## PIANC De Paepe-Willems Award 2019 – Third Place

# SEAPORTS IN GERMANY – VULNERABILITY AND ADAPTATION TO CLIMATE CHANGE

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## 1 INTRODUCTION

Seaports play an important role as hubs in the transhipment of goods and are an important driver of the economy and employment in the respective regions. Due to their location on the coast, they are particularly affected by the impending sea level rise due to climate change. Their functionality is also threatened by other consequences of climate change, such as the increase in extreme weather events. To ensure that seaports are equipped to meet both economic and environmental demands in the future, their vulnerability to climate change must be analysed at an early stage and measures to increase their resilience must be taken into account in port management.

In 2020, the PIANC Working Group 178 published the guideline 'Climate Change Adaptation Planning for Ports and Inland Waterways' [PIANC, 2020]. The guideline contains recommendations for the preparation of an adaptation strategy for ports and waterways in a four-stage process, whereby the relevant stakeholders are involved in each stage. The four stages cover the following:

1. Context and objectives
2. Climate information
3. Vulnerabilities and risks
4. Adaptation options

This paper presents the application of the PIANC guideline to German seaports, which was carried out as part of the project PortKLIMA 'Development and Pilot Implementation of Educational Modules for Integrating Climate Change Adaptation into the Planning, Construction and Operation of Seaports in Germany'. A total of seven German seaports respectively their management organisations were involved in the project (Figure 1). As part of the project, interviews were conducted with the involved port management organisations in order to assess how the seaports involved are currently affected by extreme weather events and whether climate change adaptation measures are already in place.


*Figure 1: Location of seaports involved in the project at the German North and Baltic Sea coast*

# 2 RISKS AND OPPORTUNITIES RESULTING FROM CLIMATE CHANGE FOR GERMAN SEAPORTS

The vulnerability of seaports to climate change is manifold. Figure 2 shows an overview of relevant climate parameters and their effects on the different areas of seaports identified within the framework of the PIANC guideline. The current impact on the German seaports involved in the project PortKLIMA is shown in the boxes. It can be assumed that the current impact will increase in the future. Therefore, the systematic documentation of current impacts is a good starting point for deriving adaptation measures. Nevertheless, further impacts may occur in the future. However, it is important to notice that the cause is not only to be found in the climate system, as human interventions, such as deepening of fairways or an increase in ship sizes, can also be the cause of increasing challenges. If weather-related damage occurs, it may also be caused by material fatigue or lack of maintenance rather than the immediate extreme weather event.

Due to their location, seaports are particularly exposed to the effects of high water levels and strong winds. High water levels are already today becoming a problem for ports when the quay levels are only slightly above the mean high water level. Such quays are protected from flooding by walls located on the quays. Cargo handling in the port can only take place at certain wind strengths. Damage as a result of storm events, such as damaged roofs, is not unusual. In the past, there have also been isolated cases of overturned empty containers. The increase in ship sizes has increased their windage area. The challenges to be mentioned in relation to strong winds and ship sizes are the mooring of ships with partly increased use of tugs, scour damage due to bow thruster and occasionally ships that have broken loose, as well as ships that cannot enter narrow port entrances in extreme situations. In a few cases, unusual strong wind events were observed. These include long-lasting strong wind events in summer and storm events from an atypical direction.

The occurrence of hot spells has different effects on seaports. Especially for employees working in non-air-conditioned areas, high air temperatures are problematic. For older workers in particular, the high temperatures in the summers of 2018 and 2019 were a major challenge. Due to the high workload, there were also occasional failures of air conditioning systems in vehicles, which could be counteracted by switching them off during the night. In some ports, high temperatures caused damage to pavements (asphalt) and to track systems or impaired the operation of movable steel bridges. Furthermore, some work cannot be carried out at high temperatures.

Heavy precipitation events have hardly caused any problems in the ports. However, the handling of moisture-sensitive goods is restricted during precipitation. Storm water can often drain off well via the terminal drainage or the quay edge. So far, flooding has only occurred locally and for short periods. Gravelled areas may have to be prepared more frequently to prevent puddles from forming.

The future handling of storm water run-off from the terminal areas needs to be discussed in order to avoid critical water quality situations in the receiving waters when water temperatures rise and thus oxygen concentrations decrease. There is also the question of the capacity of the receiving waters in the event of rising sea levels.

In the past, a lack of precipitation affected the ports in different ways. Due to the resulting low water levels on the Rhine, a shift of freight flows to the railways could be observed, which led to a shortage of rail wagons, but also to a redistribution of goods to other port locations. Water levels that are too low also pose the risk of falling below the design water levels at the quays, so that the affected quays had to be closed for cargo handling.

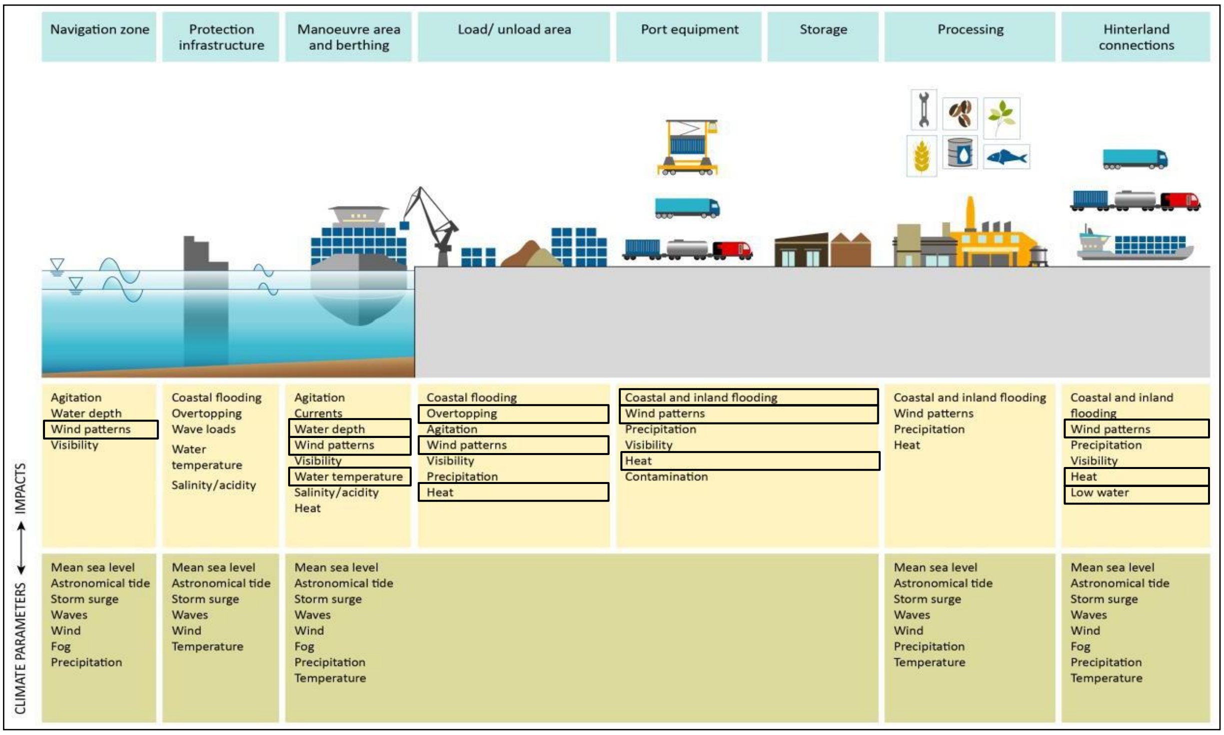


*Figure 2: Climate parameters and possible impacts on a seaport [PIANC, 2020]. The impacts highlighted in the boxes have already been observed in the German seaports participating in the project PortKLIMA.*

The hinterland connections by ship, rail or truck are essential for maintaining the flow of goods. In the past, they were disrupted by low water levels and rail line failures due to storm damage or embankment fires as a result of extreme weather events.

Sediment transport or management in ports depends on a variety of factors. Both positive and negative effects on sediment management have been observed by affected ports, without being able to prove the exact causes in detail. Rising water temperatures and low oxygen concentrations may in future further limit the days on which sediment management measures such as dredging are permitted.

Locally, salt spray occurred within two years in a row. As a result, there have been problems with the power supply and the failure of overhead lines on railway tracks in the affected region. The event is actually considered to occur rarely.

In some ports, a change in freight flows due to extreme weather events could be observed. In addition to a diversion of goods as a result of low water, these include timber imports as a result of storm damage and grain exports or feed imports as a result of extreme drought. The changes in the flow of goods have so far not been negative for the ports for the most part, but not necessarily positive either.

Overall, the current impact on the ports involved is not to be classified as exceptional compared to historical conditions. However, the first challenges related to changing climatic conditions are becoming apparent.

In the final workshop of the PortKLIMA project, after the expected future regional climatic changes had been presented, the participants were asked for their personal assessment of the greatest future direct impact on the respective port (Figure 3). According to this, the greatest direct impact is the height of storm surge water levels, followed by the rise in mean sea level, the increase in heavy rain and severe weather events, extreme heat periods and storms.

Even if the negative consequences of climate change outweigh the positive ones, climate change will have positive effects. For example, it is expected that ice and snow will occur less frequently in winter due to increased mean air temperatures. Rising sea levels will also increase water depths in waterways and harbours. A possible competitive advantage may arise from a port being better prepared than other locations to meet the challenges. Opportunities may also arise from climate change-related changes in freight flows.

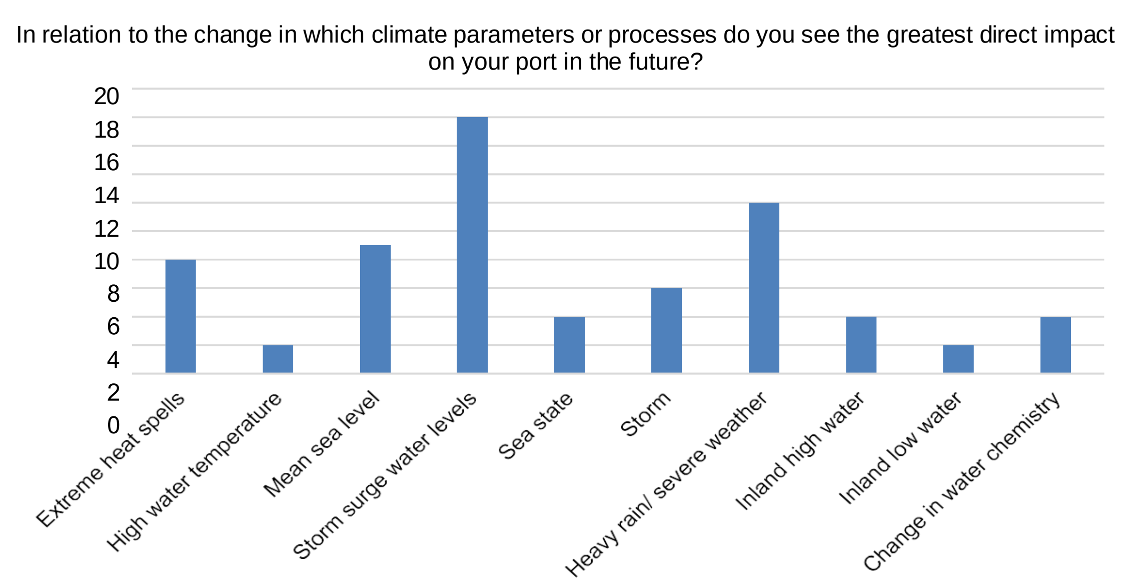


*Figure 3: Result of the survey conducted during the final workshop regarding the greatest direct impacts expected for the port in the future (multiple-choice question, 22 participants)*

# 3 RELEVANT ASSET SERVICE LIVES AND THEIR SIGNIFICANCE FOR ADAPTATION MEASURES

For the development of an adaptation strategy, the planning horizon should take into account the service life of assets and the extent of change in relevant climate parameters and processes in relation to the service life of the assets. Table 1 shows an overview of average economic service lives of assets in seaports.

| Asset | Average economic service life [Years] |
|---|---|
| Terminal- and port superstructure | Container bridge: 20[1], 15[2]<br>Mobile crane: 15[1]<br>Straddle carrier: 6[3], 5-10[1]<br>RoRo ramp: 15[3]<br>Warehouse: 25[3], 40[1]; concrete: 25[2]; lightweight: 10[2] |
| Pavement | Asphalt: 10-15[1]; concrete: 20[1];<br>Roads/surface pavements: 15[2] |
| Railway track | According to legal requirements: 25[2]; other: 12[2] |
| Drainage | Drainage: 33[2] |
| Quay wall | Concrete: 40[3]; steel: 25[3]<br>Sheet piling: 50[1], 20[2]; open berth: 50-100[1],<br>Rubber fender: 10[3], 10-20[1] |
| Flood protection structure | >100[1] |
| Breakwater | 50[3], 100[1] |
| Dolphin | 20[2] |
| Pontoon | Concrete: 30[2]; metal/ steel: 30[2] |
| [1] Thoresen (2010)<br>[2] Bundesfinanzministerium (2020)<br>[3] United Nations Conference on Trade and Development (1985) | |

*Table 1: Average economic service life of assets in seaports. Actual service lives of individual assets depend on individual asset conditions and use and can therefore extend beyond the average economic service life*

For assets with short service lives or measures with short reaction times, it is generally easier to consider climate change impacts in planning. Measures can be implemented when a clear trend emerges and assets or equipment need to be renewed regardless of climate change. However, weather-related downtime and damage can already occur as a result of extreme weather. Therefore, if the potential damage is high, adaptation measures may already be appropriate for assets with short service lives. Terminals for special industries also have the advantage that they often have short service lives of up to 30 years, as the assets have to be adapted more frequently to changing economic and technical requirements. However, especially for assets with long service lives or long reaction times, the effects of climate change need to be considered at an early stage. If the potential damage is low, risks can be accepted. A possible decision matrix for evaluating the need for adaptation measures is shown in Table 2. At present large investments solely for the purpose of adaptation are generally not made for economic reasons.

| **Potential damage**<br>**Service life/ reaction time** | Low | High |
|---|---|---|
| Short | Ad-hoc measures | Continuous investigation |
| Long | Accept risks | Take preventive action early |

*Table 2: Decision matrix to assess the need for adaptation measures according to Norpoth et al. (2020)*

The participants of the final workshop were asked about their personal assessment of an extraordinary need for adaptation in their area of responsibility (Figure 4). Approximately half of the participants see an extraordinary need for adaptation or none at all.

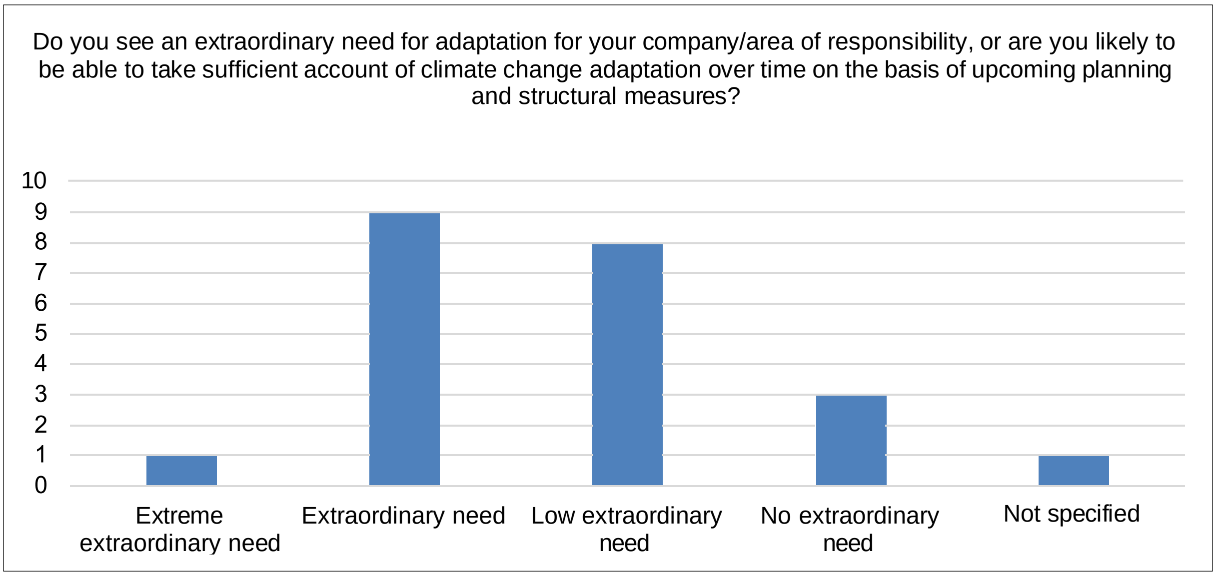


*Figure 4: Result of the survey carried out during the final workshop of the project PortKLIMA regarding the extraordinary need for adaptation*

# 4 REGIONAL IMPACTS OF CLIMATE CHANGE

After identifying relevant assets, port-related activities and related time horizons, as well as relevant climate parameters and processes, climatic changes for the recent past as well as for the future are determined. An overview of climatic changes for the North German coast is presented below, separated into meteorological (Table 3) and oceanographic (Table 4) parameters.

Extreme conditions are of particular interest for the dimensioning of assets and restrictions in operation. In this context, annualities are often used in planning, which are determined on the basis of probability or distribution functions and extreme values determined from hydrographs, e.g. annual maximum. In contrast, climate models are often used to investigate the change of certain threshold values (e.g. annual 98$^{th}$ percentile) for climatically relevant time horizons without considering the effects on the annuality. Especially since reliable statements about the change in annualities of particularly rare extreme events require extensive ensembles, and their changes cannot be inferred across-the-board from change signals of less rare extreme events, even in the context of climate change [Lang and Mikolajewicz, 2020]. Thus, in addition to uncertainties in climate projections, there is another source of uncertainty as a result of the required transfer of climate projection results to relevant design parameters, which cannot be quantified in more detail or minimised substantially based on the available information.

In the long term, seaports will be affected primarily by the influence of sea level rise on the frequency of extreme water levels. The extent of the impairment depends not only on future greenhouse gas emissions, but also on the elevation of port areas. Depending on the scenario, by the end of the century a mean sea level rise of at least 0.4 m can be expected, which can also reach around 1.0 m or more if extreme changes occur (see Table 4). Beyond 2100, sea level rise of about 1.0 m is expected even with strong climate action [IPCC, 2019]. The effects of sea level rise on tidal dynamics are subject to uncertainties i.e. due to the future evolution of bathymetry associated with sea level rise [Winkel et al., 2020]. Overall, the influence on characteristics of high and low tides in German seaports is estimated to be small [Rasquin et al., 2020]. The same is true for the influence of mean sea level rise on wind surge (cf. Seiffert et al. (2014), Arns et al. (2017), Gräwe and Burchard (2012)) and wave parameters [Groll et al., 2014 ; Mai and Zimmermann, 2004]. Nevertheless, a rather small and negligible increase in terms of absolute height, also due to existing uncertainties, may have a more significant impact on the recurrence interval of an extreme water level event, so that, if necessary, the influence of tide and wind surge should be considered in the context of change in annuality.

In addition, increasing air temperatures and related events such as prolonged periods of heat and drought, extreme precipitation events, and rising water temperatures are to be expected [IPCC, 2021]. Annual maximum air temperature is expected to increase more than mean air temperature [IPCC, 2021]. Reliable statements for changes in design precipitation values based on the KOSTRA Heavy Rain Atlas are difficult due to the large model resolution required [Rauthe et al., 2020]. The Clausius-Clapeyron relationship appears to be a good benchmark to estimate the change in future extreme precipitation, but other dynamic factors, such as tracks of extratropical storms, also play a role [Lehmann et al., 2015]. Using the Clausius-Clapeyron relationship, it is possible to infer the increase in maximum air water vapour content with an increase in air temperature. There is also evidence of a disproportionate increase in convective heavy precipitation compared to the Clausius-Clapeyron relationship, although this weakens with increasing air temperature (from about 20° C) [Berg et al., 2013] and is therefore less relevant for summer heavy precipitation with the potential for particularly high precipitation intensities. As an alternative to the Clausius-Clapeyron relationship, an orientation towards the tolerance ranges according to KOSTRA [Junghänel et al., 2017], i.e. depending on the annuality +10 % ($T \leq 5a$), +15 % ($T \leq 50a$), or +20 % ($T \leq 100a$), can be recommended.

Future changes in mean sea level and air temperature show robust change signals with more or less increase depending on the climate scenario, thus are mainly subject to scenario uncertainty. Future changes in storm climate and mean precipitation characteristics show less robust change signals. They are characterized by model uncertainty - the influence of the driving climate model - and are subject to stronger natural variability, i.e. their climate change signals often do not stand out as clearly from the natural background variability [DWD, 2020 ; Helmholtz-Zentrum Hereon, 2021a ; de Winter et al., 2013 ; Ganske, 2019]. Uncertainties in the future wind climate inevitably affect statements about the future development of wind surge and sea state.

| Climate parameter | Historic change | Future change |
|---|---|---|
| Average air temperature | +0,8°C (year), significant change[1] | +1,0 to +5,1°C (year)[2] |
| Hot days (Tmax ≥ 30 °C) | +2 days (year), no significant change[1] | +0 to +30 days (year)[2] |
| Ice days (Tmax < 0°C) | -7 to -5 days (year), no significant change[1] | -37 to -3 days (year)[2]<br>Despite decrease, potential for cold winters increases[3] |
| Mean precipitation | +8 % (winter/ summer), no significant change[1] | -46 to +56 % (summer), +3 to +42 % (winter)[2] |
| Heavy rainfall days (≥ 20 mm) | No change[1] | 0 to +5 days (year)[2] |
| Heavy rain intensity | No statement possible due to available data[4] | +7% per °C as rough approximation[5] |
| Mean wind speed | +2 % (year), +6 % (winter), significant change[1]<br>Shows decadal variability | Mid-century: -3 to +4 % (year),-5 to +7 % (winter)[6]<br>End-century: -4 to +7 % (year), -8 to +14 % (winter)[2] |
| Storm intensity<br>vmax at 10 m height | +1 % (year), +5 % (winter), no significant change[1]<br>Shows decadal variability | Mid-century: -2 to +5 % (year),-4 to +11 % (winter)[6]<br>End-century: -4 to +4 % (year), -8 to +10 % (winter)[2] |
| Storm days (vmax > 62 km/h) | +3 days (year), +3 days (winter), no significant change[1]<br>Shows decadal variability | Mid-century: -7 to +13 days (year),-4 to +7 days (winter)[6]<br>End-century: -8 to +14 days (year), -8 to +10 days (winter)[2] |
| Wind direction | N. s. | More frequent winds from westerly directions possible[7] |
| Severe weather risk | No statement possible due to available data [8] | No significant change for the North German coast[9] |

1 1986-2015 relative to 1961-1990 for the North German region Helmholtz-Zentrum Hereon (2021b)
2 2071-2100 relative to 1961-1990 for the North German region Helmholtz-Zentrum Hereon (2021a)
3 Dethloff et al. (2018)
4 Becker et al. (2016); 5 Lehmann et al. (2015)
6 2036-2065 relative to 1961-1990 for the North German region Helmholtz-Zentrum Hereon (2021a)
7 de Winter et al. (2013), Gaslikova et al. (2013), Dreier et al. (2015), Ganske (2019)
8 Kunz et al. (2017); 9 Púčik et al. (2017)

*Table 3: Observed and possible future change of meteorological climate parameters in northern Germany*

| Climate parameter | Historic change | Future change |
|---|---|---|
| Mean sea level | Corresponds approximately to global SLR (1900-2015):[1] 1,7 mm/a German North Sea<br>1 to 1.7 mm/a German Baltic Sea | Corresponds approximately to global SLR[1]<br>Mid-century (2046-2065): Approx. 0.25 to 0.30 m [2]<br>End-century (2100): Approx. 0.40 to 0.85 m [2] / 1,1 m [3]<br>Extreme-scenario: 1.74 m [4] |
| Tidal characteristics | Tidal high water has increased more than tidal low water over the last 100 – tidal range has increased[5] In estuaries strongest changes (human intervention)[6]<br>Nevertheless, a global influence is emerging[7]<br>Causes of the increase have not been conclusively clarified[8] | Varies locally; in general, the influence of SLR is expected to be negligible[9] |
| Storm surge | Depending on tide gauge: increase in frequency of minor storm surges due to SLR or no change10 | SLR will have the greatest impact on storm surge water levels<br>Additional increase in wind surge due to SLR will affect mainly middle/upper areas of estuaries as well as inland areas of the Baltic Sea [11,12]<br>Increasing storm intensities are expected to result in an increase in wind surge in the range of a few decimetres (up to 0.1 to 0.2 m along the coast and 0.3 m in the middle/ upper reaches of the estuaries) [11,12] |
| Annuality | N. s. | 100-year event will occur approx. every 10-20 years at the end of the 21st century[13] |
| Sea state | Correlates with the development of wind14 | In the case of large water depths, such as those found in seaports, the change in wind speed plays a particularly important role[15]<br>Correlates with the development of wind[14]<br>As a rough approximation for wave height: change of about the same order of magnitude in percentage (non-fully developed sea) or twice the order of magnitude in percentage (fully developed sea) as change in storm intensity |
| Inland low-water | N. s. | Little relevant to marine waterways or lower estuary<br>Significant increase in impact on shipping at the end of the 21st century for the RCP8.5 scenario (Rhine, Elbe, Ems and Danube)[16] |
| Inland high water | N. s. | Little relevant to marine waterways or lower estuary<br>Increase expected from middle of 21st century especially for RCP8.5 scenario (winter), but with only a few days on which shipping is restricted[16] |
| Water temperature | N. s. | +1-3°C (German North Sea), +3-4°C (German Baltic Sea)[17]<br>Increase in frequency of thresholds critical for water quality (T >25°)[18] |
| Salinity | N. s. | Up to -1‰ (German North Sea)19, up to -2‰ (German Baltic Sea)20 Shift of brackish water zone upstream[11] |
| pH value (global) | -0.121 | Up to -0,3 (RCP8.5)[13] |

[1] Deutsches Klima Konsortium and Konsortium Deutsche Meeresforschung e.V. (2019); [2] 50th percentile of RCP2.6 to RCP8.5 scenario relative to 1986-2005; [3] 83th percentile of RCP8.5 scenario relative to 1986-2005; [4] Schade et al. (2020), considers uncertainty of Arctic/Antarctic ice sheets; [5] BMVI (2015); [6] Winterwerp and Wang (2013); [7] Jensen and Mudersbach (2004); [8] Mawdsley et al. (2015); [9] Rasquin et al. (2020); [10] Helmholtz-Zentrum Hereon (2021c); [11] Seiffert et al. (2014); [12] Gräwe and Burchard (2012) [13] IPCC (2019) [14] Weiße and Meinke (2017); [15] see e. g. Mai and Zimmermann (2004) [16] Nilson et al. (2020); [17] Klein et al. (2018); [18] for example, up to 35 days for the RCP8.5 scenario in the Elbe and Rhine (Nilson et al. 2020); An increase in bacterial counts or human pathogens can be expected (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2010); [19] Schrum et al. (2016); [20] Meier (2015); [21] European Environment Agency (2017)

*Table 4: Observed and projected future change in hydrological and oceanographic climate parameters in northern Germany. SLR: Sea level rise*

# 5 VULNERABILITY AND RISK FOR SEAPORTS IN GERMANY

Based on expected changes of relevant climate parameters and processes at the German coast, a general assessment of exposure and vulnerability for different assets and activities in German seaports was carried out. The assessment is done qualitatively based on the PIANC guideline [PIANC, 2020]. Table 5 shows an example of the result of the overarching vulnerability analysis based on Level 3 of the PIANC guideline for a moderate greenhouse gas scenario (RCP4.5), which must currently be considered a realistic scenario [Hausfather and Peters, 2020].

| | Compared to historical data, how does exposure change due to potential climate hazards within the planning horizon?<br>Significant increase<br>Increase<br>No change<br>Decrease<br>Significant decrease | | | | | Considering relevant thresholds and existing adaptive capacity, how is vulnerability likely to change?<br>↑↑ Significant increase<br>↑ Increase<br>No change<br>↓ Decrease<br>↓↓ Significant decrease | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Examples of relevant climate parameters and processes →<br>Examples of critical assets, operations, systemes ↓ | Extreme heat | Sea level rise | Storm intensity | Sea state | Heavy rain | Extreme heat | Sea level rise | Storm intensity | Sea state | Heavy rain |
| Access to the berth – fairway | ↑ | ↑ | → | → | ↑ | → | →/↓[1] | → | → | → |
| Locks | ↑ | ↑ | → | → | ↑ | → | →/↑[2] | → | → | → |
| Quays | ↑ | ↑ | → | → | ↑ | → | →/↑[2] | → | → | → |
| Other berthing facilities | ↑ | ↑ | → | → | ↑ | → | →/↑[3] | | | → |
| Mooring facilities | ↑ | ↑ | → | → | ↑ | → | →/↑[2] | → | → | → |
| Mooring, loading and unloading | ↑ | ↑ | → | → | ↑ | ↑ | →/↑[2] | → | → | ↑ |
| Handling equipment | ↑ | ↑ | → | → | ↑ | ↑ | →/↑[2] | → | → | → |
| Flood protection facilities | ↑ | ↑ | → | → | ↑ | → | →/↑[2] | → | → | → |
| Storage areas | ↑ | ↑ | → | → | ↑ | →/↑[4] | →/↑[2] | → | → | →/↑[2] |
| Warehouses | ↑ | ↑ | → | → | ↑ | ↑ | →/↑[2] | → | → | →/↑[2] |
| Roads | ↑ | ↑ | → | → | ↑ | →/↑[4] | →/↑[2] | | | → |
| Railway tracks | ↑ | ↑ | → | → | ↑ | ↑ | →/↑[2] | → | → | →/↑[2] |
| Drainage systems | ↑ | ↑ | → | → | ↑ | → | →/↑[2] | | | ↑ |
| Buildings | ↑ | ↑ | → | → | ↑ | ↑ | →/↑[2] | → | → | →/↑[2] |

[1] Depending on development of sediment transport
[2] Depending on existing freeboard/ the elevation/ the topography
[3] Depending on asset and service life
[4] Depending on pavement (asphalt, concrete, paving) and service life

*Table 5: Exemplary result of an overarching vulnerability analysis for seaports in Germany based on PIANC (2020) for the near and distant future of the 'moderate' scenario (RCP4.5).*

The analysis shows that for the scenario in question, it is above all the rise in air temperature and mean sea level as well as heavy rainfall that result in an increase in the vulnerability of seaports in Germany. However, statements are partly dependent on individual conditions on site (freeboard, significant wave height, geographical orientation of berth). In principle, the analysis should be differentiated according to various climate scenarios.

Schröder et al. (2013) questioned 10 ports on the Baltic Sea coast when a sea-level rise would have problematic effects for the respective port. 20 % of respondents indicated a sea level rise of 40-59 cm and 90 % a rise of 80-99 cm as problematic. If the results of the study are applied to the entire German coast, the majority of ports would only be significantly affected by a sea-level rise such as that expected under the 'business as usual' scenario at the end of this century.

With regard to the influence of extremely high temperatures, in addition to the stress on employees in non-air-conditioned rooms, an increased vulnerability of or increased need for air-conditioning must be mentioned. Furthermore, materials can also be affected by extreme temperatures. In addition to asphalt pavements, which can be adapted during replacement, depending on their service life, sun- exposed steel components and electronic switching elements should be considered. Heavy rainfall primarily affects drainage systems and, if they are overloaded, areas affected by flooding as well as buildings, and leads to impairments in handling activities.

As part of the development of an adaptation strategy, the probability of being affected and the degree of risk for the port must be assessed. Compared to identification of relevant climate parameters and processes according to Storch et al. (2018), this is the area with the greatest potential for uncertainty regarding the effects of climate change on seaports. However, from the current perspective, this potential for uncertainty cannot be significantly reduced due to the diverse factors influencing future impacts.

In the next step, adaptation measures can possibly already be derived directly from the vulnerability analysis. However, more detailed risk assessments are also possible. Risk analysis considers the impact of a potential climate hazard and the probability of its occurrence or classification. Figure 5 shows the result of such an exemplary assessment for the consequences of sea-level rise. Ultimately, only areas affected by flooding whose flooding has at least moderate significance for the functionality of the port are subject to a high risk for the corresponding climate hazard or scenario.

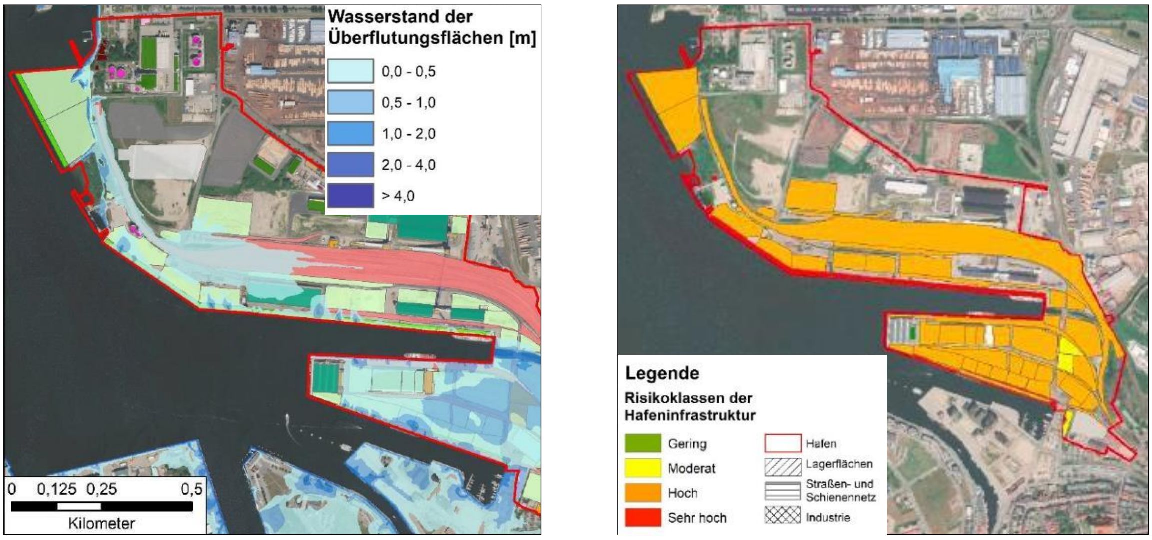


*Figure 5: Left: Flood hazard map of a harbour area for a climate hazard (storm surge, including sea level rise). Right: Risk resulting from superposition of probability of climate hazard and impact of climate hazard. [Baumgärtner, 2020].*

Table 6 shows operational thresholds in respect of handling and berthing operations, above which operations in seaports are affected. Not all facilities have to be affected to the same extent. Ultimately, both mooring system (winch, mooring line, bollards) and cargo handling equipment would have to be adapted for increased adaptation. Apart from that, for safety reasons, it is advisable to stop activities in the port above a certain wind speed. It can therefore be assumed that operational threshold values for wind speeds cannot be significantly increased due to technical measures, but that activities must be stopped at certain wind speeds, as has been the case up to now. Thus, adaptation measures are limited to minimise the extent of storm-related damage or accidents.

| Beaufort scale/ description | Wind speed [m/s]* | Effect on operations** | |
|---|---|---|---|
| | | Vessel | Facilities |
| 6 Strong breeze | 11,5 – 14,0 | Berthing limit | Crane operations cease |
| 7 Near gale | 14,5 – 17,0 | Tugboat limit | |
| 8 Fresh gale | 17,5 – 20,5 | Ferry operations cease | Loading arms disconnected |
| 9 Strong gale | 21,0 – 24,0 | Emergency mooring lines | |
| 10 Whole gale | 24,5 – 28,5 | Large vessels put to sea | Facilities secured, cranes lashed etc. |
| 11 Storm | 29,0 – 32,5 | | |
| 12 Hurricane | ≥ 33,0 | | |
| * Round to 0,5 m/s<br>** Due to wind, in exposed locations wave action may lead to greater restrictions | | | |

*Table 6: Critical wind speed thresholds for seaport operations (Gaythwaite (2004), modified).*

The North German Climate Monitor (Helmholtz Centre Hereon 2021b) indicates an average of about 40 storm days per year (maximum wind speed ≥ 8 Beaufort) for the North German coast in the period 1961-1990. Climate projections show, depending on the model run, a possible increase or decrease in the number of storm days of +14 to -8 for the end of the 21st century [Helmholtz-Zentrum Hereon, 2021a]. Accordingly, an increase in the frequency of wind-related operational restrictions in seaports in Germany is not necessarily given.

# 6 ADAPTATION OF SEAPORTS IN GERMANY TO CLIMATE CHANGE

Adaptation to climate change has so far been taken into account to varying degrees, from very high to very low, in the participating port management companies (Figure 6). In addition, the majority of participants estimate that there is up to five years left to sufficiently integrate the topic of climate change adaptation into the company respectively the area of responsibility (Figure 7).

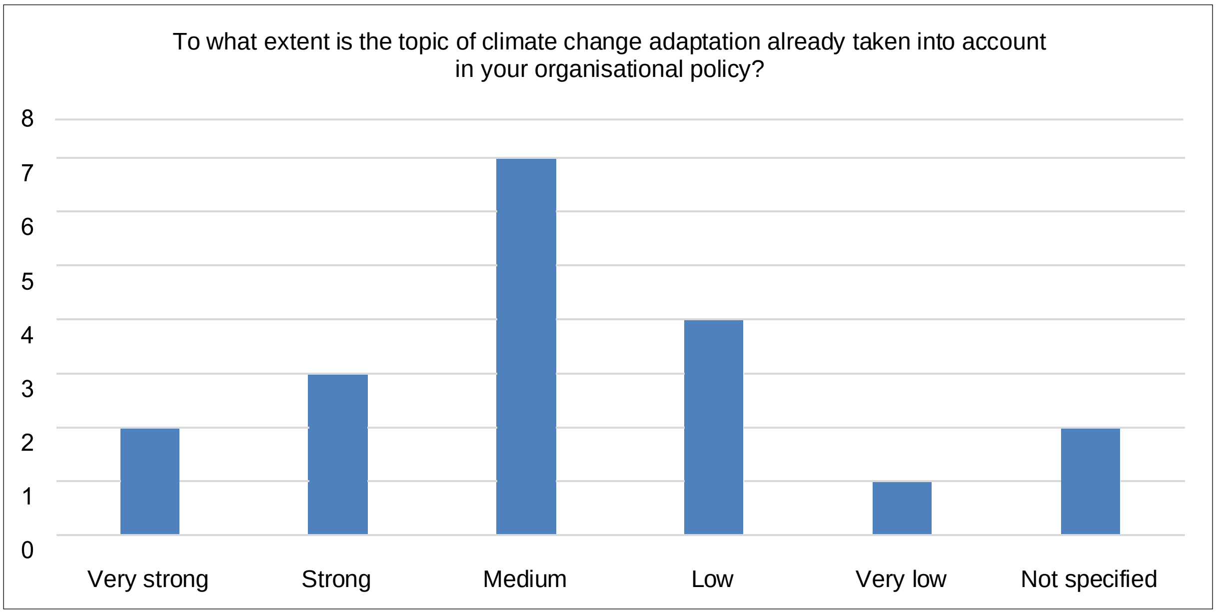


*Figure 6: Result of the survey conducted during the final workshop regarding the current consideration of the topic of climate change adaptation in the organisational policy.*

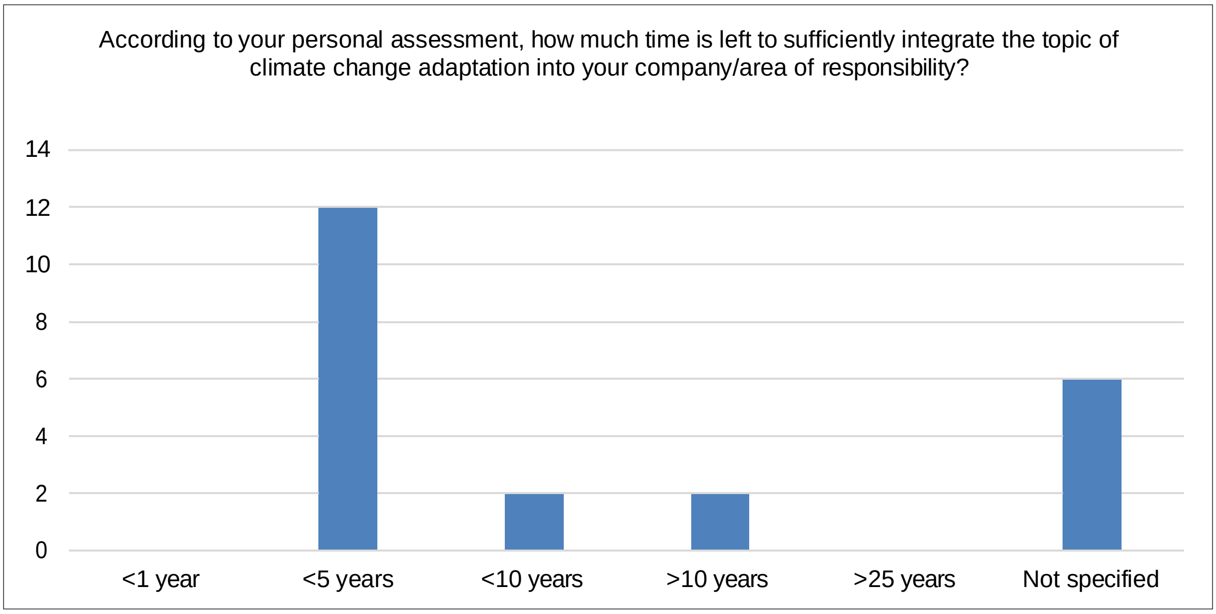


*Figure 7: Result of the survey conducted during the final workshop regarding the time horizon available to sufficiently integrate the topic of climate change adaptation into the organisational policy*

In principle, the portfolios presented in the PIANC guideline [PIANC, 2020] provide a comprehensive catalogue of measures to significantly increase the resilience of ports to climate change. Adaptation options in the PIANC guideline are divided into physical, social and institutional measures. Physical measures in particular require economic investments, which can be significant depending on the expected impacts. Social and institutional measures usually require smaller investments. The time required for the implementation of measures is strongly dependent on available human and financial resources and can be small to considerable depending on the measure.

At present, the most important measure is the implementation of an adaptation strategy. The importance of this lies above all in dealing with the future impact of climate change at an early stage, so that measures can already be planned preventively and implemented with the greatest possible economic efficiency. Even if the climatic changes and the associated effects will only become clearer in the future, the probability of extreme weather events such as heat waves is already increased today [Vautard et al., 2020)]. Furthermore, it makes sense to integrate the consequences of climate change at an early stage, especially in new construction and planning projects with a long time horizon and to set up monitoring programmes in order to build up a supportive data basis on one's own affectedness for future decisions. In other words, it is recommended that climate change adaptation is considered today, even if in principle there is time for adaptation and the current need for action tends to be manageable. The timeframe of up to five years indicated by the majority of participants in the final workshop of the PortKLIMA project for the appropriate integration of climate change adaptation therefore seems realistic. Whether there is already a need for specific action with regard to physical measures at present or in the near future depends on the individual circumstances of the individual ports, which in some cases vary greatly due to natural conditions such as topography or location along a stretch of water, the comparison of costs and benefits of such a measure, the relevant climate parameters and the remaining service life of assets.

The participants of the final workshop were asked about their assessment of the effort required for adaptation in their company respectively area of responsibility (Figure 8). The majority of the participants estimate the effort for adapting to the consequences of climate change as medium for the RCP2.6 scenario and as high for the RCP8.5 scenario. However, there are also estimates that the effort will be above or below this. Even for the RCP8.5 scenario, there are still estimates from participants that the effort will be low or very low. About one third of the respondents come from the port construction/ infrastructure management sector and about half from the strategic sector.

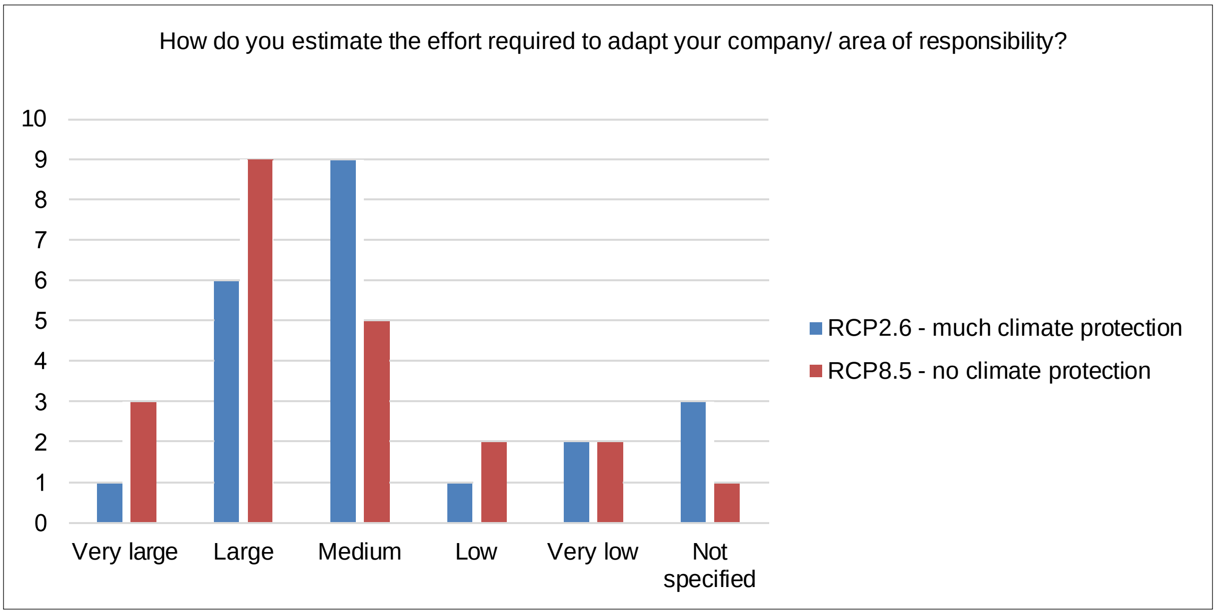


*Figure 8: Result of the survey conducted during the final workshop regarding the effort required to adapt the company or area of responsibility to climate change*

The participants of the final workshop were also asked about their assessment of the greatest challenge in connection with adaptation to climate change. The greatest challenge is seen in dealing with uncertainties, followed by technical feasibility and financing (Figure 9).

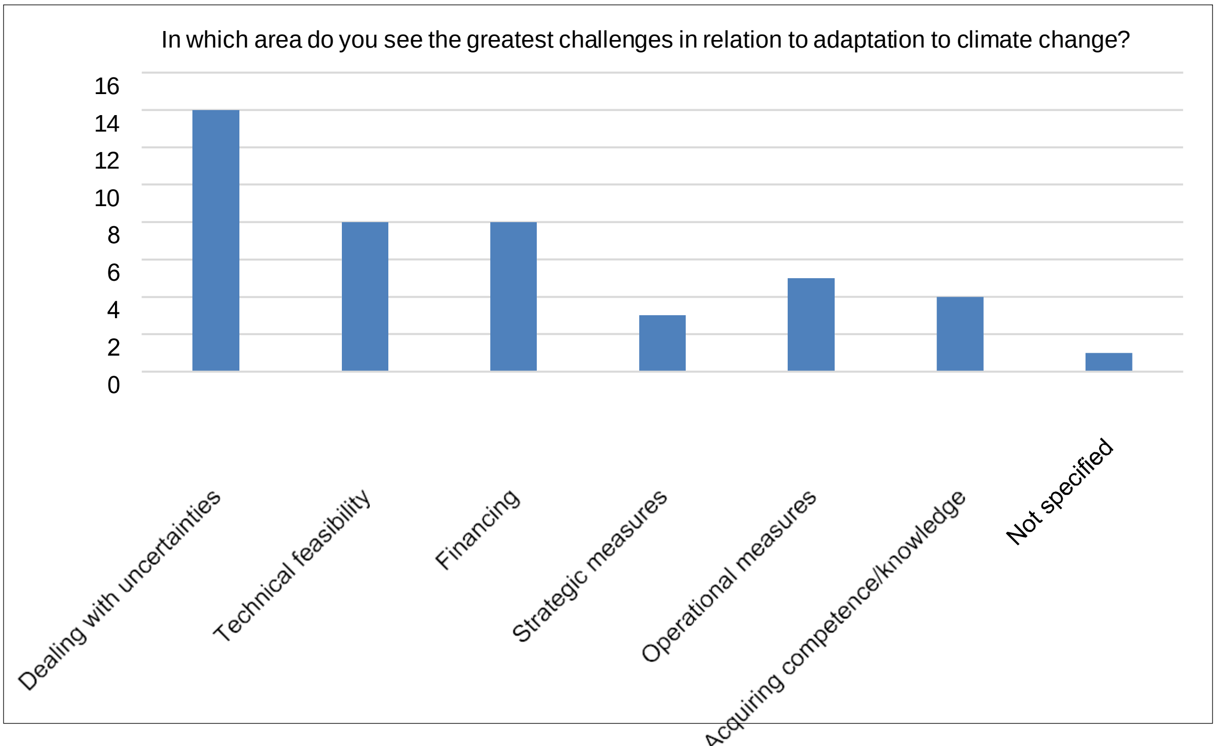


*Figure 9: Result of the survey conducted in the framework of the final workshop regarding the greatest challenges in relation to adaptation to climate change*

Uncertainties will not be eliminated due to the unknown future development of greenhouse gas emissions. Uncertainties can be addressed by keeping the timing of implementation flexible with the use of so-called adaptation pathways (step 4.5 of the PIANC guideline). In order to minimise existing uncertainties about current impacts, it is recommended to set up monitoring programmes. Measures that have no disadvantages or special requirements can be implemented immediately (no-regret measure). Providing flexibility or construction reserves in designs, incorporating redundancies for particularly vulnerable or significant assets or systems, as well as planning for or mitigating the consequences of failure and implementing appropriate emergency management are also suitable measures for dealing with uncertainties (see Chapter 4.1.3 of the PIANC guideline). Further uncertainties also exist in how the changes in climate will be reflected in the actual weather patterns relevant from an operational and technical perspective. One question that arises in this context is, for example, whether there will be more frequent freeze-thaw cycles in the future, or how the change in water and air chemistry will affect the durability of building materials such as steel and concrete.

Technical feasibility will certainly reach its limits in some cases, such as the handling of goods during a storm event, but above all technical feasibility is related to the challenge of appropriate financing. However, major investments solely for the purpose of adapting to climate change are unlikely to be made in the future. The additional effort required to adapt buildings and transport routes to climate change as part of upcoming investments is estimated at 10 % of the investment volume [Wenzel and Treptow, 2014].

Adaptation to climate change has so far only been taken into account in a few regulations applied in Germany, and if so, then in a less precise manner [Kind et al., 2021]. At the same time, the expected climate-related changes in a variety of design parameters are of importance in a wide range of regulations [Siefer et al., 2018]. Rules and regulations initially have only a recommendatory character. It is therefore in principle possible, even without actual changes in regulations, to take additional precautions, e.g. on the basis of climate surcharges, without any justifications. As port management companies are part of the public sector, they have to account for their expenditures. Climate change- adapted design principles or official recommendations are what could make measures justifiable in the first place. Regardless of current recommendations, the majority of participants in the final workshop consider it rather likely to very likely that they would deviate from the recommendations in the future (Figure 10).

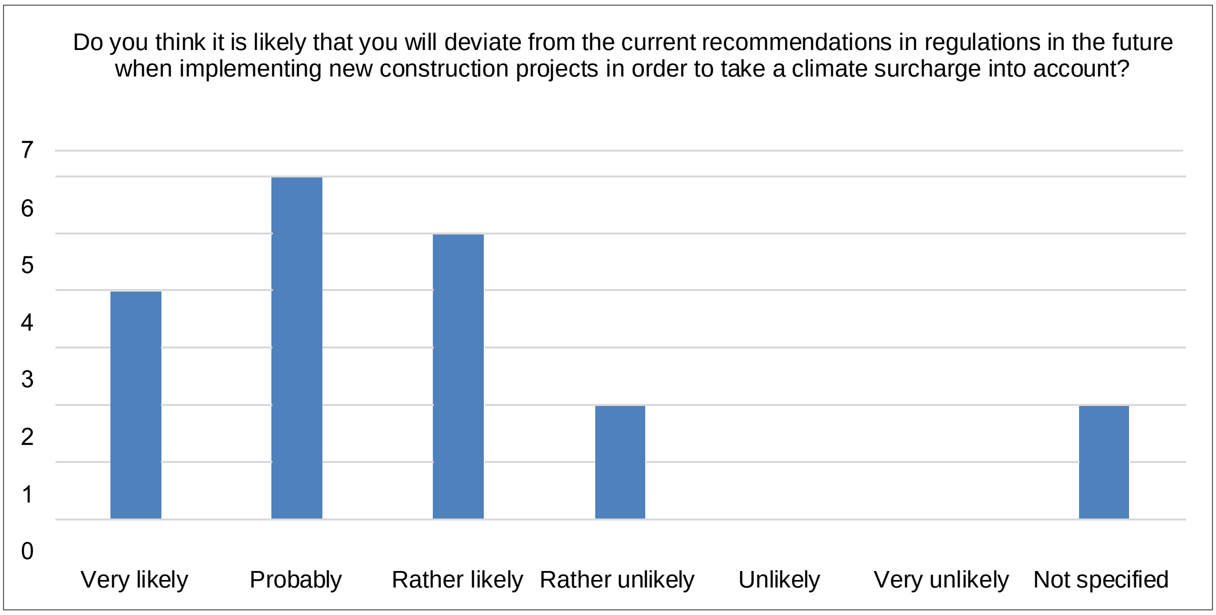


*Figure 10: Result of the survey conducted during the final workshop regarding the consideration of climate surcharges, independent of current recommendations in rules and regulations*

Recommendations for adaptation can refer to take into account climate surcharges or at least to carry out sensitivity studies, to create hazard maps so that defence measures can be taken at vulnerable locations, or to adapt behaviour patterns. Table 7 shows an overview of significant climate parameters, their probability of change and recommendations for adaptation compiled on the basis of the results of the PortKLIMA project.

| Climate parameter | Probability of change | Recommendations for adaptation |
|---|---|---|
| Sea level rise | Certain | +0,5 to +1,0 m of sea level rise until 2100 Consider implementation of a construction reserve Create flood hazard maps<br>Identify influence on drainage capacity of receiving waters and groundwater levels |
| Temperature | Certain | Observe heat related operational restrictions especially in relation to steel components, e.g. bridges and switches, cool components if necessary<br>Adaptation of work safety for employees, if necessary<br>Consider increased cooling demand for buildings, machinery and electronics |
| Heavy precipitation | Probable | Sensitivity analysis: design value +10 %<br>Identify flow paths/create flood hazard maps<br>Implementation of retention volumes, if possible<br>Protection of assets from storm water run-off where required |
| Wind | Uncertain | No clear climate signal available. Therefore, currently no recommendation to increase design values.<br>Review and practice safety measures against wind-induced projectiles |
| Air/ water chemistry | Uncertain | Observe and document affectedness |

*Table 7: Climate parameters, their probability of change and recommendations for adaptation*

# 7 RESUME

As hubs in world trade, seaports are of central importance. At the interface between water and land, seaports will be particularly affected by sea level rise, but other extreme weather events such as high winds and heavy precipitation, as well as high and low water situations, and their impact on the entire logistics chain, will also become increasingly important. The adaptation of seaports to the consequences of climate change should be seen as a permanent task.

A potential approach to adapting seaports to consequences of climate change is outlined in the PIANC guideline. Despite the fact that climate changes are only gradually occurring and there are uncertainties regarding the consequences of climate change, the PIANC guideline provides a framework for action that can already be implemented today, which currently relates in particular to the assessment of risks, the adaptation strategies to be derived from this, and suitable monitoring systems for evaluating one's own impact. Particularly when planning new assets with long service lives, appropriate climate surcharges may already be necessary today.

It is still possible to limit consequences of climate change to a tolerable level for seaports. Otherwise, seaports in Germany may be faced with considerable adaptation costs and operational downtime in the future. In this context, addressing the consequences of climate change highlights the importance of climate protection measures, the effect of which benefits significantly from immediate implementation.

In order to communicate current state of knowledge into practice, a continuous transfer of knowledge is of great importance. Information should be available as centrally as possible, but with a regional focus, and should be prepared for specific target groups. The involvement of professional associations and regulatory bodies supports professional planners, who have the technical know-how of possible adaptation measures, in taking adaptation to climate change into account appropriately. The forward-looking examination of climate change adaptation also has the potential to identify questions and thus initiate knowledge transfer between research and application at an early stage.

# 8 ACKNOWLEDGEMENTS

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## SUMMARY

The resilience to climate change of seven German seaports was examined and both strategies and measures for their adaptation to the consequences of climate change are presented. The work was conducted as part of the project PortKLIMA – 'Development and Pilot Implementation of Educational Modules for the Integration of Climate Change Adaptation in the Planning, Construction and Operation of Seaports in Germany'. The basic framework for the study is the guideline of the PIANC Working Group 178 – 'Climate Change Adaptation Planning for Ports and Inland Waterways', published in 2020.

The expected impact on the seaports involved in the project in the context of climate change, which can be observed in the ports themselves but also in hinterland logistics, is emerging. The future vulnerability of seaports depends to a large extent on the development of greenhouse gases and the associated consequences of climate change. Especially in a severe greenhouse gas mitigation scenario, the consequences for seaports in Germany can turn out to be manageable. However, if greenhouse gas emissions continue to rise uncontrolled, the consequences can be considerable, especially as a result of unabated sea-level rise.

From the current point of view, the most important adaptation measure is to implement an adaptation strategy in order to be able to objectively assess the impact on the port and to take future consequences into account in port management and development as early as possible. Seaports have always been subject to changing economic requirements, e.g. as a result of technical innovations or growth in ship size. From an economic point of view, it is therefore plausible to implement adaptation measures over time in the case of upcoming investment measures. Facilities with long service lives, such as flood protection facilities or locks, require early integration of possible climate impacts. From a planning perspective, recommendations for adaptation to climate change in regulations are urgently recommended in order to justify investments to be made using public funds.



## RESUME

La résilience au changement climatique de sept ports maritimes allemands a été examinée et les stratégies et mesures pour leur adaptation aux conséquences du changement climatique sont présentées. Ce travail a été réalisé dans le cadre du projet PortKLIMA – "Développement et mise en œuvre pilote de modules éducatifs pour l'intégration de l'adaptation au changement climatique dans la planification, la construction et l'exploitation des ports maritimes en Allemagne". Le cadre de base de l'étude est la directive du groupe de travail 178 de PIANC – "Planification de l'adaptation au changement climatique pour les ports et les voies navigables intérieures", publiée en 2020.

L'impact attendu sur les ports maritimes impliqués dans le projet dans le contexte du changement climatique, qui peut être observé dans les ports eux-mêmes mais aussi dans la logistique de l'arrière-pays, se dessine. La vulnérabilité future des ports maritimes dépend dans une large mesure de l'évolution des gaz à effet de serre et des conséquences associées du changement climatique. Dans un scénario d'atténuation des gaz à effet de serre, les conséquences pour les ports maritimes allemands peuvent s'avérer gérables. Toutefois, si les émissions de gaz à effet de serre continuent à augmenter de manière incontrôlée, les conséquences peuvent être considérables, notamment en raison de l'élévation continue du niveau de la mer.

Du point de vue actuel, la mesure d'adaptation la plus importante consiste à mettre en œuvre une stratégie d'adaptation afin de pouvoir évaluer objectivement l'impact sur le port et de prendre en compte le plus tôt possible les conséquences futures dans la gestion et le développement du port. Les ports maritimes ont toujours été soumis à des exigences économiques changeantes, par exemple à la suite d'innovations techniques ou de l'augmentation de la taille des navires. D'un point de vue économique, il est donc plausible de mettre en œuvre des mesures d'adaptation dans le temps lors des prochaines mesures d'investissement. Les installations ayant une longue durée de vie, comme les installations de

protection contre les inondations ou les écluses, nécessitent une intégration précoce des impacts climatiques possibles. Du point de vue de la planification, il est urgent de recommander l'adaptation au changement climatique dans les réglementations afin de justifier les investissements à réaliser avec des fonds publics.


## ZUSAMMENFASSUNG

Die Widerstandsfähigkeit von sieben deutschen Seehäfen gegenüber dem Klimawandel wurde untersucht und es werden sowohl Strategien als auch Maßnahmen zur Anpassung an die Folgen des Klimawandels vorgestellt. Die Arbeiten wurden im Rahmen des Projekts PortKLIMA – "Entwicklung und Pilotierung von Bildungsmodulen zur Integration der Anpassung an den Klimawandel in Planung, Bau und Betrieb von Seehäfen in Deutschland" durchgeführt. Grundlage für die Studie ist der Leitfaden der PIANC-Arbeitsgruppe 178 – "Climate Change Adaptation Planning for Ports and Inland Waterways", der im Jahr 2020 veröffentlicht wird.

Es zeichnen sich die zu erwartenden Auswirkungen auf die am Projekt beteiligten Seehäfen im Kontext des Klimawandels ab, die in den Häfen selbst, aber auch in der Hinterlandlogistik zu beobachten sind. Die künftige Verwundbarkeit der Seehäfen hängt in hohem Maße von der Entwicklung der Treibhausgase und den damit verbundenen Folgen des Klimawandels ab. Insbesondere in einem strengen Treibhausgasminderungsszenario können die Folgen für die Seehäfen in Deutschland überschaubar ausfallen. Steigen die Treibhausgasemissionen jedoch weiter unkontrolliert an, können die Folgen, insbesondere durch einen ungebremsten Meeresspiegelanstieg, erheblich sein.

Die wichtigste Anpassungsmaßnahme ist aus heutiger Sicht die Umsetzung einer Anpassungsstrategie, um die Auswirkungen auf den Hafen objektiv abschätzen zu können und die zukünftigen Folgen möglichst frühzeitig in der Hafenwirtschaft und -entwicklung zu berücksichtigen. Seehäfen sind seit jeher veränderten wirtschaftlichen Anforderungen unterworfen, z.B. durch technische Innovationen oder die Zunahme der Schiffsgröße. Aus wirtschaftlicher Sicht ist es daher plausibel, bei anstehenden Investitionsmaßnahmen Anpassungsmaßnahmen im Zeitablauf durchzuführen. Anlagen mit langer Nutzungsdauer, wie z.B. Hochwasserschutzanlagen oder Schleusen, erfordern eine frühzeitige Einbindung möglicher Klimaauswirkungen. Aus planerischer Sicht sind Empfehlungen zur Anpassung an den Klimawandel im Regelwerk dringend zu empfehlen, um Investitionen mit öffentlichen Mitteln zu rechtfertigen.



## RESUMEN

Se ha examinado la resistencia al cambio climático de siete puertos marítimos alemanes y se presentan tanto estrategias como medidas para su adaptación a las consecuencias del cambio climático. El trabajo se llevó a cabo en el marco del proyecto PortKLIMA – "Desarrollo e implementación piloto de módulos educativos para la integración de la adaptación al cambio climático en la planificación, construcción y operación de los puertos marítimos en Alemania". El marco básico para el estudio es la directriz del Grupo de Trabajo 178 de la PIANC – "Planificación de la adaptación al cambio climático para puertos y vías navegables", publicada en 2020.

El impacto previsto en los puertos marítimos que participan en el proyecto en el contexto del cambio climático, que puede observarse en los propios puertos pero también en la logística del interior, es emergente. La futura vulnerabilidad de los puertos marítimos depende en gran medida de la evolución de los gases de efecto invernadero y de las consecuencias asociadas al cambio climático. Especialmente en un escenario de mitigación severa de los gases de efecto invernadero, las consecuencias para los puertos marítimos en Alemania pueden resultar manejables. Sin embargo, si las emisiones de gases de efecto invernadero siguen aumentando de forma incontrolada, las consecuencias pueden ser considerables, sobre todo como resultado de la subida incesante del nivel del mar.

Desde el punto de vista actual, la medida de adaptación más importante es aplicar una estrategia de adaptación para poder evaluar objetivamente el impacto en el puerto y tener en cuenta las consecuencias futuras en la gestión y el desarrollo portuarios lo antes posible. Los puertos marítimos siempre han estado sujetos a los cambios en los requisitos económicos, por ejemplo, como resultado de las innovaciones técnicas o del crecimiento del tamaño de los buques. Desde el punto de vista económico, es por tanto plausible aplicar medidas de adaptación en el tiempo en el caso de las próximas medidas de inversión. Las instalaciones con una larga vida útil, como las instalaciones de protección contra inundaciones o las esclusas, requieren una integración temprana de los posibles impactos climáticos. Desde el punto de vista de la planificación, es urgente recomendar la adaptación al cambio climático en la normativa para justificar las inversiones que se realicen con fondos públicos.