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PLANNING PORTS FOR CHANGING MEAN AND EXTREME WATER LEVELS

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ABSTRACT

Change in mean sea level, being a long-term process, is an effect of climate change which will have an influence in coastal areas over this century and potentially beyond. For existing ports, these changes are important as mean and extreme water levels will change compared to those for which current infrastructure was designed. Similarly, new ports should expect such changes.

The rate and magnitude of future sea-level change vary with future emission scenarios, as well as being regionally and locally influenced by a range of other processes, such as gravitational effects, glacial isostatic adjustment (GIA) and deltaic subsidence. A global assessment of these changes contrasting different emission scenarios (using the IPCC's lowest and highest Representative Concentration Pathways (RCPs)) indicates that sea-level change will have a significant impact within the design life of existing port infrastructure. In particular, mean relative sea-level rise will influence the height of extreme water levels and their associated return periods (e.g. with large effects in certain regions such as the Mediterranean).

Consideration of both mean and extreme changes within the planning and design process should ensure that these changing levels of risk can be addressed by design and/or scheduled maintenance/upgrade/adaptation for both existing and proposed port infrastructure, maintaining appropriate levels of safety and operation.

Keywords: Sea-level rises, port infrastructure, design, return period, coastal flooding

1. INTRODUCTION

Critical to global commerce, ports are potentially one of the greatest points of vulnerability within the shipping system as they are 'pinch points' when any disruption can have wide reaching effects. Recent flooding of US Gulf Coast ports by Katrina in 2005, New York ports by Sandy in 2012 and Immingham, UK in 2013 demonstrate that climate events can be important for ports (Barbier, 2015, Binder et al., 2015, Wadey et al 2015). Similarly, while not climate related, the Tōhoku earthquake in Japan illustrates the investment needed to address a change in mean water levels. A growing number of port operators are recognising that, while changes related to climate may not seem imminent or initially inconsequential, atmospheric and oceanic adjustments to a global temperature increase will feature among the potential sources of disruption. Including these within the planning process will therefore allow them to offset detrimental and enhance any beneficial effects, maintaining their essential service provision (Transportation Research Board, 2011, Becker et al., 2013, Merk, 2014).

Current port planning timescales are often rather short-term, being linked to the immediate bottom line. However, significant levels of change due to climate change may be apparent within the expected lifetime of important port infrastructure (see Table). Hence, there is a mismatch to the much longer timescales of climate change. Primary among the climate change drivers for ports is sea-level rise. Sea-level rise rose about 20 cm during the 20th Century and could rise a metre or more during the 21st Century (Church et al., 2013). This may lead to damage of existing structures (e.g. variation in water pressures behind structures, unexpected scour), reducing overhead clearance, changes in coastal morphology) leading to a reduction in functional effectiveness. However, the most immediate concern is to raise the level of infrastructure to prevent flooding; both in new designs and the adaptation of existing structures. There is therefore a need to assess the changes that will occur during lifetime of a structure.

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Table : Examples of port infrastructure with anticipated design and economic life (taken from Thoresen, 2014).

	Type of port infrastructure	Life expectancy (years)
Design life	‘General’ berths	50+
	‘Specialist’ berths (containers, oil, etc.)	<30
	Shore protection (breakwaters, etc.)	100
	Flood protection	100+
Economic life	Breakwater	100
	Reinforced open berth	50-100
	Steel sheet pile berth	50

Although port planning processes are not usually equipped to incorporate the high levels of uncertainty associated with climate change (e.g. Gallivan et al., 2009), sea-level rise is one of the more certain consequence of climate change. It is relatively well understood and existing information provides a reasonable basis for examining impacts on port and coastal infrastructure (e.g. Headland et al., 2011, Thoresen, 2014). Sea-level rise due to climate change is expected to continue over this century and beyond due to the long response time of the oceans to changes in surface temperature – usually termed the commitment to sea-level rise (see Figure 1). This effect means that, even if the global temperature increase is stabilised at 2°C, sea levels will continue to rise although at a slower rate.

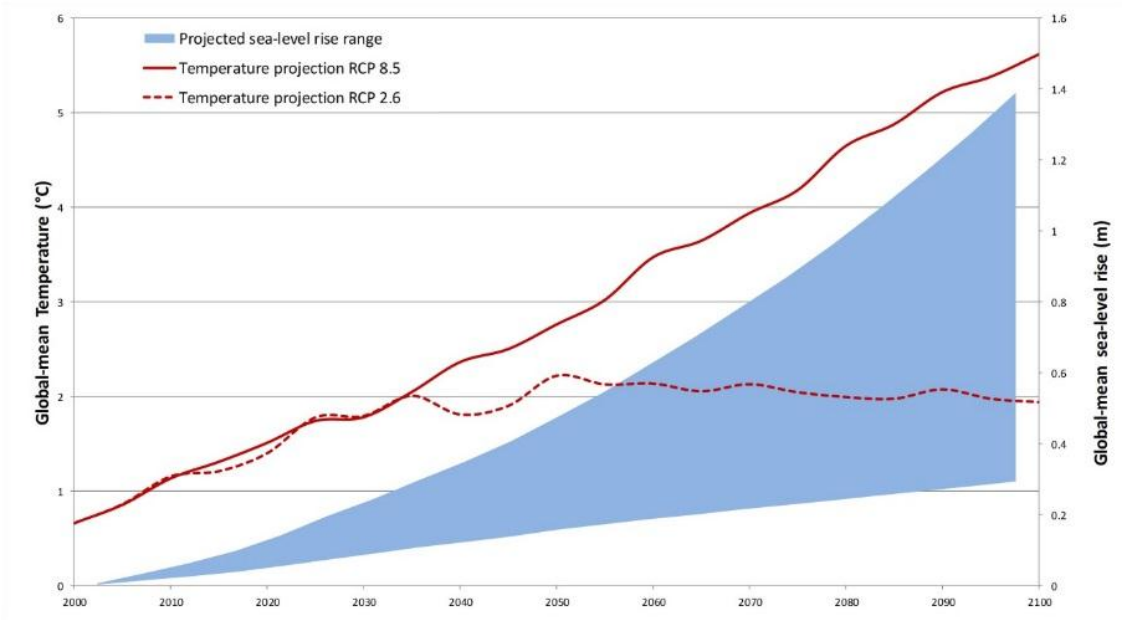

Figure 1: Projected global-mean temperature rise and the corresponding range of sea-level rise under the RCP2.6 and RCP8.5 emissions scenarios, illustrating the commitment to sea-level rise.

To gain an appreciation of the uncertainty within which planning decisions need to be made, especially as it is unclear which temperature trajectory is expected, ports need to consider the full potential sea-level range from the lowest to the highest projection, with particular attention in the upper bound. This is a prudent approach for risk management (Hinkel et al., 2015). A further complication for port planning is that climate-related future sea levels are regionally variable due to a range of atmospheric and oceanic factors and the degree of expected ice melt (see Church et al., 2013). In addition, spatially variable rates of vertical land movement can either exacerbate or offset the effects of climate-induced changes. Combined these factors are termed relative sea-level rise (RSLR) (e.g. Nicholls et al., 2014): RSLR is what planners need to consider.

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This paper therefore presents an initial global analysis of RSLR and its consequences for the effectiveness of coastal structures at ports in terms of their ability to prevent flooding. The range of future RSLR is encompassed by the use of the IPCC's upper and lower emissions scenarios; Representative Concentration Pathway (RCP) 2.6 representing a mitigation scenario in which global mean temperature increase is restricted to 2°C and RCP 8.5 representing a scenario in which emissions are not controlled and global-mean temperature continues to rise unabated. The analysis will include global uncertainties and regional variations in RSLR, identifying those ports where the changes might be the greatest or the most uncertainties will be faced. It will also look at the timing and magnitude of change, and how this might affect the planning process.

While it is recognised that all ports will be affected, for clarity the results focus on the trends and changes that may occur over the wider shipping system with reference to the 149 ports classified as large within the World Port Index (NGIA, 2015).

2. METHODOLOGY

2.1. REGIONAL RELATIVE SEA-LEVEL RISE PROJECTIONS

For this study the highest and lowest of the IPCC's Representative Concentration Pathway (RCP) emissions scenarios, RCP 8.5 and 2.6, are used to generate sea-level projections to 2100 using the Dynamic Interactive Vulnerability Assessment (DIVA) database and model. The DIVA model is an integrated model of coastal systems that assesses biophysical and socioeconomic impacts of sea-level change. It comprises a one-dimensional global database that divides the world's coasts (excluding Antarctica) into 12,148 linear segments and associates about 100 pieces of data with each segment covering physical, ecological, and socioeconomic characteristics of the coast (e.g. Vafeidis et al., 2008), including any change in sea level and storm surge heights.

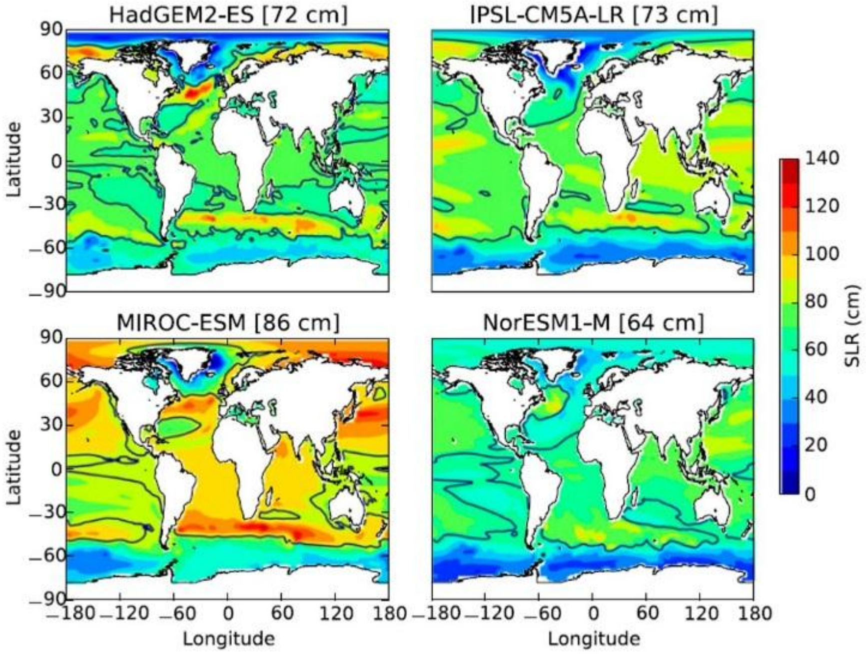

Figure 2. Regionally variable sea level rise under the four climate models used (in 2100 under RCP8.5 and the medium ice melt scenario) (Hinkel et al., 2014)

To calculate relative sea-level rise (RSLR) at the segment level, the model combines projections of climate-related sea-level rise with vertical land movement output at 5 year intervals to 2100. With an interest in identifying the potential range of sea-level projections rather than the mean, four climate models were used to characterise different patterns of climate-induced regional sea-level change. Sea-level change is associated with the DIVA segments by overlaying the grids of the four general circulation models (GCMs) for each RCP

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with the vectorised coastline segmentation. Regional variations show predominantly latitudinal pattern of regional sea-level rise (see Figure 2) due to the reduced gravitational pull from the decline in high-latitude ice masses. Ocean circulation also has regional/localised effects; for example the relatively high sea-level rise along the Northeastern United States coast in three of the four models, around the Antarctic Circumpolar and Aghullas currents, North Atlantic subpolar gyre and the Kuroshio current off Japan (Hinkel et al., 2014 (supplementary material)). To cover the most uncertain contribution to global sea-level rise, the melting of the Antarctic ice sheet (Church et al., 2013) which has a long-tailed risk of very-high sea-level rise (e.g. under RCP8.5 emissions, upper 95th percentile is 41 cm, median approximately 10 cm, and the lower 5th percentile around 2 cm), three scenarios are included (high, median, low) (see Hinkel et al., 2014).

This creates a total of six future scenarios for each climate model (see Table 1). Vertical land movement due to glacial isostatic adjustment (resulting from the loading and unloading of ice sheets during the last Ice Age) was added to the climate-related sea-level change at the segment level for each future scenario from the Peltier ICE model (Peltier, 2000) and delta subsidence rates from Ericson et al. (2006) or an assumed rate of 2mm/yr for other known deltaic segments. Relatively, the changes tend to be more pronounced under the mitigated RCP2.6 scenarios. For each future RCP/icemelt scenario, the maximum and minimum values for RSLR from across the four climate models were selected to represent the uncertainty which needs to be addressed when planning for change.

Table 1: Summary of future scenarios inputs used for each of the four climate models (see Hinkel et al., 2014 for full details)

Future scenario name	**Vertical land movement**	**Emissions pathway description**	**Ice melt input**
RCP8.5h	Constant rate of isostatic land movement (Peltier, 2000) and delta subsidence consistent across all scenarios	RCP 8.5: surface temperature as likely as not to exceed 4°C; rising pathway (IPCC, 2013)	High
RCP8.5m			Median
RCP8.5l			Low
RCP2.6h		RCP 2.6: surface temperature unlikely to exceed 2°C; stabilisation and overshoot pathway (IPCC, 2013)	high
RCP2.6m			median
RCP8.5l			low

2.2. PORT LOCATIONS

Port location was taken from the World Port Index (NGIA, 2015) and was associated with the nearest coastal segment within the DIVA model. From the over 3500 ports in the Index, this paper considers the 149 ports classified as large for illustrative purposes. This category is based on several factors including area, facilities and wharf space (NGIA, 2015) and includes a global distribution of ports (see Figure 3).

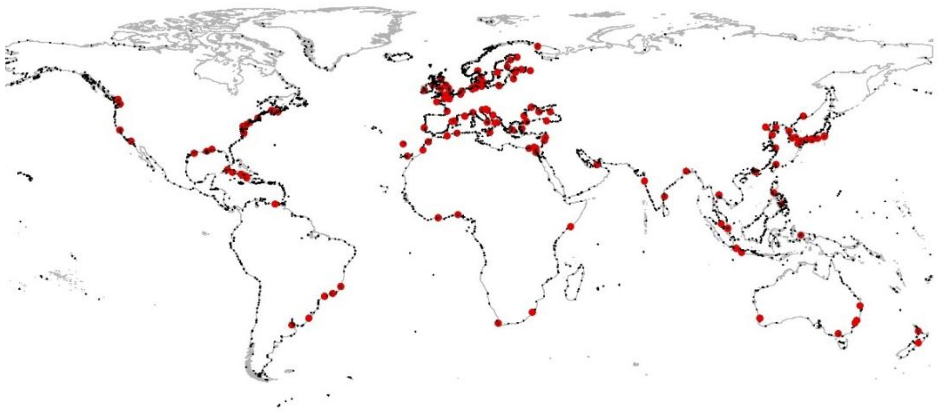

Figure 3: Global distribution of the 149 large ports considered in this paper

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3. GLOBALLY VARIABLE RELATIVE SEA-LEVEL RISE

Using the methodology described above, for most coastal segments there is an overlap between the two RCP emissions scenarios over the majority of the century – under RCP2.6h (high ice melt component), RSLR is greater than under the RCP8.5l (low ice melt) (Figure 4). This continuum across the scenarios means for planning purposes, given the future emissions trajectory is unknown, the full spectrum should be considered particularly in the short- to mid-term and the range can be regarded as an estimate of uncertainty.

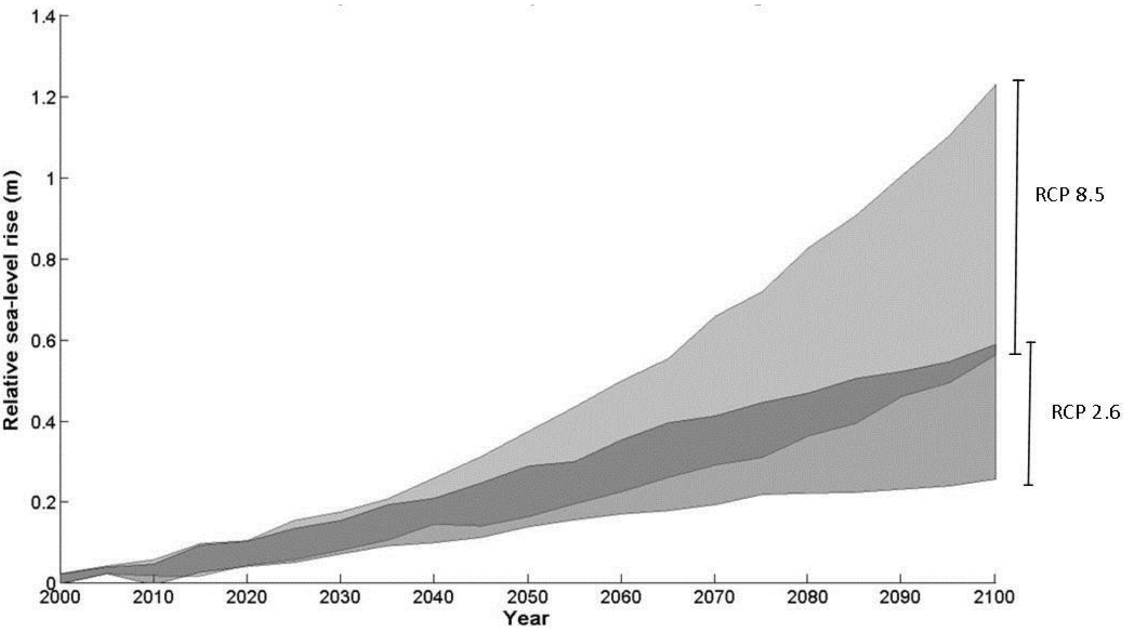

Figure 4: Illustration of the overlap between the RSLR scenarios used

An initial assessment of the magnitude of RSLR, the highest occurs, unsurprisingly, under the RCP8.5h scenario; significantly higher than even the other RCP8.5 futures due to the increased rate of anticipated ice melt. Ports where climate-related sea-level rise is exacerbated by subsidence (e.g. Ganges-Brahamaputra, Mississippi and Nile deltas) see the highest magnitudes of RSLR in 2050 (see Table 2); by 2100 this factor becomes less influential as the constant subsidence is rate is dominated by the increase rate of climate-related sea-level rise within the model and fewer of these ports appear. Instead ports located on the east coast of the United States of America see high magnitudes due to the influence of major ocean currents.

However, this information needs to be assessed in conjunction with two other factors; the range of RSLR projections both within and across scenarios and any variation in rise over time. The range in RSLR, if considered to represent the uncertainty in the projections, indicates the degree of flexibility which needs to be incorporated into any adaptation planning. For example, Calcutta whose maximum rise in 2050 is projected to be 0.88m with a range of 0.21m (see Table 3) could decide that planning for the maximum would be more beneficial or economically viable than staging a series of responses over time. However by 2100, when the anticipated range is 1.61m, the more flexible approach might be more appropriate and designs be developed that allow for future adaptation when necessary.

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Table 2: Ports with the highest magnitude of projected RSLR in 2050 and 2100 (large ports only)[1]

	Maximum RSLR (RCP8.5h) in 2050		**Maximum RSLR (RCP8.5h) in 2100**	
	Port	**(m)**	**Port**	**(m)**
1	CALCUTTA, India	0.88	CALCUTTA, India	2.25
2	NEW ORLEANS, United States	0.60	NEW ORLEANS, United States	1.67
3	ALEXANDRIA, PORT SAID, DAMIETTA, Egypt	0.60	MOBILE, United States	1.65
4	MOBILE, United States	0.60	TOYOHASHI, Honshu, Japan	1.65
5	NOVOROSSIYSK, Russia	0.60	ALEXANDRIA, DAMIETTA, Egypt	1.62
6	SAMSUN, Turkey	0.58	PORT SAID, Egypt	1.61
7	ODESA, ILLICHIVSK, SEVASTOPOL, Ukraine	0.57	TIANJIN XIN GANG, China	1.59
8	ISTANBUL, Turkey	0.57	HAMPTON ROADS, NORFOLK, United States	1.53
9	VARNA, Bulgaria	0.57	BROOKLYN, NEW YORK CITY, United States	1.50
10	GDANSK, GDYNIA, Poland	0.53	HALIFAX, Canada	1.50
11	TOYOHASHI, Honshu, Japan	0.53	BALTIMORE, United States	1.50
12	ROTTERDAM, AMSTERDAM, Netherlands	0.51	CHESTER, United States	1.49
13	LONDON, UK	0.51	PHILADELPHIA, United States	1.49
14	TIANJIN XIN GANG, China	0.50	SHANGHAI, China	1.49
15	IMMINGHAM, UK	0.49	BOSTON, United States	1.48

Table 3: Table showing the maximum range in projections for RSLR across all scenarios for the ports in Table 2

	Maximum Range (RCP8.5h to RCP2.6) in 2050		**Maximum Range (RCP8.5h to RCP2.6l) in 2100**	
	Port	**(m)**	**Port**	**(m)**
1	CALCUTTA, India	0.21	CALCUTTA, India	1.61
2	NEW ORLEANS, United States	0.25	NEW ORLEANS, United States	1.08
3	ALEXANDRIA, PORT SAID, DAMIETTA, Egypt	0.22	MOBILE, United States	1.07
4	MOBILE, United States	0.25	TOYOHASHI, Honshu, Japan	0.85
5	NOVOROSSIYSK, Russia	0.44	ALEXANDRIA, DAMIETTA, Egypt	0.99
6	SAMSUN, Turkey	0.44	PORT SAID, Egypt	0.99
7	ODESA, ILLICHIVSK, SEVASTOPOL, Ukraine	0.44	TIANJIN XIN GANG, China	0.81
8	ISTANBUL, Turkey	0.44	HAMPTON ROADS, NORFOLK, United States	0.86
9	VARNA, Bulgaria	0.43	BROOKLYN, NEW YORK CITY, United States	0.85
10	GDANSK, GDYNIA, Poland	0.33	HALIFAX, Canada	0.86
11	TOYOHASHI, Honshu, Japan	0.28	BALTIMORE, United States	0.83
12	ROTTERDAM, AMSTERDAM, Netherlands	0.35	CHESTER, United States	0.84
13	LONDON, UK	0.34	PHILADELPHIA, United States	0.83
14	TIANJIN XIN GANG, China	0.27	SHANGHAI, China	0.70
15	IMMINGHAM, UK	0.33	BOSTON, United States	0.83

The time period over which RSLR should be assessed should probably therefore be related to the life expectancy of a structure rather than a given point in time. This is particularly true for the lower RCP emissions scenarios where fluctuations in the projections are more pronounced.

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[1] Note, RSLR has been rounded to 2 decimal places; nearby ports have been grouped together when the projected RSLR is the same.

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4. EFFECT ON STORM FREQUENCY (RETURN PERIODS)

In addition to the direct effect on mean water levels at the coast, sea-level change also has an effect on the frequency of extreme water levels (storm surge), an effect not often considered, especially in developing areas (e.g. HR Wallingford, 2014). This effect is important in the design of defence structures (e.g. harbour arms, breakwaters, seawalls) which use frequency data, in the form of return periods, for water levels in their design (US Army, 2014). For example, flood protection structures commonly use the water level currently associated with a 1:100 year frequency as the design standard against which exceedances can be measured.

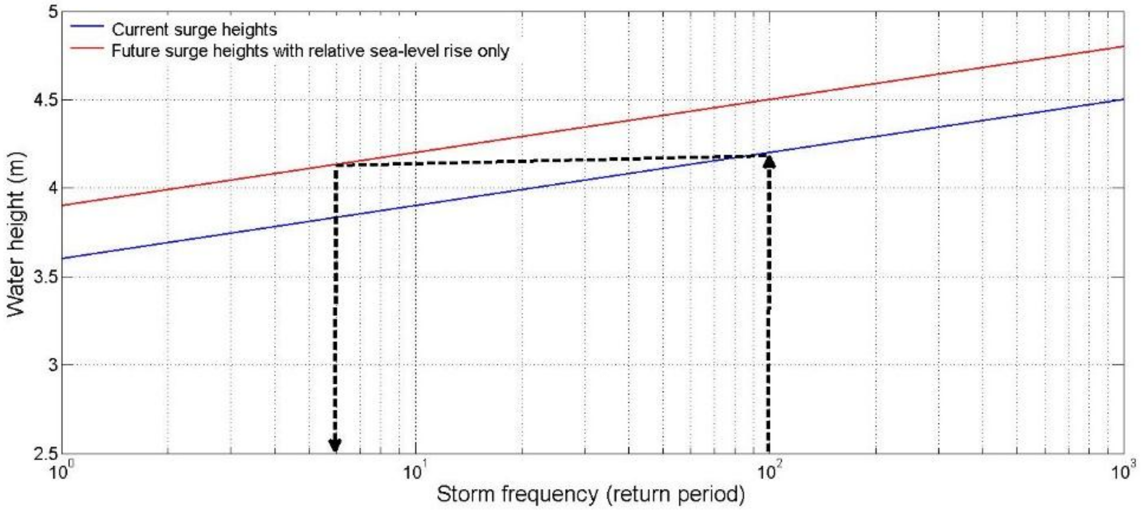
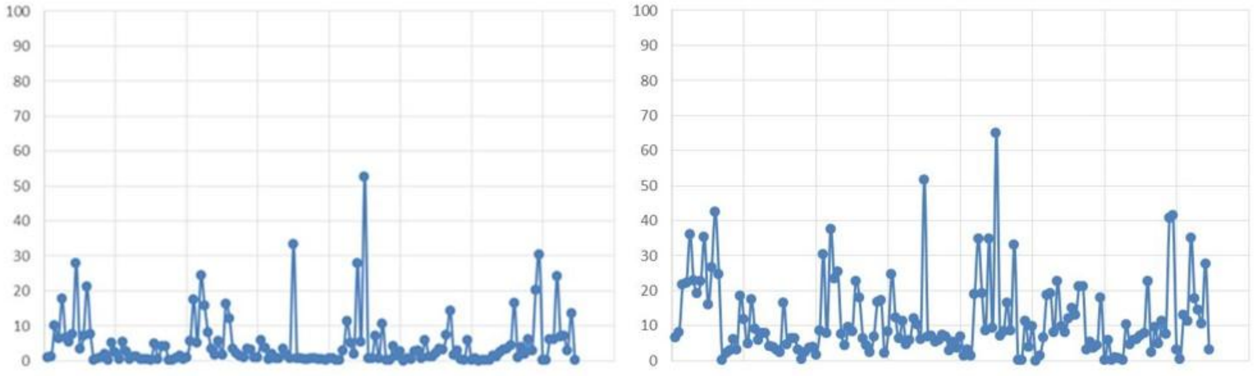


Figure 5: Illustration of the change in storm frequency associated with a rise in RSLR

The conceptual consequence of RSLR on the frequency of water levels is illustrated in Figure 5 and can have significant impacts on coastal water levels (e.g. Kriebel and Geiman, 2013). Using this approach the change in return period for the 1:100 year water level for the 149 ports was calculated; the results for the highest (RCP8.5h) and lowest (RCP2.6l) are shown in Figure 6. By 2050 under both scenarios, the frequency of the 1:100 year storm surge height has doubled for nearly all of the ports (reduced from a 1:100 year to 1:50 year frequency) with a significant number having the potential to experience that water level on an annual basis (1:1).



Change in return period	Future scenario	
	RCP8.5 high	RCP2.6 low
< 1:50	148	147
< 1:10 (decadal)	130	91
<1:1 (annual)	58	11

Figure 6. Comparison of the return period for the current 1:100 year storm height in 2050 under a) RCP8.5 high ice melt and b) RCP 2.6 low ice melt scenarios

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The ports with the lowest reduction in frequency are where either RSLR is projected to be low, e.g. Sydney (Australia), RSLR is small in comparison to the storm surge height, e.g. Rotterdam (Netherlands) or where relative sea-level rise is offset by rising vertical land movement, e.g. Kotka (Finland). By 2100 the frequency of the current 1:100 storm level increases further, the majority of ports being subject to these water levels greater than annually.

5. BENEFITS OF MITIGATION AND ADAPTATION

These changes in water levels at the coast can be addressed in two ways, mitigation and adaptation. Mitigation, by the reduction of emissions (represented here by RCP 2.6), limits the potential range of RSLR which will need to be considered. If the 2°C stabilisation of global-mean temperature is achieved (RCP2.6), the upper bound for climate-related sea-level rise globally could effectively be halved (for the models used here) and the frequency of storm water levels less affected. Due to the commitment to sea-level rise there is little obvious difference in the RSLR projected to 2050 but Table 4 shows the ports with the highest RSLR and the potential range projected under this stabilisation scenario in 2100. The ports at the top of the table are consistent with those in Table 2 mainly because they are located in deltas where subsidence, independent of climate change, is a large component of RSLR. For other ports, such as Tokyohashi, Japan, RSLR and its potential range is substantially reduced.

Table 4: Maximum RSLR and potential range under the mitigated emissions scenario (RCP2,6)

	Port	**Maximum RSLR (RCP2.6h) in 2100 (m)**	**RSLR Range in 2100 (m)**
1	CALCUTTA, India	1.61	0.36
2	NEW ORLEANS, United States	1.09	0.38
3	MOBILE, United States	1.08	0.38
4	NOVOROSSIYSK, Russia	1.03	0.75
5	SAMSUN, Turkey	1.03	0.75
6	ILLICHIVSK, ODESA, SEVASTOPOL, Ukraine	1.03	0.76
7	ISTANBUL, Turkey	1.02	0.75
8	VARNA, Bulgaria	1.02	0.75
9	ALEXANDRIA, Egypt	1.00	0.27
10	DAMIETTA, Egypt	1.00	0.26
11	PORT SAID, Egypt	0.99	0.26
12	HALIFAX, Canada	0.86	0.49
13	HAMPTON ROADS, NORFOLK, United States	0.86	0.50
14	TOYOHASHI, Honshu	0.85	0.44
15	GDANSK, GDYNIA, Poland	0.85	0.49

Adaptation, the upgrading or rebuilding of coastal structures is the other option for reducing potential impacts; in most cases this involves the raising of structure heights. Using the lower limit of the allowance of 0.25m by 2050 for sea-level rise from the Port Designers Handbook (Thoresen, 2014), the increase in frequency under any future RSLR projection is reduced, see Figure 7. Under the high RCP 8.5 scenario, for some ports the raising of structures by the recommended amount is sufficient to maintain the relative frequency of the 1:100 year water level. For others it is an over adjustment, e.g. where upward land movement reinforces the effect of adaptation in reducing RSLR (Helsinki, Finland), or an under adjustment, e.g. where the 0.25m increase in structure height is insufficient to counter the effects of RSLR (New Orleans, USA). Under the mitigated scenario the recommended adaption allowance substantially over estimates the amount of RSLR for many ports and the

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frequency for the current 1:100 year event is effectively reduced to over 1:500 years. For other ports the allowance is still insufficient, again mainly for ports located in deltas where the subsidence component of RSLR is dominant. The temporal variation in RSLR under this scenario is also greater, so more care in selecting an amount of RSLR to be incorporated into the planning and design process needs to be taken.

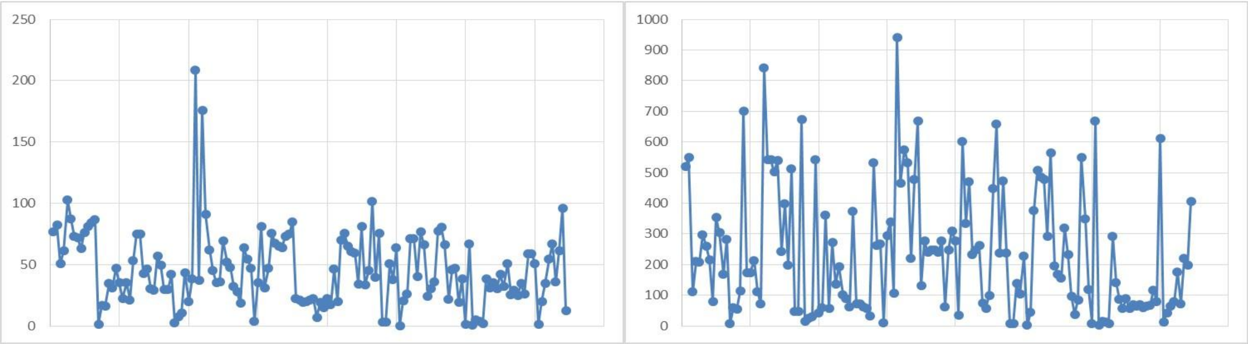

Figure 7: Comparison of the effect of raising port structures 0.25m in 2050 under a) RCP8.5 high ice melt and b) RCP 2.6 low ice melt scenarios

6. FUTURE WORK

Further work for the analysis on climate change impacts on the coast will include consideration of storm location and intensity. There is some evidence for potential movement of storm belts, although the IPCC considers there is a large uncertainty, and a move towards more intense individual storms and fewer weak storms is likely as temperatures increase (Collins et al., 2013, Gleixner et al., 2014). US Atlantic coast for example may expect a change in hurricane patterns and speed (Gallivan et al., 2009). The inclusion of these factors within the global model will allow the identification of ports where additional adaptation planning may be required.

7. CONCLUSIONS

While the sea-level projections discussed here are not predictions, they do indicate the types of change that might be experienced for ports around the world. Such changes will need to be addressed in order to maintain their functionality in the face of climate change in the form of RSLR. However, care must be taken that it is not just the rise in mean sea levels that are addressed, the impact of the frequency of extreme water levels is as, if not more, important in ensuring that flood events, structure failure and port unavailability are less likely to occur.

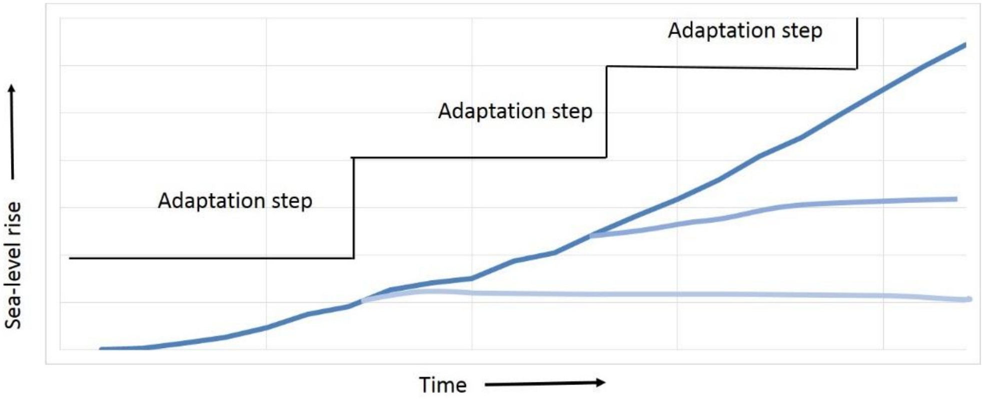

Figure 8: Illustration of how incremental adaptation could be applied in response to observed RSLR.

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Using the uncertainty or range of sea-level projections can allow the development of proactive adaptation plans which are flexible and provide adaptation strategies whatever the actual rate and magnitude of sea-level rise, as opposed to the projections (Figure 8). This approach requires a long-term strategy as it requires initial adaptation to support future actions, e.g. an initial seawall needs to be able to support the construction of additional height at a later date or pipework needs to be easily accessible if a further raising of ground levels is required. This type of staged adaptation has been recently adopted in coastal management as illustrated by the Thames Estuary 2100 project (Ranger et al., 2013).

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REFERENCES

Barbier, E. B. (2015) Hurricane Katrina's lessons for the world. Nature, 524, 7565 pp285-287

Becker, A. H., Acciaro, M., Asariotis, R., Cabrera, E., Cretegny, L., Crist, P., Esteban, M., Mather, A., Messner, S., Naruse, S., Ng, A. K. Y., Rahmstorf, S., Savonis, M., Song, D.-W., Stenek, V. & Velegrakis, A. F. (2013) A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. Climatic Change, 120**, 4** pp683-695 http://dx.doi.org/10.1007/s10584-013-0843-z

Binder, S. B., Baker, C. K. & Barile, J. P. (2015) Rebuild or Relocate? Resilience and Postdisaster Decision-Making After Hurricane Sandy. American Journal of Community Psychology, 56, 1-2 pp180-196 http://dx.doi.org/10.1007/s10464-015-9727-x

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T. S., D & Unnikrishnan, A. S. (2013) Sea level change. Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P. M.(Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, Intergovernmental Panel on Climate Change (IPCC) pp1137-1216

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. & Wehner, M. (2013) Long-term climate change: projections, commitments and irreversibility. Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P. M.(Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, Intergovernmental Panel on Climate Change (IPCC) pp1029–1136

Ericson, J. P., Vorosmarty, C. J., Dingman, S. L., Ward, L. G. & Meybeck, M. (2006) Effective sea-level rise and deltas: causes of change and human dimension implications. Global and Planetary Change, 50**,** pp63-82

Gallivan, F., Bailey, K. & O'Rourke, L. (2009) Planning for the impacts of climae change at U.S. ports. Transport Research Record, 2100**,** pp15-21

Gleixner, S., Keenlyside, N., Hodges, K. I., Tseng, W. L. & Bengtsson, L. (2014) An inter-hemispheric comparison of the tropical storm response to global warming. Climate Dynamics, 42**, 7-8** pp2147-2157 http://dx.doi.org/10.1007/s00382-013-1914-6

Headland, J., Trivedi, D. & Boudreau, R. (2011) Coastal Structures and Sea Level Rise: Adaptive Management Approach. Coastal Engineering Practice. American Society of Engineers (ASCE), Reston, VA, USA pp449-459 http://ascelibrary.org/doi/abs/10.1061/41190%28422%2937

.

Hinkel, J., Jaeger, C., Nicholls, R. J., Lowe, J., Renn, O. & Peijun, S. (2015) Sea-level rise scenarios and coastal risk management. Nature Clim. Change, 5**, 3** pp188-190 http://dx.doi.org/10.1038/nclimate2505

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C. & Levermann, A. (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. Proceedings of the National Academy of Sciences, 111**, 9** pp3292-3297 http://dx.doi.org/10.1073/pnas.1222469111

HR Wallingford (2014) The use of climate services for long-lived port infrastructure. Future Climate for Africa study - Scoping Paper. Wallingford, UK, HR Wallingford http://futureclimateafrica.org/wp-content/uploads/2015/02/Report-on-ports.pdf Last accessed 20 October 2015

IPCC (2013) Summary for policy makers. Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P. M.(Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, Intergovernmental Panel on Climate Change (IPCC) pp1-30

Kriebel, D. L. & Geiman, J. D. (2013) A Coastal Flood Stage to Define Existing and Future Sea-Level Hazards. Journal of Coastal Research**,** pp1017-1024 http://dx.doi.org/10.2112/JCOASTRES-D-13-00068.1

Merk, O. (Ed.) (2014) The competitativeness of global port-cities: Synthesis report, Main findings of the OECD Port-Cities programme. Organisation for Economic Co-operation and Development (OECD), Paris, France www.oecd.org/regional/portcities Last accessed 20 October 2015

NGIA (2015) World Port Index. Pub. 150 24th edition. National Geospatial Intelligence Agency http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015 Last accessed 22 October 2015

Nicholls, R. J., Hanson, S. E., Lowe, J. A., Warrick, R. A., Lu, X. & Long, A. J. (2014) Sea-level scenarios for evaluating coastal impacts. Wiley Interdisciplinary Reviews-Climate Change, 5**, 1** pp129-150 http://dx.doi.org/10.1002/wcc.253

Peltier, W. R. (2000) ICE4G (VM2) Glacial Isostatic Adjustment Corrections. in Douglas, B. C., Kearney, M. S. & Leatherman, S. P. (eds.) Sea Level Rise: History and Consequences. Academic Press, San Diego CA, USA http://www.psmsl.org/train_and_info/geo_signals/gia/peltier/

Ranger, N., Reeder, T. & Lowe, J. A. (2013) Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. European Journal on Decision Processes,, accepted**,**

Thoresen, C. A. (2014) Port Designers Handbook, Third Edition. Institution of Civil Engineers (ICE), London, UK

Transportation Research Board (2011) Adapting transportation to the impacts of climate change: State of the practice 2011. Transportation Reseach Circular E-C152 . Special Task Force on Climate Change and Energy. Washington DC, USA, Transportation Research Board of the National Academies http://onlinepubs.trb.org/onlinepubs/circulars/ec152.pdf Last accessed 20 October 2015

US Army (2014) Procedures to evaluate sea-level change: impacts, responses and adaptation. Engineering Technical Letter 1100-2-1. Washington DC, USA, US Army Cops of Engineers http://www.iwr.usace.army.mil/Media/NewsStories/tabid/11418/Article/494304/procedures-to-evaluate-sea-level-change-impacts-responses-and-adaptation.aspx Last accessed 20 October 2015

Vafeidis, A. T., Nicholls, R. J., McFadden, L., Tol, R. S. J., Hinkel, J., Spencer, T., Grashoff, P. S., Boot, G. & Klein, R. J. T. (2008) A new global coastal database for impact and vulnerability analysis to sea-level rise. Journal of Coastal Research, 24**, 4** pp917-924 http://dx.doi.org/10.2112/06-0725.1

.

Wadey, M. P., Haigh, I. D., Nicholls, R. J., Brown, J. M., Horsburgh, K., Carroll, B., Gallop, S., Mason, T. & Bradshaw, E. (2015) A comparison of the 31 January – 1 February 1953 and 5 – 6 December 2013 coastal flood events around the UK. Frontiers in Marine Science, 2, http://dx.doi.org/10.3389/fmars.2015.00084

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APPENDIX 1: LIST OF LARGE PORTS INCLUDED IN THE ANALYSIS

- ALGER, Algeria
- ORAN, Algeria
- BUENOS AIRES, Argentina
- BRISBANE, Australia
- FREMANTLE, Australia
- MELBOURNE, Australia
- NEWCASTLE, Australia
- SYDNEY, Australia
- ANTWERPEN, Belgium
- RIO DE JANEIRO, Brazil
- RIO GRANDE, Brazil
- SANTOS, Brazil
- TUBARAO, Brazil
- VARNA, Bulgaria
- CANAPORT, Canada
- HALIFAX, Canada
- VANCOUVER, Canada
- LAS PALMAS, Gran Canaria
- CHIWAN, China
- DALIAN, China
- QINGDAO GANG, China
- SHANGHAI, China
- TIANJIN XIN GANG, China
- ABIDJAN, Cote d'Ivoire
- RIJEKA LUKA, Croatia
- SPLIT, Croatia
- ANTILLA, Cuba
- GUANTANAMO, Cuba
- CIENFUEGOS, Cuba
- LA HABANA, Cuba
- NUEVITAS BAY, Cuba
- SAGUA DE TANAMO, Cuba
- COPENHAGEN, Denmark
- KOBENHAVN, Denmark
- AIN SUKHNA, Egypt
- ALEXANDRIA, Egypt
- DAMIETTA, Egypt
- PORT SAID, Egypt
- AS SUWAYS, Egypt
- TALLINN, Estonia
- HELSINKI, Finland
- KOKKOLA, Finland
- KOTKA, Finland
- OULU, Finland
- PORI, Finland
- BORDEAUX, France
- BREST, France
- CHERBOURG, France
- LE HAVRE, France
- TOULON, France
- BREMEN, Germany
- BREMERHAVEN, Germany
- HAMBURG, Germany
- KIEL, Germany
- ROSTOCK, Germany
- PIRAIEVS, Greece
- HONG KONG, Hong Kong
- CHENNAI, India
- CALCUTTA, India
- MUMBAI, India
- CILACAP, Java
- JAKARTA, Java
- KASIM TERMINAL, Raja Ampat
- BRINDISI, Italy
- GENOVA, Italy
- NAPOLI, Italy
- SIRACUSA, Italy
- TARANTO, Italy
- TRIESTE, Italy
- LIDO-VENEZIA, Italy
- KAWASAKI KO, Honshu, Japan
- KOBE, Honshu, Japan
- NAGASAKI, Kyushu, Japan
- ONOMICHI-ITOZAKI, Honshu, Japan
- OSAKA, Honshu, Japan
- TOKYO KO, Honshu, Japan
- TOYOHASHI, Honshu
- WAKAMATSU, Kyushu
- WAKAYAMA KU, Honshu
- YOKOHAMA KO, Honshu
- RIGA, Latvia
- BAYRUT, Lebanon
- FUNCHAL, Madeira
- JOHOR, Malay Peninsula
- PORT KLANG, Malay Peninsula
- AGADIR, Morocco
- CASABLANCA, Morocco
- AMSTERDAM, Netherlands
- ROTTERDAM, Netherlands
- AUCKLAND, North Island
- WELLINGTON, North Island
- LAGOS, Nigeria
- OSLO, Norway
- CEBU, Cebu
- MANILA, Luzon
- GDANSK, Poland
- GDYNIA, Poland
- LISBOA, Portugal
- FOYNES, Republic of Ireland
- MURMANSK, Russia
- NOVOROSSIYSK, Russia
- SANKT-PETERBURG, Russia
- VLADIVOSTOK, Russia
- JURONG ISLAND, Jurong Island
- KEPPEL, Singapore
- MUQDISHO, Somalia
- CAPE TOWN, South Africa
- DURBAN, South Africa
- PUSAN, South Korea
- GWANGYANG, South Korea
- INCHON, South Korea
- BARCELONA, Spain
- TARRAGONA, Spain
- GOTEBORG, Sweden
- MALMO, Sweden
- STOCKHOLM, Sweden
- BANIYAS, Syria
- CHI-LUNG, Taiwan
- BANGKOK, Thailand
- ISTANBUL, Turkey
- IZMIR, Turkey
- SAMSUN, Turkey
- ILLICHIVSK, Ukraine
- ODESA, Ukraine
- SEVASTOPOL, Ukraine
- MINA JABAL ALI, UAE
- BELFAST, Northern Ireland
- DUNDEE, Scotland
- IMMINGHAM, England
- LIVERPOOL, England
- LONDON, England
- SOUTHAMPTON, England
- TEESPORT, England
- BALTIMORE, USA
- BOSTON, USA
- BROOKLYN, USA
- CHESTER, USA
- GALVESTON, USA
- HAMPTON ROADS, USA
- LOS ANGELES, USA
- MOBILE, USA
- NEW ORLEANS, USA
- NEW YORK CITY, USA
- NORFOLK, USA
- OAKLAND, USA
- PHILADELPHIA, USA
- SAN FRANCISCO, USA
- SEATTLE, USA
- PUERTO LA CRUZ, Venezuela