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ARTICLE

Towards port infrastructure adaptation: a global port climate risk analysis

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Abstract In this paper, a new concept of "port climate risk exposure function along the sea–land boundary axis" is introduced as a critical component towards port adaptation. This concept derived from a global survey which was conducted over 29 countries to assess perceived climate risks to port infrastructure from relevant experts. The methodology used 48 climate scenarios developed based on existing data. Ultimately, this paper serves as a global climate risk indicator to guide further adaptive initiatives in ports.

Keywords Port infrastructure · Adaptation · Risk · Climate change

1 Background

In December 2015, a new agreement was negotiated at the COP 21 conference in Paris and this has globally raised hope and confidence in the world leadership commitment to fight climate change. Moreover, climate inertia is unfortunately adding further complexity ("Thermal Inertia and Climate," 2005; Vogt-Schilb, Meunier, & Hallegatte, 2012) to the current impasse. Despite the global commitment to reduce GHG, it is expected that climate will still continue to change for a long period before it reaches a state of equilibrium (Becker, Inoue, Fischer, & Schwegler, 2012; Hansen et al., 2013; IPCC, 2014; Plattner, 2009; Rosenschöld, Rozema, & Frye-Levine, 2014; Tebaldi & Friedlingstein, 2013). Sea level rise, droughts, floods, increase heat, intense storm and waves will still be experienced throughout a good part of the present century. This prompts the need for port adaptation, given that seaports are located in areas highly vulnerable to climate variations (Becker et al., 2011; Villatoro et al., 2014; Arns, Wahl, Haigh, Jensen, & Pattiaratchi, 2013; Demirbilek, 2013; PIANC, 2008; Nursey-Bray et al., 2013).

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Meanwhile, while there is a wide recognition for the need to adapt seaports to climate change (Rosenberg et al., 2010; Mcevoy & Mullett, 2014; Becker et al., 2013; "Climate Change and Adaptation Planning for Ports," 2015; Nursey-Bray & Miller, 2011; Wright, 2013; Kintisch, 2008; Karambas, 2014; Dawson, 2008), silo decision-making approach in adaptation initiatives has largely led to the prevailing ineffectiveness of solutions in the industry. This paper analyses global trends on the perceived climate risks in ports with the view to serve as a high-level guideline indicator towards adaptation at ports.

2 Methodology

2.1 Port infrastructure

Port infrastructure forms part of the built environment. They are created by humans to achieve specific functions, and they are expected to have a useful life of 50 to 100 years depending on the design criteria. Since they are conceived by humans during early planning stage of projects, it is paramount that provision to prepare-adapt-respond to climate change (in the wider context of logistic supply chain) be factored during their conceptual stages in order to alleviate or minimise any possible future adaptation which is generally costly and extremely disrupting.

There is currently a large disparity in the literature in respect to the definition of port infrastructure. This ranges from physical port assets to notions that include soft assets such as operating procedures, management practices and development policies ("Sea Port Infrastructure Maintenance Expenditure," 2015; Flor & Defilippi, n.d; "Investment in Sea Port Infrastructure," 2013; Haralambides, n.d.; Taneja, Vellinga, & Sol, 2014). In terms of the physical assets, there is a strong tendency to regroup port infrastructure into six (6) families of basic assets (Tsinker, 1997; Bruun, 2005; Beatley & Wright, 2001; Høgedal, Knudsen, & Lassen, 2001; Homer, Law, & Molyneaux, 2015) vulnerable to the effect of climate change (RMIT University, 2013): berthing structures, protection barriers, port superstructure, channels and harbours, road and rail networks. The term port infrastructure in this paper refers and is limited only to the above families of assets.

2.2 Climate variables

A study by RMIT University1, ed., (2013) concluded that climate variables which would affect long-term performance of the port infrastructure were identified as sea level rise, water table, temperature, rainfall/runoff, wave, wind, salinity and humidity. This research will therefore be limited to the abovementioned climate variables which are most relevant to port.

2.3 Climate narrative

In order to respond to the needs of decision-makers to assess climate risks in ports, climate data projections from a statically downscaled and spatial interpolation methods present significant limitations. The main tools used to project climate are general circulation models (GCMs), which are computer models that mathematically represent various physical processes of the global climate system ("Global Climate Change," n.d.). Processes in this system are generally well known but difficult to be reliably transposed into a localised-port-specific model due to the unique characteristics of each port-city region. Thus, GCM should ideally be considered only at global or continental scales for climatic conditions at longer time scales. For finer spatial and temporal scales, a downscaling process is necessary. This process relies on the assumption that local climate is a combination of large-scale climatic/atmospheric features (global, hemispheric, continental, regional) and local conditions such as topography, water bodies and land surface properties ("Global Climate Change," n.d.). Representation of the local conditions requires additional local-based information, data and assumptions which are generally beyond the capacity of current GCMs. This has led to further uncertainties and limitations of the results.

Because each port is unique and located in distinctive geographical locations (PIANC 2014), it makes it difficult to develop a climatic representation that fits all port geographical and climatic conditions. For this reason, a standard climate narrative is essential to assess port risk, vulnerability and resilience. Impact on ports will be measured based on a standard medium-term variation in climate indices from existing prevailing climatic conditions at corresponding ports. Standard variations in climate indices are considered as the basis for developing a climate narrative to be used across all ports, and consequences of such change on port infrastructure and on logistic supply chain will then be assessed.

Existing predictions from IPCC,[1] NRC,[2] USACE[3] and NOAA[4] (IPCC, 2014; PIANC, 2014; Nicholls, et al., 2008) were assessed and were found to have significant disparities in their results. Meanwhile, results from these assessments highlight visible and clear trends for sea level and temperature-related indices and this is reflecting on the climate narrative developed (Table 1). However, trends on rainfall, wave, wind, salinity, humidity and water table remain extremely uncertain with large disparity. From existing recorded measurements, prediction variations on these variables exceed sometimes the 100 % range from one port to another. This is largely attributed to the close dependence of these variables to port local conditions which are very difficult to factor into climate models. Given the preventive nature of risk assessment approach and for the purpose of this research, larger projection ranges (50 % increase) are used on the standard climate narrative (Table 1) as a conservative way to factor uncertainty for rainfall, wave, wind, salinity, humidity and water table. However, in practical term, when assessing climate risk in specific ports, it is recommended that each port develops its unique and realistic climate narrative that suits local conditions.

2.4 Scenarios

The development of scenarios facilitates communication on climate risks (LTAS, 2015). A scenario in this paper is defined as the exposure of a port family asset to a

[1] Intergovernmental Panel on Climate Change
[2] National Research Council
[3] United States Army Corps of Engineers
[4] National Oceanic and Atmospheric Administration

Table 1 Climate narrative

Climate variables	Unit	Projected medium-term variation
Sea level	m	0.75
Ground water	m	5
Temperature	Degree C	1
Precipitation	%	50
Wave height	%	50
Wind speed	%	50
Salinity	%	50
Humidity	%	50

particular climate variable event. In this respect, the number of scenarios considered in this paper is as follows:

Equation 1: *calculation of number of scenarios*

$$8\text{Climate variables} \times 6\text{port infrastructure families} = 48\text{scenarios}$$

This paper aims at presenting the results of the survey conducted with the view to analyse the trends on the perceived climate risks at ports globally. The survey conducted sought at gathering the views of port experts on the risk and vulnerability associated with 48 standard climate narrative scenarios (Fig. 1) at their respective ports. Based on evaluation and trends, results are

	Sea level variation of 0.75m	5m variation in Water table	Temperature variation of 1deg.C	50% variation in Rainfall	50% variation in Wave heights	50% variation in Wind speed	50% variation in Salinity	50% variation in Humidity
Protection barriers	1	2	3	4	5	6	7	8
Channels and basins	9	10	11	12	13	14	15	16
Berthing structure	17	18	19	20	21	22	23	24
Port super-structure	25	26	27	28	29	30	31	32
Road network	33	34	35	36	37	38	39	40
Rail network	41	42	43	44	45	46	47	48

Fig. 1 Forty-eight scenarios' representation

then analysed. This shall ultimately serve as the basis for developing a framework for adaptation.

3 Survey questionnaire

In recent decades, in order to gain competitive advantage, it is increasingly becoming essential to focus on logistic chain as a way of reducing the price of goods (PIANC, 2014). Efficiency on the logistic chains has nowadays become the main drivers for trade (Liu and Lam 2015). Ports, as essential players in the logistic chains, are increasingly expected to fulfil seamless logistic chain requirements (Gaur 2006). This has resulted in a gradual shift from assessing risk within the port boundaries to a larger scale within logistic chain.

In this study, risk is defined as the probability of affecting smooth running of the port logistic service (movement of goods) as a result of climate scenario. The survey questionnaire was developed with the view to assess the perceived risk associated with each of the 48 scenarios in different ports from various relevant experts. It was designed in such a way that each identified high-risk scenario triggers a subsequent drop-down question. This sub-question aims at assessing vulnerability by evaluating the existing capacity to deal with the identified risk. High-risk scenarios were also subjected to further scrutiny by evaluating whether the port has provision for any redundancy in the system in order to allow seamless port logistic services.

Closed questions were used and answers were to be selected among five given options: "Not relevant", "Low risk", "Medium risk", "High risk" and "I don't know" in respect to the first part of the questionnaire relating to "RISK EVALUATION". The second part titled "EVALUATION OF ALTERNATIVES/REDUNDANCY" only focuses on high-risk scenarios from part 1. High-risk scenario responses from part 1 triggered an additional drop-down question. The additional question served to evaluate whether there was any provision for redundancy/alternatives. Respondents were therefore provided with two options: "Yes" or "No". On the third part of the survey titled "RESILIENCE MEASUREMENT", high-risk scenarios from part 1 are assessed to evaluate the approximate time required to repair and bring the infrastructure to its original functionality. Seven options were provided for selection: "Less than 1 month", "1 to 2 months", "2 to 3 months", "3 to 4 months", "4 to 5 months", "5 to 6 months" and "greater than 6 months". In addition, at the end of the survey, an optional open question was used to seek respondents' general comments on the survey but a very poor participation of less than 5 % was unfortunately recorded in this respect.

The survey questionnaire layout is illustrated in Fig. 2.

4 Survey participation

As the researcher is a member of PIANC5, the survey was primarily disseminated via a link on SurveyGizmo to all PIANC members. Additionally, current

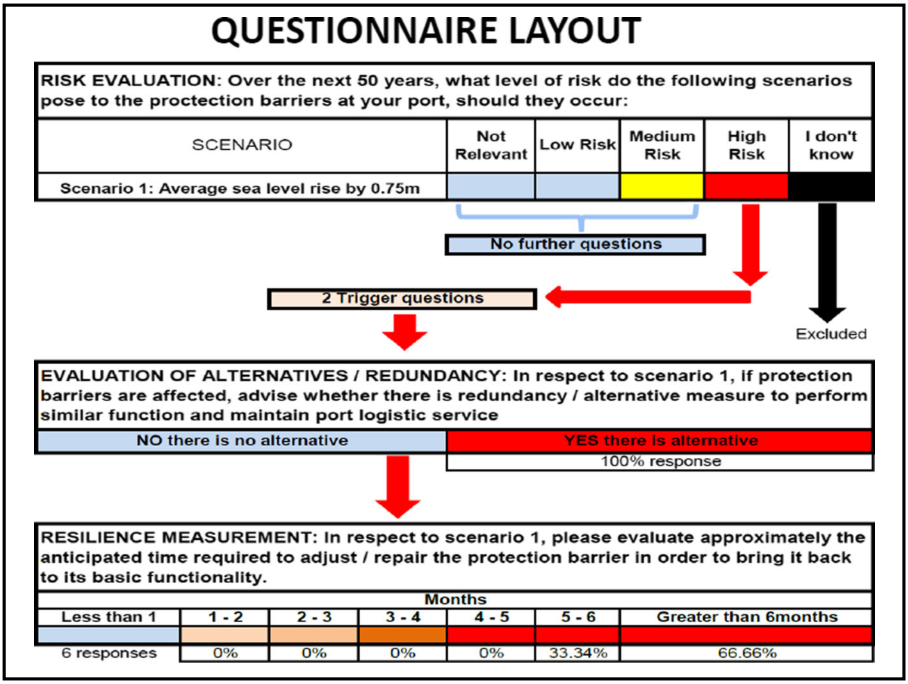

Fig. 2 Survey questionnaire layout

WMU6 master students and alumni groups were contacted via email to assist with further dissemination to the relevant experts in their respective ports. The survey opened on 11 May 2015 and closed on 29 July 2015. Given that the survey was conducted online and disseminated to PIANC[5] members via PIANC global secretariat in Brussels, it is impossible to determine with accuracy the actual response rate. Nevertheless, based on SurveyGizmo online record, from a total of 115 potential participants who had at least clicked on the survey link, we have received 69 responses of which 50 were valid, representing an impressive virtual response rate of 43.5 %.

Table 1 provides details of survey participants, and the participation distribution was fairly equitable and satisfactory as shown in Fig. 3.

5 Survey results: data processing and interpretation

5.1 Risk evaluation

For risk evaluation, a Likert scale from 0 to 3 was introduced to facilitate data processing with 0, 1, 2 and 3 representing, respectively, “Not relevant”, “Low”, “Medium” and “High risk”. In order to ensure fair representation of results, all “I don’t know” responses (representing in red on Table 2) were omitted from the

[5] The World Association for Waterborne Transport Infrastructure (www.pianc.org)

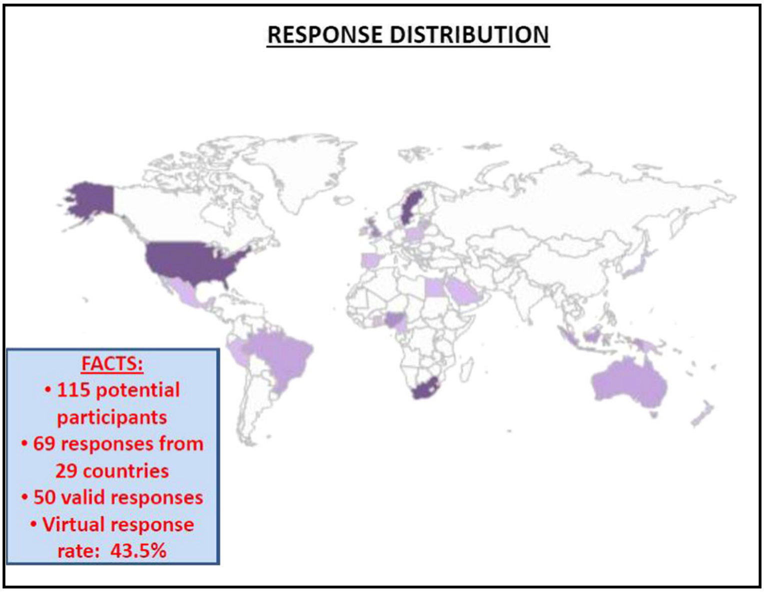

Fig. 3 Participation distribution

scale and disregarded. This practice assisted in improving accuracy of results during data processing and it also led to different response rates for the different scenario questions. For each scenario, using a Likert scale, a mean score could then be calculated.

The graphical representation (Fig. 4) suggests that, with respect to climate change, industry is generally concerned about the impact of wave and wind force variation on protection barriers in ports. This trend also reinforces the general prevailing sentiment across the industry that climate extremes (often a combination of wind and wave at extreme proportion) are the main climate concern (PIANC, 2009) in ports. However, it is worth placing on record that the above results are only a representation of a global trend. Given the particularity of each port, there are certainly ports that may in fact present different climate risk configurations. As such, it should be noted that this information should therefore be considered as a high-level guideline to assist ports in developing specific solution-focussed initiatives to climate change.

5.2 Evaluation of alternative (redundancy) and resilient measurement

Judging from survey responses, for all high-risk scenarios, there are no alternative or redundancy for maintaining smooth logistic services. Based on responses to triggered question 3, for all high-risk scenarios, repairs (in order to bring back the port infrastructure to its original functionality) will take a minimum of 5 months or longer. Given that vulnerability and resiliency of the port logistic system are, respectively, defined by the provision of alternative and ability to recover promptly (PIANC, 2014), all high-risk scenarios therefore

Table 2 Survey participation

Country	No.	Percent (%)
South Africa	17	24.6
USA	9	13.0
Nigeria	4	5.8
Kenya	4	5.8
Indonesia	4	5.8
Portugal	3	4.4
Brazil	3	4.4
UK	2	2.9
Netherlands	2	2.9
Egypt	2	2.9
Peru	1	1.5
Angola	1	1.5
Poland	1	1.5
Saudi Arabia	1	1.5
Thailand	1	1.5
Sweden	1	1.5
Papua New Guinea	1	1.5
Sri Lanka	1	1.5
Gambia, The	1	1.5
Cameroon	1	1.5
Panama	1	1.5
Australia	1	1.5
Guatemala	1	1.5
Brunei	1	1.5
Latvia	1	1.5
Jamaica	1	1.5
Italy	1	1.5
Mexico	1	1.5
Ireland	1	1.5
	69	

present high vulnerability and low resiliency in the context of the port logistic system, a major cause of concern.

5.3 Trend analysis

It was found from Fig. 5 that port climate risk score is higher on sea side and gradually reducing towards land side. Moreover, due to each port unique configuration, it is difficult to allocate firm distances along the *X* axis for each family asset. Therefore, reduction in climate risk score from sea to land boundary of port cannot be represented in terms of regression, although the graph on figure clearly suggests a progressive and

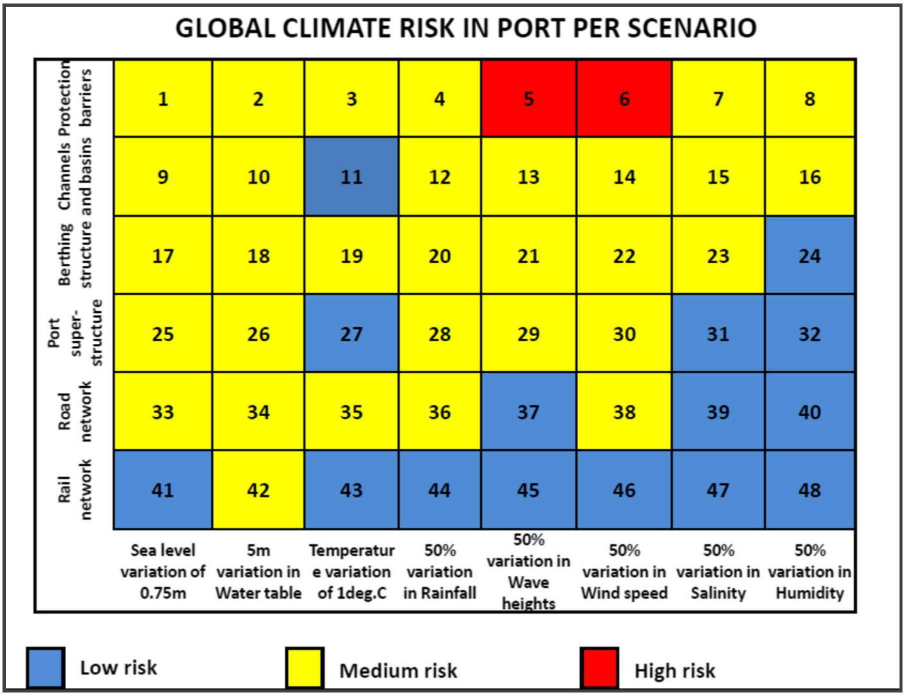

Fig. 4 Results of global climate scenario based on average mean score

significant reduction in risk score from sea to land boundaries. An illustration of this climate risk exposure along the sea–land boundary axis is clearly shown in Fig. 6.

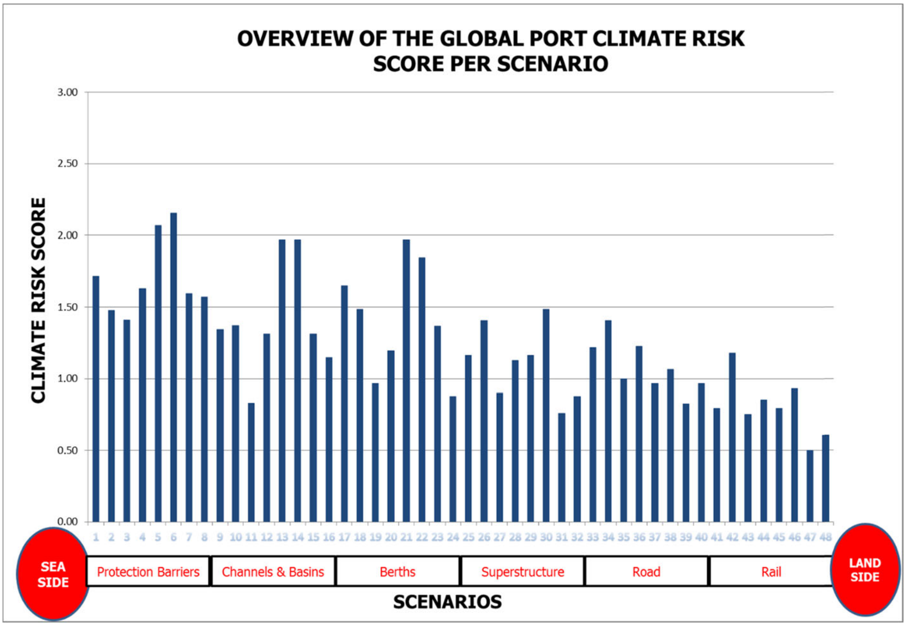

Fig. 5 Global port climate risk score per scenario

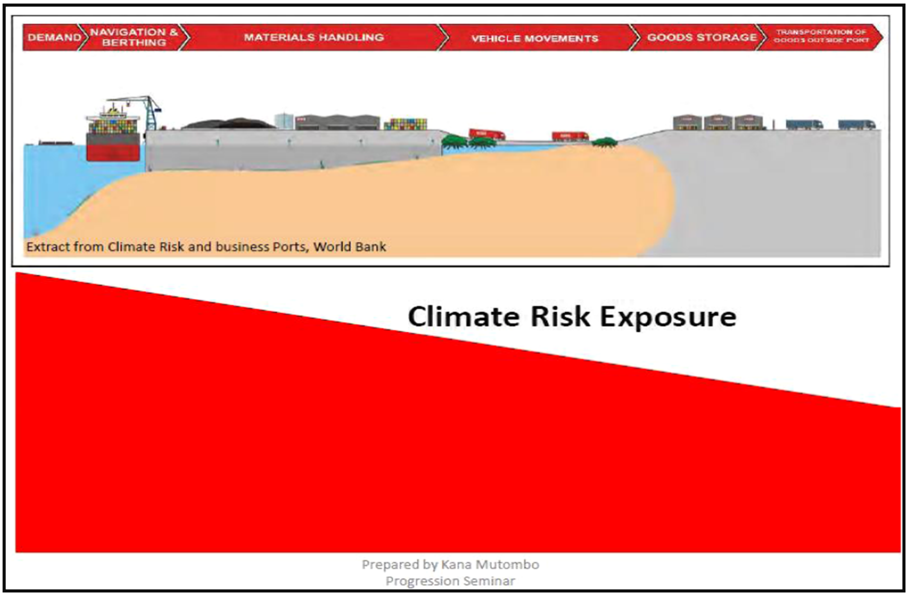

Fig. 6 Illustration of sea–land boundary axis

Additionally, as shown in Fig. 7, changes in wind, wave, ground water, sea level rise and precipitation are port's biggest climate concerns, scoring, respectively, *1.58*, *1.49*, *1.39*, *1.31* and *1.22*. On the contrary, changes in salinity, humidity and temperature are relatively classified as low risk in ports, scoring, respectively, *1.06*, *1.01* and *0.98*. The top two port climate concerns are wind and

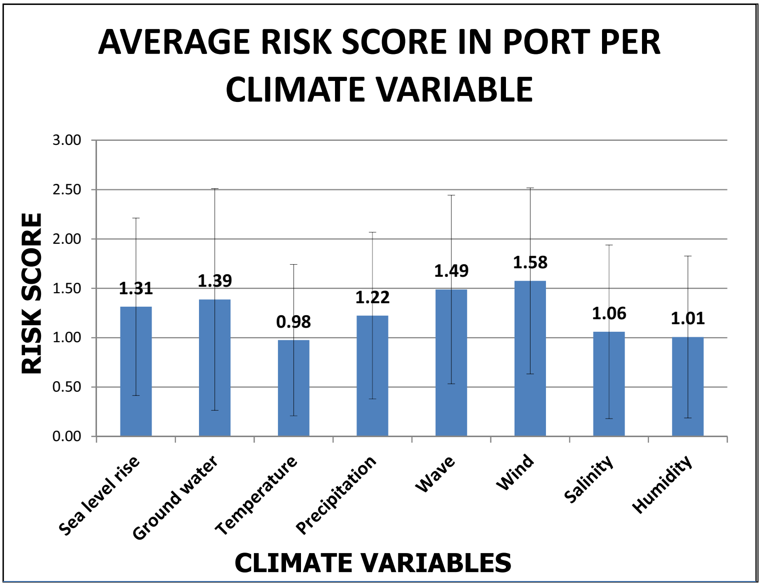

Fig. 7 Global average risk score per climate variable

wave; a tendency that reflects largely in many literature (Hunter, Church, White, & Zhang, 2013; PIANC 2014; IPCC 2014) as climate extreme.

6 Conclusion

The climate risk exposure along the sea–land boundary axis is critical in steering the way climate adaptation investments are allocated in ports. Furthermore, it should trigger new way of thinking with respect to port planning and design approaches. This information should influence by large port configuration during the early stage of development and it could provide significant guidance for design engineers when factoring climate change in infrastructure design calculations. Traditionally, approach to infrastructure design is based on an optimal solution for the worst possible case scenario plus a standard safety factor. New approach taking into consideration a climate safety factor which will be dependent on the position of the infrastructure along the sea–land port axis could therefore be essential.

In the light of this, since climate risk sensitivity differs from port to port, it is encouraged that each port determines its unique sea–land port boundary axis with regression by taking into consideration infrastructure distance measurements and develop a function of risk along such axis. However, in smaller ports with limited resources or in a port where climate change is not perceived as a major threat, in the absence of a specific sea–land climate risk function, the above general function in Fig. 5 could be very useful for guidance.

Meanwhile, it is worthwhile mentioning that this study is conducted based on perceptions of risks which could be vastly subjective. It is therefore recommended that, when assessing climate risk score, each port should consider various techniques (e.g. Delphi) in order to minimise subjectivity and increase reliability of results.

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