest area, however, their adaptation costs are lower than those for Japan, which has the second largest port area in the study. The average all-in cost of construction in Tokyo is more than 4.8 times that for Beijing. This is because Japan has much higher material and labour costs in US dollar terms (as per Turner and Townsend estimates, see Appendix 2) and a higher proportion of buildings and warehouse areas, which are significantly more expensive to elevate than yard areas. Similarly, total adaptation costs for the main ports in South Korea are only a little below those of China despite a much smaller port area (about 15% of China's). In this case, the proportion of the warehouse areas is 17% compared to 3.8% in China and the construction costs for warehouses are about three times as much, compounding the effect on total costs.

3 It costs US$1.8b to build phase one of the new Tuas port (size 2.94 km^2). Assuming the total size of the new Tuas port will be the same as the current ports in Singapore at 11km^2, it will cost US$6.7b (US$6.7b = 11 km^2 / 2.94 km^2 x US$1.8b) to build the new port. The adaptation cost estimate of US$1.3b is 19% of the new port cost.

Table 3: Estimated port adaptation costs by market

Market	Cost to adapt - Low case (US$ billion)	Cost to adapt - High case (US$ billion)	Total port area (km²)	Container yard area (km²)	Warehouse area (km²)	Average cost per km² - Low case (US$ million)	Average cost per km² - High case (US$ million)
Japan	13.8	23.3	183	90	29	75.3	127.5
China & HK	5.2	8.5	610	173	23	8.5	14.0
South Korea	4.2	8.0	94	33	16	44.7	85.0
Australia	2.5	3.1	75	20	1.4	33.4	41.5
Taiwan	1.1	1.8	19	11	2.9	57.6	94.3
Singapore	1.1	1.3	11	7	0.7	98.3	117.5
India	0.9	1.0	9	5	1.5	101.0	114.8
Malaysia	0.7	0.8	14	9	1.3	50.9	59.3
Others	1.4	1.5	18	12	2.2	76.9	84.5
TOTAL	**30.9**	**49.4**	**1,033**	**360**	**78**	**29.9**	**47.8**

Note: Values do not sum to total due to rounding.
Sources: ARE calculations; World Port Index database, the U.S. National Geospatial-Intelligence Agency; Google Earth Pro; Turner and Townsend, International Construction Market Survey, 2017

1.3 The full list of ports

Japan has the costliest ports to adapt due to warehouse area/ local construction prices

Table 4 below shows the cost estimate of each port area and its corresponding estimated size. Ports size ranges from 1 km² to 319 km², the largest being Qinghuangdao port in China. The total cost estimates depend on the size of warehouses relative to the size of yards. The costs of constructing buildings range from 2.5 times the costs of constructing yards per cubic meter in Australia to 13.6 times in Singapore. Hence, the costliest harbours to adapt to climate change are those with higher warehouse-to-area ratios, such as Onomichi-Itozaki and Nagasaki ports in Japan. Detailed assumptions of the construction costs can be found in Appendix 2.

Costs relative to harbour size are most expensive in developed countries in the region such as New Zealand, Russia, Japan and Singapore at more than US$100 million per square kilometre. Surprisingly, costs per kilometre square in India are almost as high as in more developed countries in Asia, due to warehouses accounting for a large proportion of port area.

Table 4: Port cost estimations

Note: Areas were identified by visual inspection and may not correspond to the legal area owned or managed by a port authority or operator

		Low case			High case		
Harbour	**Area** *km²*	**Warehouse** *US$ m*	**Yards** *US$ m*	**Total** *US$ m*	**Warehouse** *US$ m*	**Yards** *US$ m*	**Total** *US$ m*
Australia	***75***			***2,504***			***3,113***
Brisbane	7	178	186	423	178	266	518
Dampier	20	28	143	214	28	221	306
Fremantle	2	67	129	234	67	156	269
Gladstone	2	8	54	117	8	62	139
Hay Point	34	230	215	493	230	396	693
Melbourne	3	147	162	378	147	210	443
Newcastle	1	70	56	153	70	64	166
Port Hedland	5	8	103	132	8	118	151
Sydney	3	127	149	360	127	194	427
China & HK	***610***			***5,211***			***8,514***
Caofeidian	228	269	101	443	473	2277	817
Dalian	18	183	86	322	215	159	447
Guangzhou	26	232	111	430	363	247	739
Hong Kong	7	589	154	911	589	263	1,061
Huanghua	81	178	74	291	201	134	387
Ningbo	17	188	83	323	230	164	467
Qingdao	53	260	152	509	447	401	1,006
Qinhuangdao	10	74	51	155	74	78	191
Shanghai	26	192	118	378	243	271	613
Shenzhen	20	188	96	363	231	211	553
Tianjin	101	330	229	680	657	652	1,525
Xiamen	23	233	103	406	367	234	708
India	***9***			***909***			***1,033***
Chennai	1	34	55	106	34	63	117
Kolkata	3	243	70	350	282	85	411
Mumbai	1	50	40	105	50	45	113
Nhava Sheva	2	26	62	106	26	81	130
Vizag	2	140	73	242	140	88	261
Indonesia	***8***			***339***			***383***
Cilacap	2	42	14	62	42	16	65
Jakarta	6	170	54	277	170	82	318

Harbour	Area km²	Low case Warehouse US$ m	Low case Yards US$ m	Low case Total US$ m	High case Warehouse US$ m	High case Yards US$ m	High case Total US$ m
Japan	***183***			***13,783***			***23,328***
Chiba	56	4,733	685	2,701	4,733	685	6,158
Kawasaki-Yokohama	39	2,812	620	1,902	2,812	620	3,871
Kitakyushu	37	3,869	549	2,260	3,869	549	4,949
Kobe	8	834	239	1,036	834	239	1,254
Mikawa	2	485	78	617	485	78	631
Nagasaki	2	828	116	937	828	116	1,049
Nagoya	27	1,215	629	1,274	1,215	629	2,066
Onomichi-Itozaki	1	771	53	856	771	53	911
Osaka	4	778	156	949	778	156	1,060
Tokyo	4	777	150	946	777	150	1,052
Wakayama	2	195	89	306	195	89	327
Korea (South)	***94***			***4,201***			***7,992***
Busan	18	622	157	940	918	335	1,488
Gwangyang	52	1,220	202	1,614	2,709	471	3,564
Incheon	2	245	71	354	245	81	367
Ulsan	22	943	178	1,292	1,880	389	2,573
Malaysia	***14***			***713***			***830***
Klang	9	247	68	365	258	110	430
Tanjung Pelepas	5	247	60	348	260	92	400
New Zealand	***1***			***179***			***203***
Auckland	1	19	50	98	19	57	114
Wellington	0	26	41	80	26	47	89
The Philippines	***6***			***504***			***545***
Cebu	1	132	34	186	132	38	192
Manila	4	218	56	318	218	82	352
Russia	***2***			***220***			***545***
Vladivostok	2	96	85	220	96	99	241
Singapore	***11***			***1,081***			***1,293***
Singapore	11	791	122	1,081	866	217	1,293
Taiwan	***19***			***1,094***			***1,792***
Kaohsiung	18	700	149	949	1,151	315	1,632
Keelung	1	64	51	145	64	58	160
Thailand	***2***			***143***			***150***
Bangkok	2	89	38	143	89	43	150
TOTAL	**1,033**	**27,437**	**7,646**	**30,880**	**31,919**	**10,986**	**49,417**

Sources: ARE calculations; World Port Index database, the U.S. National Geospatial-Intelligence Agency; Google Earth Pro; Turner and Townsend, International Construction Market Survey, 2017

Chapter 2: Developing a cost model

The main assumptions are climate change scenario and engineering approach

The estimation process required assumptions to address three linked questions: how weather patterns will change; what engineering solutions ports can use to address these; and what the solutions will cost. This section presents answers to these questions in the form of climate scenarios and engineering assumptions, before looking at the more detailed modelling methodology. Our engineering models draw on an approach set out in the Stanford paper *Estimation of Cost Required to Elevate US Ports in Response to Climate Change: A Thought Exercise for Climate Critical Resources*.

2.1 Climate assumptions

Greenhouse gases pose threats to ports through increased sea levels and stronger storms

Greenhouse gases trapped in the earth's atmosphere absorb and emit radiation in the thermal infrared range, causing the greenhouse effect, which results in increased temperatures. While the direction of climate change is clear, the extent and the full implications for coastal adaptation are not. Consequently, we used two scenarios for climate change, Climate scenario 1 and Climate scenario 2. These have different sets of assumptions for the primary threats to ports: a) sea level rise and b) increased storm intensity.

Sea level rise is documented to be accelerating

a) The higher temperatures result in warmer seas and cause higher sea levels through the expansion of water at higher temperatures and due to the melt of large on-land ice areas that store water, such as in Greenland, the polar caps and mountain glaciers. According to the IPCC, sea levels have been increasing at an global average rate of 1.7mm/year in the 20th century. Technological advances provided by satellite imagery available since the 1990s have since observed that global average sea levels are rising at a rate of 3.2mm/year, which is accelerating. The exact rate varies by location.

There are signs that storm intensity is increasing

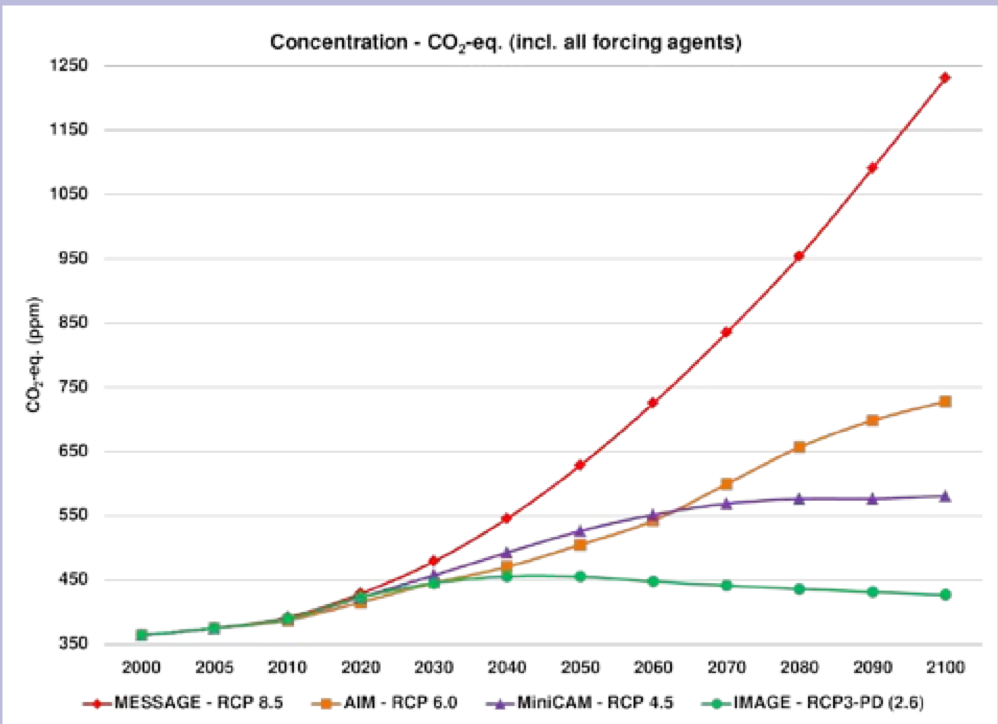
b) Of the two effects, sea-level rise appears to be better described, while we found less certainty in how to model increases in storm intensity and related storm surge. However, there are several regional studies showing strong relevant effects. For example, a 2016 study published in *Nature* found that typhoons that land in East and Southeast Asia have intensified by 12-15% over the past four decades.[4] The study also found storms that are categorised level 4,

4 Mei, Wei & Xie, Shang-Ping. (2016). *Intensification of landfalling typhoons over the northwest Pacific since the late 1970s.* Nature Geoscience.

the most damaging, have doubled to tripled. The increase in intensity is correlated to the surface temperature of oceans, which have risen around ocean regions of East and Southeast Asia.

What is a Representative Concentration Pathway (RCP)?

Figure 1: Representative Concentration Pathways



The RCPs are a set of standard models used primarily by climate modellers, adopted by the Intergovernmental Panel on Climate Change (IPCC), a scientific body under the United Nations. They adopted the latest RCPs in 2014. As climate models are expensive, the RCPs serve to reduce duplication and save money. They standardise various scenarios to make them easier to understand and help form a common analytical basis to compare the results of different scientific, social and policy studies.

There are four Representative Concentration Pathways. RCP2.6, RCP4.5, RCP6 and RCP8.5. Each RCP is developed independently by a different modelling team and provides trajectories of emissions and concentrations of greenhouse gases to 2100. The numbers refer to radiative global energy imbalances, measured in watts per square metre, by the year 2100.

There are various possible climate scenarios...

The climate change scenarios are based on Representative Concentration Pathways (RCP) – see boxed text – which are future scenarios of CO_2 concentration described in the *Intergovernmental Panel on Climate Change 5th Assessment Report*. Each RCP implies a range of possible increases in global temperatures as well as projections for likely sea level rise through to 2100. Our climate change scenarios also include projections for the increase in storm intensity and consequent storm surge.

...that ports will need to consider

Ports are typically designed to resist storms with a 1% probability of occurring in any single year. The findings of the studies on storm intensity are that a storm with a 1% probability of occurring at the end of the century will have a higher intensity and drive higher storm surges than such storms earlier in the century.

Table 5: Two potential climate futures

	Climate scenario 1	Climate scenario 2
Emissions scenario	RCP4.5: peak in emissions around 2040, with temperature increases likely between 1.1°C and 2.6°C	RCP8.5: emissions continue to rise throughout the century, with temperature increases likely between 2.6°C and 4.8°C
Sea level rise	Between 0.3m and 0.6m	Between 0.45m and 0.8m
Storm intensity	Average storm intensity increases 10% to 20%	Average storm intensity increases 20% to 30%
Storm surge	Storm surge increases by 0.5m to 1m from base assumption of 5m	Storm surge increases by 1m to 1.5m from base assumption of 5m
Required elevation	1.6m = 0.6m + 20% x 5m	2.3m = 0.8m + 30% x 5m

Sources: ARE sets of assumptions, RCPs from IPCC, Texas A&M University

We estimate extra height requirements of between 1.6m and 2.3m

Ports will need to adapt to the new risk levels, with engineering solutions designed for the higher end of the risk range. We estimate this requires factoring in extra protection to adapt to storm surges of 1.6m higher in Climate scenario 1 and 2.3m higher in Climate scenario 2. These figures are derived for each scenario by adding the highest projected sea level rise to the highest expected storm surge increase for storms with a 1% probability. For Climate scenario 1, this is based on 0.6m + 20% x 5m for a total of 1.6m. For Climate scenario 2, the calculation is 0.8m + 30% x 5m for a total of 2.3m.

We have some sense of the geographic variation in physical risks. For example, China and the Philippines face growing storm surge risks, but these risks are much lower in other countries, such as Singapore, which is naturally sheltered.

Nevertheless, we used common assumptions based on the likely maximum for each climate scenario. One reason was that there is already a high level of uncertainty contained in the scenarios, while differences in the height increase do not lead to significant variations in costs. Further, there is lack of consistent projections in different regions for all the components of sea level rise and storm intensity/storm surge increase. Finally, we did not have relevant data on port height to take advantage of localised estimations.

Some countries have prepared for sea level rise

Uncertainty around local effects should not deter action, but rather encourage ports and governments to undertake local studies. Notably, the port of Rotterdam built a concrete sea wall up to a height of 14m to protect against its local worst-case scenario up to 2060.

2.2 Engineering assumptions

A consistent approach is used to model engineering based on elements that are fully in the ports control. These include elevating relevant yard areas, including rebuilding warehouses, and using walls to protect other, less sensitive areas. This allows for a consistent methodology that can be applied to various ports. However, elevation and rebuilding are extremely costly. Consequently, we expect that even if there were no alternatives, such as longer walls and tide breaks out at sea, port operators will minimise the port areas requiring elevation. Hence, the model considers this through two sets of assumptions that differ in the proportion of yard areas assumed to be elevated. Table 6 provides the main elements of the assumptions.

Table 6: Engineering assumptions

Engineering approach	The ports will have to elevate certain areas and may have discretion over further areas. Consequently, we assume full elevation for the first 1km^2, 0.2 km^2 and 0.5km^2 of container yards, automobile yards and warehouse areas respectively. We used varying assumptions for beyond these initial area.
Assumption A	Elevation of initial area + 10% of residual area
Assumption B	Elevation of initial area + 30% of residual area

Source: ARE

2.3 Detailed modelling

The combination of climate scenarios and engineering approaches creates four overall cost estimates as set out in Table 2. The estimate took a two-step approach. First, we estimated the port areas and different parts of the ports using Google Earth Pro – see example images in Appendix 1. We identified these areas by visual inspection and consequently they may not correspond to the legal area owned or managed by an authority or operator. Then we modelled engineering solutions for different components of the ports. There were three different methods, depending on whether the area would be elevated, protected by an external wall along the coast, or walled off around its perimeter. The height of the elevated yards and walls depends on the higher range of two separate climate scenarios, 1.6m and 2.3m respectively.

The model then used construction cost estimates covering material and labour costs, based on the Turner and Townsend, *International Construction Market Survey 2017* – details are provided in Appendix 2.

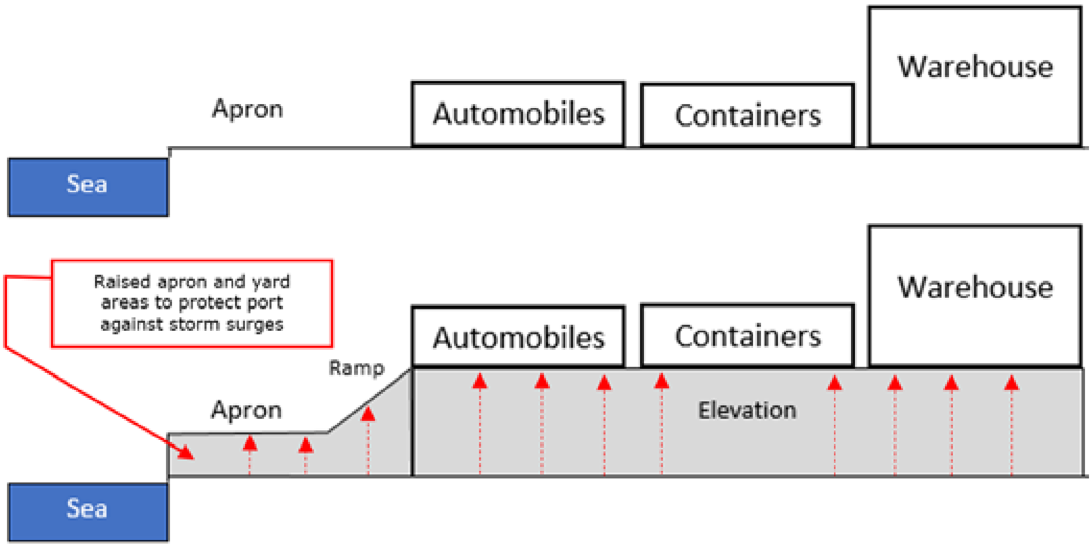
Warehouse rebuild costs a driver of overall costs

Notably, in our model, the rebuild costs for warehouses are a major component of overall of costs and do not vary with the height of elevation.

Port area estimation

We locate the port cities on Google Earth Pro and demarcate components of the ports such as yard, warehouses and apron areas using software tools. The software provides calculations for areas and length measures based on drawings and selections. This allowed estimations for the total port surface area and for the different area types (warehouses, building and parking lots, container yard, dry docks, etc.). Similarly, it allowed estimation of required wall lengths, such as for protective walls. Examples of the process can be found in Appendix 1: Port area drawing examples. The figures shown there illustrate the identification of port areas, using the Chinese ports of Qingdao and Dalian as examples. Figures 6, 7, 8 and 9 illustrate the mark-up of individual components of the ports showing in turn warehouses, silos, and dry dock areas.

Figure 2: Apron and yard elevation



Source: ARE

Areas for elevation

We assumed that a proportion of the areas identified as apron, container, automobile, or warehouse would need to be elevated. These are shown schematically in Figure 2.

The model inputs for elevation are elevation area, elevation height, material quantity required, and unit construction costs.

a. Elevation area

We measured all yard areas separately on Google Earth Pro, with the exception of apron areas. Here we measured their length on Google Earth Pro and then used a common assumption for surfaces along the coastline of a width of 35m.

Due to the high costs of elevation, we assumed that ports will raise only selected portions of the yards, leaving wider internal areas behind walled protection. We assumed full elevation for areas up to the first $1km^2$, $0.2km^2$ and $0.5km^2$ of container yards, automobile yards and warehouses respectively. We also assumed that warehouse reconstruction will only occur in the elevated areas. We assumed that ramps would be built half-way between the apron and the elevated areas and included ramp construction costs in the overall elevation costs for yards, rather than modelling them separately.

In our model, we established a range of costs depending on the total areas to be elevated. This included the minimum threshold areas in addition to a further proportion of total yard area. In assumption set A, we assumed that the port will elevate 10% of residual yard areas in addition to the minimum elevated area, while in assumption set B we assumed elevation of 30% of the residual areas.

b. Elevation height

We modelled two climate scenarios using an elevation height of 1.6m for the less severe scenario and 2.3m for the more intense scenario – we did not vary elevation height by port location. We elevated the yard areas by the respective amount for each climate scenario.

For the apron areas, we modelled a lower apron height increase of 0.6m in the less severe climate scenario and 0.8m in the more intense scenario, matching the sea level rise projections only. The apron areas need be elevated in steps – for example, with an initial increase of 0.3m – to allow smooth loading and unloading operations.

c. Materials used

The model assumes yard areas are elevated with dredged filling material covered with three layers of pavement: crushed stones, intermediate concrete and surface tiles, made of concrete, sand and stabiliser. The volume of materials required is estimated as follows:

- Tiles pavement layer, made of 10cm of concrete + 3cm of sand and stabiliser
- Central pavement layer, made of 20cm concrete
- Crushed stones pavement layer of 15cm
- Dredged filling height = total elevation height minus the height of previous layers

For elevating the apron, we assumed a single concrete layer in the first stage of elevation (aprons may need reinforcement of underwater supports, but we assumed this would be left to a later stage).

d. Construction costs

The different materials cost different amounts. For the yard layers, we were able to obtain the US costs from the Stanford paper.[5] In order to estimate the costs for other countries, we first assess the concrete equivalent volume that could be bought for the value represented by each layer. This provides the estimated costs of each layer of different material expressed in concrete equivalent costs.

Table 7: Cost-equivalent thickness in concrete for different layers

Layer	Material thickness (cm)	Concrete cost-equivalent thickness (cm)
Tiles	13	11.8
Central concrete pavement layer	20	20
Crushed stones	15	3.8
Dredged fill (for total elevation of 1.6m)	112	2.22
Dredged fill (for total elevation of 2.3m)	182	3.60

Sources: ARE calculations, Stanford University

We then localised the costs for each country using the concrete costs provided by the *International Construction Market Survey 2017* by Turner & Townsend. When a specific country was not available, we used the cost values of a similar country in the region.

We assumed the full reconstruction of warehouses when their surface is elevated. We used costs estimates for the construction of warehouses from the abovementioned Turner & Townsend survey; where costs for a specific country were not available, we approximated these using the values of proxy countries.

5 *Estimation of Cost Required to Elevate US Ports in Response to Climate Change: A Thought Exercise for Climate Critical Resources*, CIFE Working Paper #WP138, December 2015, Stanford

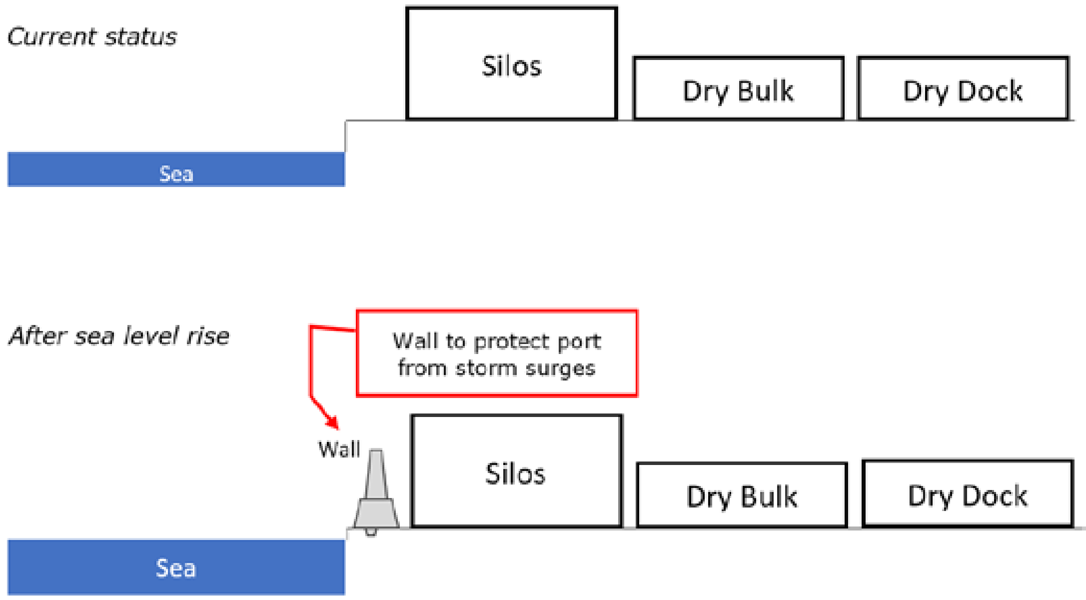
Walled areas

We assumed walls would be built to protect other areas where vessel loading and unloading does not require an apron next to the coastal line.

a. Wall protected areas

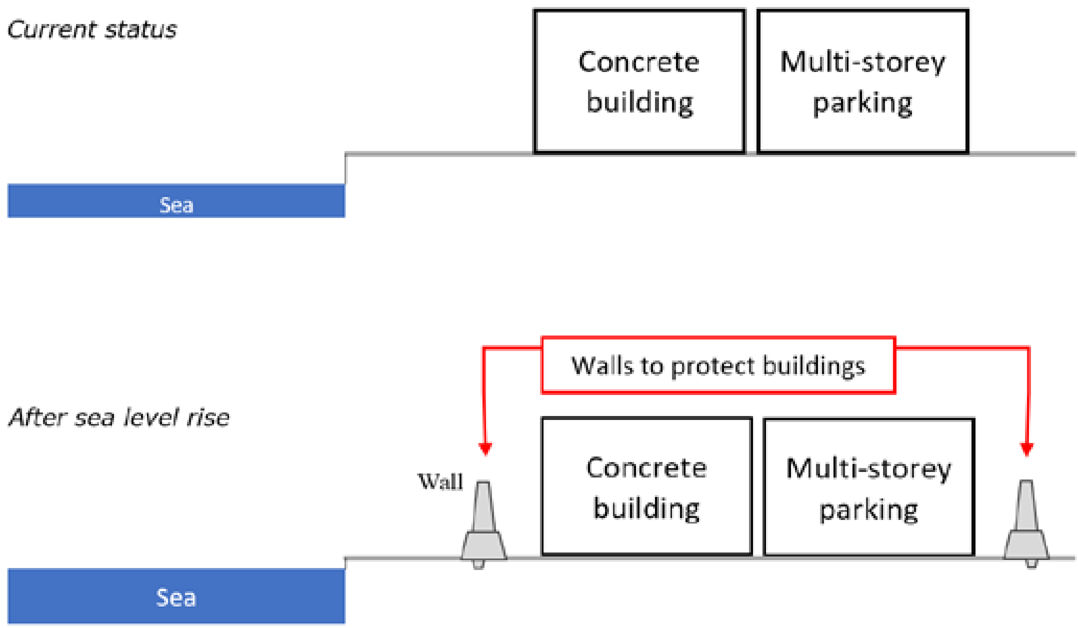
There were two types of areas. We modelled silos, dry bulk and dry dock with a single wall and concrete buildings and multi-storey parking with a surrounding wall.

Figure 3: Areas protected with a single wall



Source: ARE

Figure 4: Areas protected with surrounding walls



Source: ARE

Figure 3 shows the schematic approach to modelling for silos, dry bulk and dry docks. In the case of the dry docks, we used the wall cost as an approximation for elevating the flooding gates (see Figure 3).

We assumed a lower-cost solution for concrete buildings and multi-storey parking, whereby these structures will not be rebuilt but instead either protected by perimeter walls when located in non-elevated areas, or adapted with ramps for access where adjacent areas are being elevated (see Figure 4).

b. Wall costs

We assume that the walls have the same height as the elevated areas, plus an extra margin 0.3m – for a total of 1.9m to 2.6m, depending on the climate scenario – so as to defend from projected flood risks deriving from both sea level rise and higher storm surges. The walls may take different shapes according to the port engineering requirements, including additional underground and balancing structures. The extra margin is applied also for containment walls between the aprons and elevated yards.

In order to estimate wall construction costs, we use a volumetric equivalent parallelogram in cross-section. We assume an average wall thickness of 40cm. We then also include the costs to place sheet piles to avoid potential sea water infiltration during storm surges.

Figure 5: Wall

Source: ARE

We estimate the costs of the walls assuming their volume to be in concrete and multiplying the total wall perimeter for each area by unitary cost of a wall of 1m in length. We localised the costs for each country using the concrete costs provided by the *International Construction Market Survey 2017* by Turner & Townsend. When a specific country was not available, we either used the cost values of a similar country in the region or interpolated the costs across similar countries.

Conclusion

The purpose of this report is to stimulate discussion between infrastructure builders, operators, financiers, and relevant governments regarding the physical effects of climate change in Asia.

The report has focussed on ports, providing as a context for such discussions cost estimates of US$31 billion to US$49 billion to adapt Asia Pacific's largest ports to rising sea levels and more intense storms.

Some ports already face challenges...

Typhoon Meranti, which hit the port of Kaohsiung in September 2016, illustrates the growing challenges. With winds of up to 370km/hr, the category 5 storm caused US$32 million in damage. Cranes were destroyed and berths damaged by ships that broke free of their moorings.

...and insurance may be withheld in future

In the short term port owners and operators may be able to pass such costs to insurers. But with more frequent incidents, insurance companies will raise premiums or deny cover to ports that have not upgraded their protections.

Some ports have already responded. For example, in 2016 the Port of Rotterdam incorporated a €725 million seawall to protect against storm surge as part of its port expansion programme.

Other transport infrastructure will face issues

Climate change will have significant impacts in other sectors and for assets beyond ports. These include transport infrastructure, such as airports, roads and rail, as well as power and other industrial infrastructure. Agriculture also faces significant challenges. In each case, the effects will also be relevant for investors, banks and insurers allocating capital to the respective assets and sectors.

We welcome comments that can help direct this work in the future. We would like to know where similar analysis would be useful.

Appendix 1: Port area drawing examples

Figure 6: Section of the port of Qingdao, China

Source: Google Earth, ARE outlines

Figure 7: Warehouses and buildings in the port of Qingdao, China

Source: Google Earth, ARE outlines

Figure 8: Silos area in the port of Dalian, China

Source: Google Earth, ARE outlines

Figure 9: Dry dock in the port of Dalian, China

Source: Google Earth, ARE outlines

Appendix 2: Port unit cost assumptions

Country	City	Currency	Exchange rate to US$	Multi-storey parking (US$/m²)	Buildings (US$/m²)	Warehouse (US$/m²)	Concrete (US$/m²)
Australia	Brisbane	AUD	1.36	654	1,195	614	228
Australia	Sydney	AUD	1.36	676	1,346	603	240
Australia	Melbourne	AUD	1.36	632	1,206	559	239
Australia	Perth	AUD	1.36	603	1,169	566	235
China	Hong Kong	HKD	7.76	1,545	2,669	2,107	190
China	Beijing	RMB	6.9	290	638	333	72
India	Bangalore	INR	69.07	250	604	448	113
Indonesia	(1)			272	790	482	69
Japan	Tokyo	JPY	115.64	1,880	2,134	1,421	128
Korea (South)	Seoul	KRW	1179	591	1,184	950	119
Malaysia	Kuala Lumpur	MYR	4.42	272	790	482	69
New Zealand	(3)			676	1,346	603	240
The Philippines	(1)			272	790	482	69
Russia	Moscow	RUB	64.74	487	973	595	150
Singapore	Singapore	SGD	1.43	860	1,419	1,508	110
Taiwan	(2)			591	1,184	950	119
Thailand	(1)			272	790	482	69

(1) Similar to Malaysia
(2) Similar to South Korea
(3) Similar to Australia/Sydney

Source: Turner and Townsend, International Construction Market Survey, 2017

Bibliography

Asian Development Bank, 2017. *A Region at Risk: The Human Dimensions of Climate Change in Asia and the Pacific.* Manila: ADB.

Becker, A. H. et al., 2013. A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. *Climatic Change*, 120(4), p. 683–695.

Gharehgozli, A. H., Mileski, J., Adams, A. & von Zharen, W., 2017. Evaluating a "wicked problem": A conceptual framework on seaport resiliency in the event of weather disruptions. *Technological Forecasting and Social Change*, Volume 121, pp. 65-75.

Google, 2017. *Google Earth Pro*. Mountain View, California: Google Inc..

Hippe, A., Becker, A., Fischer, M. & Schwegler, B., 2015. *Estimation of Cost Required to Elevate US Ports in Response to Climate Change: A Thought Exercise for Climate Critical Resources*, Stanford, CA: Stanford University, Center for Integrated Facility Engineering.

Intergovernmental Panel on Climate Change, 2014. *Fifth Assessment Report (AR5)*, Geneva: IPCC.

Mei, W. & Xie, S.-P., 2016. Intensification of landfalling typhoons over the northwest Pacific since the late 1970s. *Nature Geoscience*, Issue 9, pp. 753-757.

Muis, S. et al., 2016. A global reanalysis of storm surges and extreme sea levels. *Nature Communications*.

Ng, A. K. et al., 2013. Climate change and the adaptation strategies of ports: The Australian experiences. *Research in Transportation Business & Management*, Volume 8, pp. 186-194.

Nicholls, R. J. et al., 2007. *Ranking of the World's Cities Most Exposed to Coastal Flooding Today and in the Future*, Paris: OECD (Environment).

Tsuboki, K. et al., 2015. Future increase of supertyphoon intensity associated with climate change. *Geophysical Research Letters*, 27 January, 42(2), p. 646–652.

Turner & Townsend, 2017. *International construction market survey*, Leeds: T&T.

U.S. National Geospatial-Intelligence Agency, 2017. *World Port Index*, Springfield, VA: NGIA.

United Nations Conference on Trade and Development, 2016. *Review of Maritime Transport*, Geneva: UNCTAD.

Wesphal, M. I., Hughes, G. A. & Brömmelhörster, J., 2013. *Economics of Climate Change in East Asia*. Manila: Asian Development Bank.

World Bank, 2017. *World Bank Open Data*. [Online] Available at: https://data.worldbank.org/

Asia Research and Engagement Pte Ltd
info@asiareengage.com

Cover photo: Zhu Difeng