Westports Climate Change Assessment

Evaluation of Climatic Changes and Initial Vulnerability Assessment

Final Report

Westports Malaysia Sdn Bhd

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The expert in **WATER ENVIRONMENTS**

Westports Climate Change Assessment

Evaluation of Climatic Changes and Initial Vulnerability Assessment

Final Report

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Background

Westports Malaysia Sdn. Bhd. (WMSB) have operated since 1994 the port located along the west side of Pulau Indah. It is a very successful port operation with a current capacity of 14 million TEUs and cargo (liquid and bulk) facilities. It presently includes nine container berths (CT1 to CT9), container yards, terminal facilities, liquid and dry bulk terminals and supporting infrastructure, and is planning to expand their facilities in the future.

Climate change has become an increasing threat to ports and other key infrastructure. As described in the Sixth Assessment Report (AR6), IPCC, 2021 /3/ the estimated rise in global surface temperature has increased since AR5 (2014), this is principally due to further warming since 2003–2012. Depending on future measures, climate change trends are likely to continue and as for many ports around the world, it may affect Westports existing infrastructure and operation in the future. This potentially represents a significant risk to business, operations, safety and infrastructure and therefore there is a need to take action to strengthen resilience and potentially adapt to meet the expected changes. To address climate change and the potential issues related to it, Westports Malaysia Sdn. Bhd. have embarked in a plan to evaluate the potential implications of climate change on their existing facilities in Port Klang. The findings of this study are summarised in this section.

Methodology

To carry out the assessment, a methodology based on 2020 PIANC “Climate Change Adaptation Planning for Ports and Inland Waterways” guidelines has been implemented /1/. This is based on three main stages as set up below:

- **Stage 1. Goals and Identification of Assets and Operations**.
- **Stage 2. Evaluation of Climate Change Changes.**
- **Stage 3. Initial vulnerability assessment**.

Goals and Assets

The main goal of this study is to evaluate the potential implications of climate change on the risk profile of the Westports facilities and to assist in the development of a medium and long-term plan for climate change adaptation planning. The climate change assessment focuses on the analysis and evaluation of various climatic and metocean parameters that include wind, water levels, waves, currents, rainfall and air temperature. The climate change assessment is for a timeframe of 60 years (2080) from a baseline period (2020)

Evaluation of Climate Changes

Several climate scenarios (high, medium, and low) presented in the study were applied to describe future changes in current and wave conditions, these are described in Table 0.1. The remaining variables were analysed for a larger number of conditions.

Table 0.1 Selected climate change scenarios to evaluate changes in metocean and meteorological conditions in the Westports area.

Climate Change Scenario	Temperature global projections	Wind projections
High	Average temperature increases by 1.7-2.1°C	Increment of wind speed of ~0.3 m/s
Medium	Average temperature increases by 1.6-2.0°C	No change of wind speed in general.
Low	Average temperature increases by 1.9-2.7°C	Decrement of averaged wind speed ~0.17 m/s

A summary of the predicted changes are presented below.

Winds: Changes in wind conditions are minor

- Changes in wind conditions within the Strait of Malacca are predicted to be minor and relatively smaller compared to other area such as in the South China Sea basin.
- Low scenario predicts a decrease in the future wind speed for most months except for March and December. July displays the largest deviations with average peak storm wind speeds decrease by ~7%.
- Medium scenario shows no significant changes in peak storm wind speeds throughout the year with changes in the order of ±2%.
- High scenario predicts increase in wind speeds throughout the year. It is observed in that higher average peak storm wind speed to be increased in the order of 5-10% and occurred between November and June.
- The evaluation of peak squall season shows considerable uncertainties associated with the downscaling of regional climate models and therefore the expected future changes of squall events during the peak season are uncertain.

Waves: Changes in wave conditions are minor.

- Low scenario predicts a decrease in the wave height throughout the year. July, October and November show larger changes with average peak storm wave heights decreased by approximately 15%.
- Medium scenario shows no apparent overall difference in peak storm wave heights with changes below 5%.
- High scenario provides the most consistent change from the present with clear seasonal signature in peak storm wave height. It is observed that higher average peak storm wave heights increase in the order of 10-20% during NE monsoon season while the SW monsoon season show less than 3% increased of peak storm wave heights.
- Overall, no clear and consistent trend is observed in the change of peak storm wave heights within the three future scenarios, with some months showing both decrease and increase in peak wave heights. The largest uncertainty in the projected wave height is found particularly in the month of November. The projections of wave climate showed inconsistent future changes in wave climate among the future climate models. The wave height changes in Westports are however observed to be minor.
- In terms of extreme conditions induced by high intensity squalls, the wind predictions show significant uncertainty and therefore it is not possible to derive conclusive quantification of changes in extreme wave conditions.

Sea Level Rise: Increase in sea levels are significant

The analysis of the sea level rise shows sea level increases of 0.47m to 0.65m representing central and 83% confidence levels. The predicted extreme water levels for 100-year return period calculated for a 60-year period are 6.48 and 6.66 mCD for central and 83% confidence values respectively.

Currents: Changes in currents are insignificant.

The model results from all three future climate scenarios indicate minimal changes with the present scenario and therefore the future projection of currents in Westports are found to be negligible.

Rainfall: There is not yet clear evidence as to how annual rainfalls will change but there are evident trends when extreme rainfall is examined with the intensity of severe storms expected to increase, and the duration of dry spells increasing. The key findings related to changes in rainfall conditions at site can be summarised as follows:

- The total annual change in rainfall experienced at the site shows that there is no clear evidence of a trend with some half of the models showing increased in annual rainfalls and the remaining half showing a reduction in annual precipitation totals. Projected changes in annual rainfall totals range from a decrease by as much as 400mm to increases of 200mm.
- The typical rainfall occurring on wet days shows four of the ten models projecting a decrease in rainfall intensity in the order of 1 to 2 mm per day and six of the ten models projecting an increase in rainfall intensity in the order of 1 to 2 mm per day.
- Monthly maximum 1-day precipitation shows more evidence of a pronounced increasing trend with seven of the ten models showing increases in the monthly maximum 1-day rainfall event ranging from 5 to 25mm and only three models finding only a minor decrease in the range 1 to 3 mm.
- Contribution to total precipitation from very wet days shows an increasing trend in nine out of ten models. Very wet days are defined as days when the total precipitation is above the 95^{th} percentile of daily precipitation. This indicates that future storm intensities for more severe events are anticipated to change by as much as 5 mm/day.
- Maximum length of dry spell which is defined as the maximum number of consecutive days where rainfalls are less than 1mm again shows predominately a positive trend with seven of the ten climate models showing dry spells increasing in length by between 1 and 4 days. Models showing a decrease in the duration of dry spells only show decreases of a single day.

Temperature. The assessment of future trends indicates that temperatures will increase for all scenarios considered. Changes in temperature indices between the baseline period and the future are summarised below:

- The number of individual heatwaves identified in a given period are projected to increase by all climate models. The chance of heatwave event occurrence in the future is more than twice that of the baseline period.
- The length of heatwaves is also projected to increase in the future but it should be noted that larger increments showing increases in the duration of heat waves of more than ten days are projected by higher emission scenarios (RCP8.5) compared to the lower (RCP2.6) and middle (RCP4.5) scenarios which shows increases in the duration of heat waves of typically 5 days.
- The peak daily value in a heatwave event is also projected to increase more for the higher emission scenarios (RCP8.5) and less so for RCP2.6 and RCP4.5. The peak daily temperature is projected to increase by between ~0.5°C to >1.0°C whilst that projected by RCP 2.6 and RCP4.5 are generally <0.5°C.
- Climate model projections at this scale do not consider the effect of local urban development which may further elevate the heat stress via urban heat island effect.

Therefore, future increase in temperature is expected to be much larger than the projected values compounded by local effect.

Initial Vulnerability Assessment

The vulnerability and risk assessment has been carried out following the general principles set out under Stage 3 of the PIANC Guidelines /1/. The general process followed in this vulnerability and risk assessment is as follows:

1. Identification of Westports port infrastructure, assets and operations that might be impacted by the predicted future climate changes. This is intended to provide an overview of areas where climate change might have an impact, therefore this focusses on groups of assets and general operations carried out in the port.
2. Where available data on these assets or operations that will assist in identifying their vulnerability to climate change is collated.
3. The criticality of the identified assets and operations to the operation and commercial viability of the port is assessed. This will assist in assessing the overall risk to port operations for any areas that are identified to be vulnerable to climate change.
4. The vulnerability of each of the identified port infrastructure, assets and operations to the climate changes is tabulated. This assessment includes the magnitude of the predicted climate change and the vulnerability of the asset or operation to this change.
5. A preliminary risk assessment has been carried out to identify the assets and operations most likely to require adaption in the future to protect the port from the impact of climate change.

The vulnerability and risk assessment has been carried out using expert judgement based on a general understanding of the port infrastructure and operations. Detailed calculations or process-based modelling of the operations have not been carried out for this assessment. These should be considered at a later stage for the assets and operations identified as most likely to require adaptation to confirm any action required and the likely timeframe in which these adaptions should be made.

Based on this assessment the facilities and operations that are most likely to be vulnerable to climate change have been identified. These are set out in Table 0.2, together with an assessment of the risk of climate change requiring significant adaptation for these facilities. This shows that:

- There is a High Risk that there may be issues with the container quays, and the dry bulk, liquid bulk and breakbulk berths due to rising sea levels. The reason that these are rated with a High Risk is that if sea level rise leads to either increased wave overtopping of the deck structure, or structural issues due to increased wave loading these are difficult to mitigate.
- There is a Moderate Risk of short duration flooding dur either to increased overtopping of revetments of the ability of the drainage system to cope with increased rainfall intensity and sea level. The reason that these are rated with a Moderate Risk is that these issues can be readily addressed by minor modifications to the storm drains or revetment crests.
- There is a Moderate Risk of reduced visibility during high rainfall events impacting navigation. The reason that this is rated with a Moderate Risk is that these will be short duration disruptions and can be managed by port operation procedures and weather forecasting.

Table 0.2 Preliminary climate change adaptation risk assessment

	Facility / Operation	Key Issues	Risk Level
1	Container Berths CT1 to CT9	Increasing water levels and wave action may lead to: • Waves from either natural causes or ship wake overtopping the jetty deck leading to potential water damage to equipment or operational issues. • Waves from either natural causes or ship wake impacting the jetty deck soffit or beams causing structural overload and / or durability issues.	High Risk
2	Dry Bulk, Liquid Bulk and Breakbulk Berths	Increasing water levels may lead to: • Waves from ship wake overtopping the jetty deck leading to potential water damage to equipment or operational issues. • Waves from ship wake impacting the jetty deck soffit or beams causing structural overload and / or durability issues.	High Risk
3	Revetments along the land boundary	Increasing water levels may lead to increased waves overtopping which could potentially increase flooding risk in the operational areas immediately landward of these revetments. For the revetments in the southern area of the container terminal there is also a small possibility of increased damage to the revetment due to increased wave action in this area.	Moderate
4	Storm water drainage network	The existing storm water drainage network may not have sufficient capacity to handle the predicted increase in rainfall intensity during high rainfall events together with increasing sea levels. This could result in localised flooding in the port operational areas for short periods of time.	Moderate
5	Electrical substations and power infrastructure	The increased flooding risk described in Item 4 above may lead to a flooding risk at the electrical substations that may cause damage to this equipment.	Moderate
6	Pump stations and associated infrastructure in liquid product terminals	The increased flooding risk described in Item 4 above may lead to a flooding risk at the product pump stations in the liquid product terminals that may cause damage to this equipment.	Moderate
7	Pilotage and navigation to / from the berths	The increased rainfall intensity during high rainfall events will lead to reduced visibility that may negatively affect navigation during these storms. Increased wave action in the navigation channel may negatively impact pilots boarding and leaving ships.	Moderate
8	Cargo handling	Predicted increased winds and rainfall intensity (causing reduced visibility) may have a negative impact on cargo handling equipment on the berths (including container cranes) and in the container yard.	Low
9	Container yard and associated road / rail transport infrastructure	The increased flooding risk described in Item 4 above may lead to a flooding risk in the container yard and on roads that might negatively impact operations in these areas for short periods of time.	Low

Recommendations for Risk Management or Mitigation

It is recommended that the following measures are implemented to continue to assess future risks and mitigate against the expected impact of climate change:

- This assessment of climate change risk should be updated every 5 years or as new predictions on climate change become available from IPCC or other recognised Authorities. This will allow the any actual changes to conditions at Westports to be assessed, and the predicted risks to be reviewed in the light of this actual data and updated predictions.
- A data collection programme should be implemented to develop a data base of met ocean conditions for use in future assessments of climate change risk. A limitation in the present assessment is the restricted availability of site-specific measured data. Measurements provide an in-depth understanding of the site conditions. Deployment of a weather station to measure wind and rainfall data and a wave recorder at the site would provide valuable information. Recent development of new hardware, software and digital solutions has made data acquisition easier and more affordable than was previously the case. Furthermore, real-time meteorological forecasts are now commercially available for weather-critical marine operations.
- Any new structures or facilities being developed for Westports should be designed taking account of predicted future climate change. This is particularly important for any new berth structures where the potential increase in sea level should be considered. For the planned extension of the container terminal south of CT9 this may well require the deck level for these berths to be higher than the +7.2 mCD of the existing berths, particularly as the design of these berths needs to take account of the increased exposure to wave action in this area as well as changes in sea level.
- If any upgrades or improvements are planned for the surface water drainage system within the port area these should be designed taking account of the predicted future increases in rainfall intensity due to climate change.

Uncertainties and Limitations in the Evaluation of Climate Change

The downscaling projections of future climate involve a significant number of stages with associated uncertainties. The main sources of uncertainties come from three sources:

1. Future emission scenarios mainly driven by the socio-economic development of the world. The future pathways of emissions and warming remain uncertain as future climate scenarios depend critically on the world's commitment in reducing the GHG within the next decade
2. Climate sensitivity of the climate models. Given similar GHG increment and radiative forcing, different GCMs will produce different future anthropogenic climate responses. This is mainly due to the different mathematical representation of the dynamical, physical and chemical processes prescribed in the models that result in different feedback mechanisms, particularly that associated with the response and impact of ocean circulation.
3. Regional climate models (RCMs) used to downscale the GCMs projections have different mathematical representations of the regional climate processes, and the magnitude of the uncertainties can be significant.

The climate scenarios produced in the present study are based on the CORDEX-SEA downscaled GCMs projections used within the IPCC's 5th Assessment Report (AR5). The latest IPCC 6th Assessment Report (AR6) released in August 2021, updated the climate models and scenario sets in AR5 that include new and better representations of physical, chemical, and biological processes, as well as higher resolution, compared to climate models considered in AR5. The AR6 climate models show higher and wider range of climate sensitivity that provide better assessment compared to its predecessors. In general, AR6 estimates a more rapid increment of global temperature and more intense heat and precipitation extremes as well as the compounded effect in both the historical observations and the future projections. Due to higher increment of temperature, the projection global sea level rise is also higher in the AR6, the differences between the two IPCC assessment reports appear to be larger (~19 cm) for the very high emission scenarios but lower for the low to intermediate emission scenarios. The current assessment based on the data produced during the AR5 timeline, may underestimate the projected impact of climate change at the study area particularly for temperature warming rate and sea level rise, however, no detailed information along the Malaysian waters is available for AR6 and the high-resolution downscaled climate projection products are not yet available and will only be released in the next 1-2 years.

Overall, the projections of future climate change in the Malacca Straits are estimated to be minimal and dominated by uncertainties and these should be considered in the adaptation planning. It is also recommended that an updated assessment should be carried out once the AR6 (or more recent) downscaled high resolution projection data are made available.

1 Introduction

Westports Malaysia Sdn. Bhd. (WMSB) have operated the port located along the west side of Pulau Indah since 1994. It is a very successful port container operation with a current port capacity of 14 million TEUs and cargo (liquid and bulk) facilities. It presently includes nine container berths (CT1 to CT9), container yards, terminal facilities, liquid and dry bulk terminals and supporting infrastructure, and is planning to expand their facilities in the future. Figure 1.1 shows the location and extent of the Westports facility in Pulau Indah.

Figure 1.1 Overview of the existing Westports facilities in Pulau Indah.

Climate change has become an increasing threat to ports and other key infrastructure. Increases in well-mixed greenhouse gas (GHG) concentrations due to human activities have been observed since around 1750 and concentrations have continued to increase in the atmosphere, reaching annual averages of 410 ppm for carbon dioxide (CO2) in 2019. Each of the last four decades has been successively warmer than any decade that preceded it since 1850. As described in the Sixth Assessment Report (AR6), IPCC, 2021 /3/ the estimated increase in global surface temperature has increased since AR5 (2014), this is principally due to further warming since 2003–2012. Figure 1.2 depicts the changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to climate model simulations of the temperature response to both human and natural drivers (brown), and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the very likely range of simulations. These data clearly show the changes in temperature observed over the years and the significant increase since the 1950's.

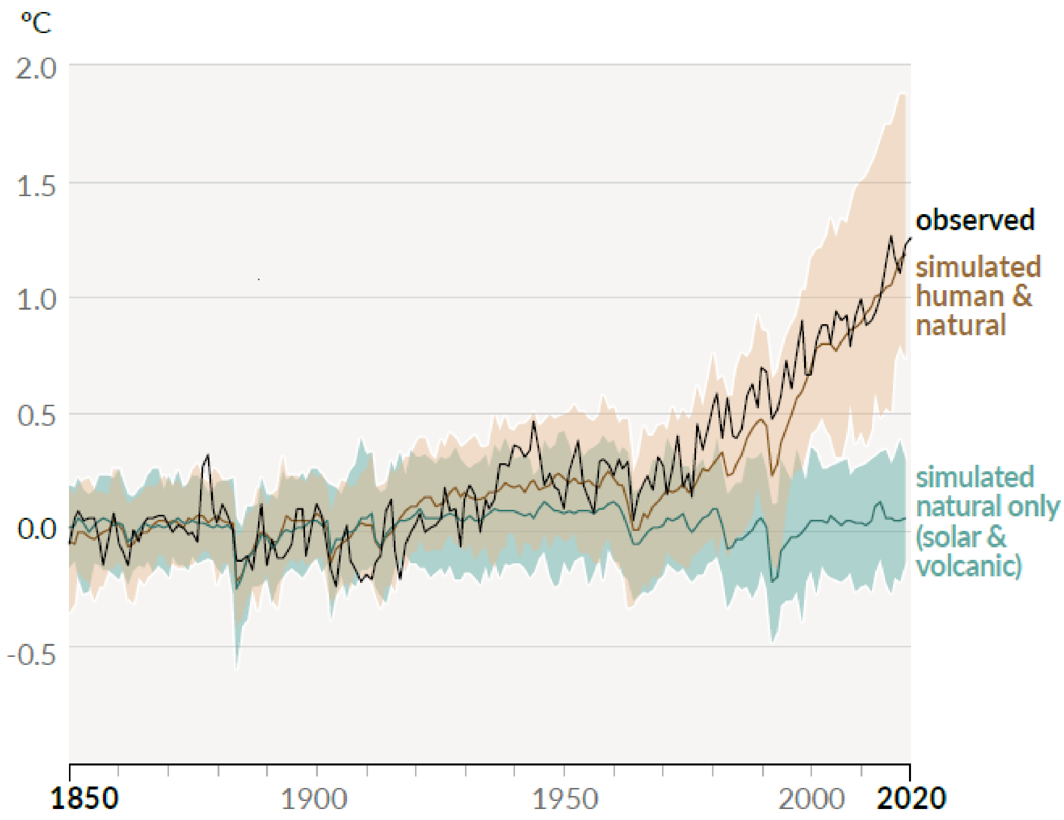


Figure 1.2 Change in global surface temperature (annual average) as observed and simulated using human and natural and only natural factors from 1850 to 2020, from Sixth Assessment Report (AR6), IPCC, 2021 Ref. /.

Depending on future measures climate change trends are likely to continue and as for many ports around the world, climate change may affect Westports existing infrastructure and operation in the future. This potentially represents a significant risk to business, operations, safety and infrastructure and therefore there is a need to take action to strengthen resilience and potentially adapt to meet the expected changes.

To address climate change and the potential issues related to it, Westports Malaysia Sdn. Bhd. have embarked in a plan to evaluate the potential implications of climate change on their existing facilities in Port Klang. DHI Water & Environment (M) Sdn. Bhd. (DHI) have been commissioned by WMSB to assist in the development of a medium and long-term plan for climate change adaptation planning.

1.1 Methodology

To carry out the assessment, a methodology based on 2020 PIANC[1] "Climate Change Adaptation Planning for Ports and Inland Waterways" guidelines has been implemented /1/. This is based on three main stages as set up below:

- **Stage 1. Goals and Identification of Assets and Operations**. To start the project goals assessment a review existing information is carried out and the assets and operations and hazards are identified.

[1] PIANC, The world Association for waterborne Transport Infrastructure

- **Stage 2. Evaluation of Climate Change Changes.** Climate change may affect some of Westports maritime infrastructure assets, operations, and systems therefore it is necessary to evaluate climate change and how they will affect the hazards in the future. This evaluation is based on data analysis and modelling works to understand slow onset changes and the expected increases in the frequency or severity of extreme meteorological, oceanographic, or hydrological events. Comparisons are made to baseline conditions, considering existing patterns or trends, and any uncertainties or limitations in the data.
- **Stage 3. Initial vulnerability assessment**. Infrastructure assets, operations, and systems will be evaluated based on the outcome of the climate change analysis. This task will provide an initial risk evaluation as well as the likelihood and potential consequences to the facilities. Based on this information, an adaptation plan can be implemented, but this is not part of this assessment.

Stage 4, adaptation option is not part of this study, and it is expected to be implemented after completion of these studies.

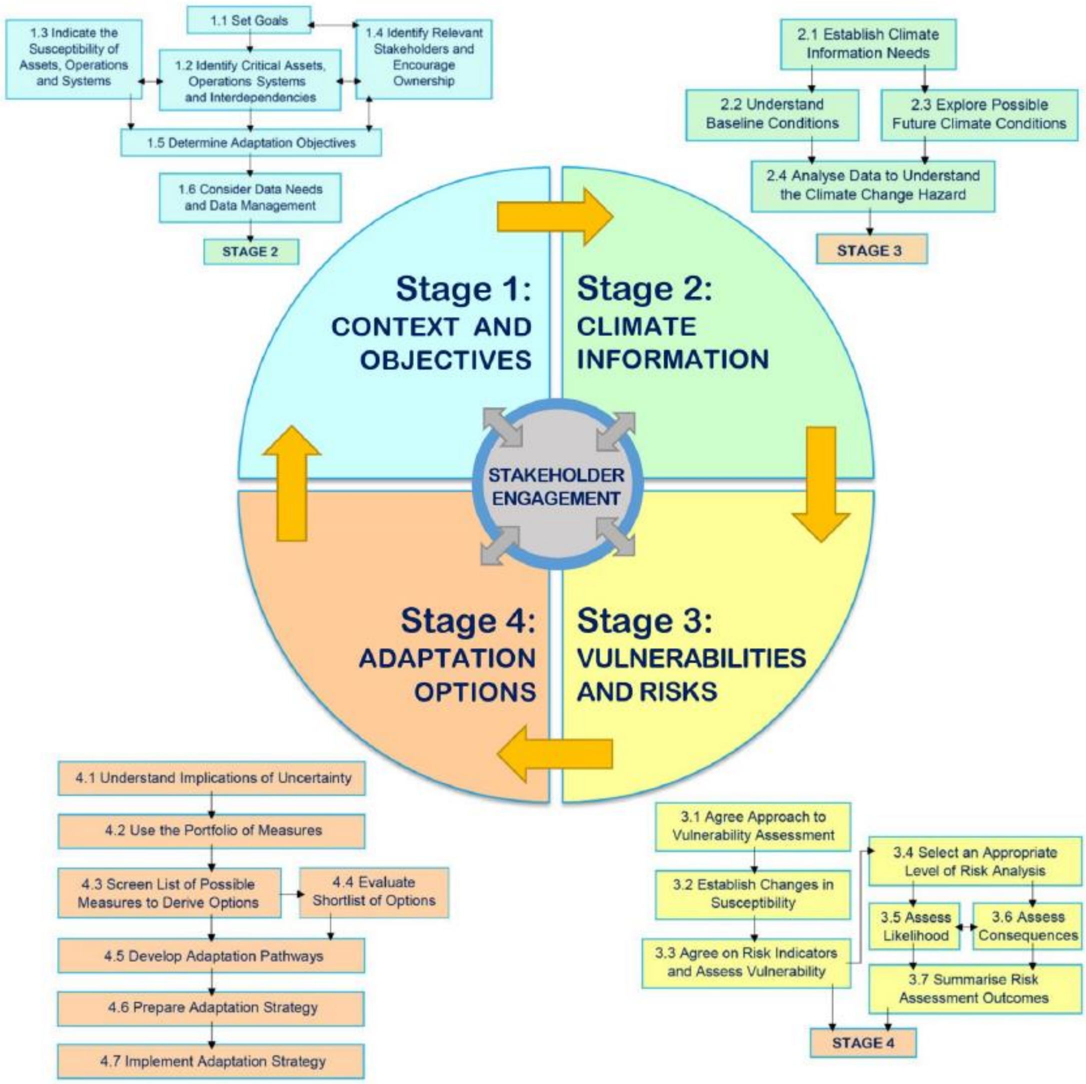


Figure 1.3 Four stages of the climate change adaptation planning process for ports and inland waterways following PIANC guidelines /1/.

1.2 Report Outline

The outcome of the present study is presented in this report that is structured as the following:

- Executive summary
- Section 1 Introduction to project background and study objectives
- Section 2. Stage 1 - Definition of goals and assets and operations
- Section 3: Stage 2 - Projection of future climate change conditions
    - Winds
    - Waves
    - Water levels
    - Currents
    - Rainfall
    - Temperature
- Section 4: Stage 3 Initial vulnerability assessment
- Section 5: References

1.3 Abbreviations and Definitions

Abbreviations	Definitions
AR5	IPCC Fifth Assessment Report (2014)
AR6	IPCC Sixth Assessment Report (2021)
BBT	Break Bulk Terminal
CD	Chart Datum
CFSR	Climate Forecast System Reanalysis
CMIP6	6th Phase of the Coupled Model Intercomparison Project
CORDEX-SEA	Coordinated Regional Climate Downscaling – Southeast Asia Domain
CT	Container Terminal
DB1	Dry Bulk Terminal I
DB2	Dry Bulk Terminal II
ENSO	El Niño–Southern Oscillation
ESGF	Earth System Grid Federation
GMC	General circulation models
GHG	Greenhouse gases
GCM	General circulation models
HD	Hydrodynamic
IPCC	International panel for climate change
LBT	Liquid Bulk Terminal
MSL	Mean sea level
NDC	Nationally determined contributions
PIANC	The World association for waterborne transport infrastructure
RCM	Regional climate models
RCP	Representative concentration pathways
SoM	Strait of Malacca

SSP2	Socio economic pathway – Middle of the road, the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns
WMO	World Meteorological Organization
WCRP	World climate research program
WRF	Weather research and forecast model

2 Stage 1 – Definition of Goals and Assets and Operations

2.1 Goals

The main goal of this study is to evaluate the potential implications of climate change on the risk profile of the Westports facilities and to assist in the development of a medium and long-term plan for climate change adaptation planning.

The climate change assessment focuses on the analysis and evaluation of various climatic and metocean parameters that include wind, water levels, waves, currents, rainfall and air temperature to evaluate their effect on assets and operations of the port. The climate change assessment is for a timeframe of **60 years (2080) from a baseline** period (2020) and is based on available data and model simulations from the IPCC Assessment Report AR5 /2/ that was issued in 2014.

2.2 Identification of Critical Assets and Operations

Relevant assets and operations of the port have been selected based on the spatial location within the port facility. Three areas are defined to identify assets and operations.

4 **Marine, offshore, in river areas**. This corresponds to areas where assets or operations are located or carried out in water.
  - Assets: Channel, fairway, and waterway, Anchorage, CT1 to CT9 container berths, dry bulk terminal, break bulk terminal, Liquid bulk terminal (LBT1 to LBT5), Dry bulk terminal II and Aids to navigation
  - Operations: pilotage, marker buoys navigation aids, dredging/disposal, maintenance of infrastructure, cargo handling gangways

5 **Land Water Interface**
  - Assets: Revetments for CT1 to CT9, revetment for dry bulk terminal I, revetment for break bulk terminal, revetment for liquid bulk terminal, revetment dry bulk terminal II

6 **Terrestrial /hinterland**
  - Operational: Cargo handling, parking, container yard, storage facilities (e.g., tank farm and other non-container storage), offices, transport infrastructure (road, rail, etc)
  - Assets: Offices, buildings, storage areas, cargo handling equipment, cranes Electricity sub-station, Drainage system Sewerage system, Water supply system, Electric supply system

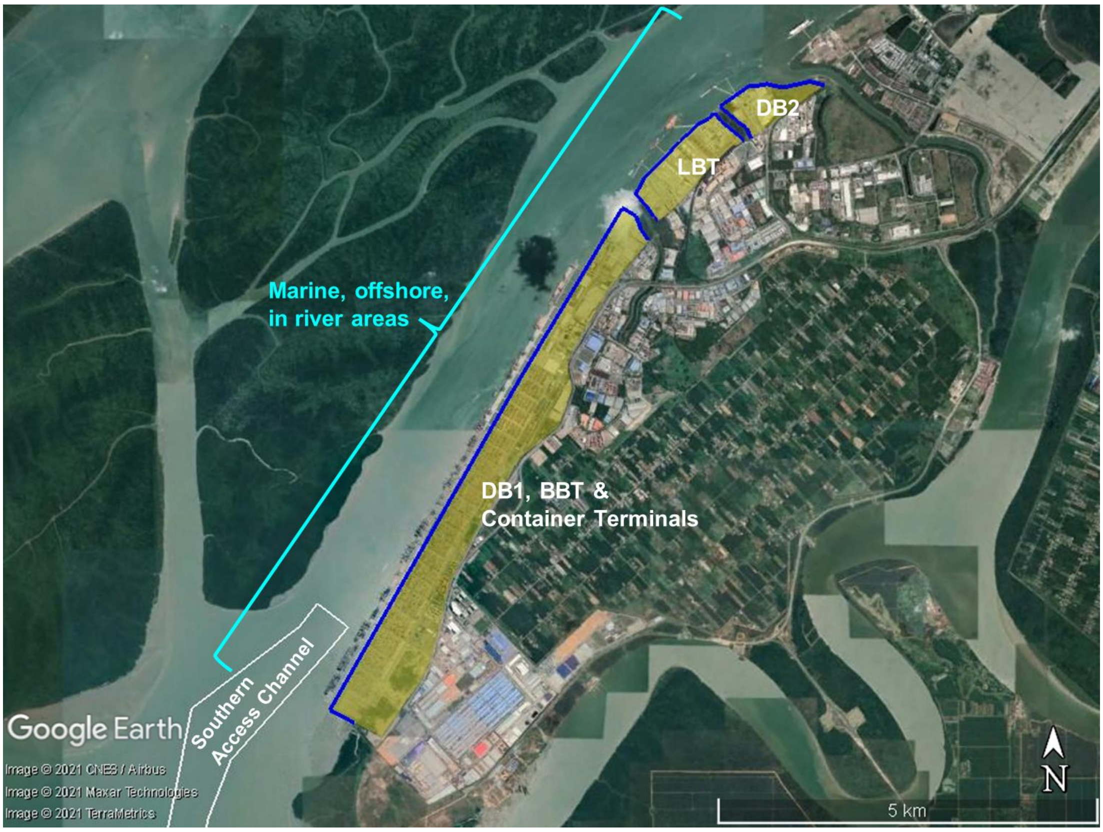


Figure 2.1 Three areas defined for identification of assets and operations: marine, offshore, in river areas; land water interface (shown as blue line); and terrestrial / hinterland (shown as yellow polygon).

3 Stage 2 - Projections of Future Atmospheric Conditions and Selection of Scenarios and evaluation of Climate Change

3.1 Selection of Climatic scenarios

To evaluate the potential future metocean conditions (waves and currents) it is necessary to define the atmospheric scenarios that represent the range of possible future conditions. For metocean conditions, future surface winds and sea level pressure play an important role and are required to derive the potential changes in the coming decades and therefore for the section of scenarios the focus has been set on changes in wind conditions.

Information on winds was extracted from the Coordinated Regional Climate Downscaling – Southeast Asia Domain (CORDEX-SEA). CORDEX is a collaborative program coordinated by World Climate Research Program (WCRP) under the World Meteorological Organization (WMO) that aims at advancing the sciences and applications of regional climate downscaling over different parts of the world. The CORDEX simulations were conducted following a unified and comprehensive protocol and were used widely within the IPCC's AR5 timeline. The simulations result has also served as crucial input to the latest IPCC’s 6th Assessment Report. CORDEX was established about the same time with the release of AR5 /2/, and used within the AR5 timeline (between the release of AR5 and AR6).The output of the experiments which were conducted following a unified and comprehensive protocol, served as crucial input to IPCC’s 6th Assessment Report /3/.

The CORDEX-SEA simulation output is made available from the Earth System Grid Federation (ESGF) which is a P2P distributed data infrastructure to archive and distribute climate simulations output around the world. The simulation details and experiment design can be found in a series of publications (e.g., see /4/, /5/, /6/ and /7/).

Example of the applications of the CORDEX-Sea output are: Tibay et al. (2021) that used a subset of the low-level winds data from CORDEX-SEA to examine tropical cyclone characteristics (/8/), /9/ Herrmann et al. (2020) analysed the future changes of low-level winds over Southeast Asia using a single set of CORDEX-SEA downscaled product (/9/). **The results concluded that there is a projected weakening of the SW monsoon mean circulations over the northern South China Sea and Pacific regions but changes over other areas remain insignificant.**

In the present study, we examined all the CORDEX-SEA simulations made available on the ESGF archive which provide both the sea level pressure and 10 m winds data. The restriction of the simulations output based on the two variables is necessary as these variables are required to drive the HD and wave models at later stages of the project. Table 3.1, below, shows the list of general circulation models driven regional climate simulations from the CORDEX-SEA archive selected for subsequent analysis. All the regional climate models (RCMs) simulations were conducted on 25 km × 25 km grid resolution. There is a total of 10 different future scenarios driven by different general circulation models (GCMs), regional climate models (RCMs) as well as Representative Concentration Pathways (RCPs).

Table 3.1 The regional climate simulations used for the analysis.

Driving General Circulation Models (GCM)	Regional Climate Models (RCM)	Considered RCP Scenarios	Data Frequency
CNRM-CM5	RCA4	RCP4.5, RCP8.5	Winds (6-hourly)
HadGEM2-ES	RCA4	RCP4.5, RCP8.5	Winds (6-hourly)
HadGEM2-ES	RegCM4	RCP2.6, RCP8.5	Winds (3-hourly)
MPI-ESM-MR	RegCM4	RCP2.6, RCP8.5	Winds (3-hourly)
NorESM1-M	RegCM4	RCP2.6, RCP8.5	Winds (3-hourly)

The 10 sets of different futures represent the uncertainties associated to climate sensitivity; downscaling models used as well as the future GHG concentrations. The RCPs are the scenarios used as boundary conditions for the GCMs simulation used in the IPCC's 5th Assessment Report. Figure 3.1, below, shows the global Net CO_2 emission as well as the global averaged surface temperature changes for the selected RCPs scenarios used in IPCC AR5 /2/ . In the high emission scenario i.e., RCP8.5, the global temperature is expected to increase ~5°C by the end of the 21st century and the emissions are expected to reach >1000 ppm CO_2 eq. For the RCP4.5, the temperature increment by the end of 21st century is expected to be 1.7-3.2°C and the emission is expected to reach between 580-720 ppm CO_2 eq. The RCP2.6 is the representation of the low end of the emission scenarios, and it is typically used to explore the mitigation scenarios aiming to limit the global mean temperature to 2°C. Note that the RCP2.6 shows negative emissions from energy use in the last quarter of the 21st century.

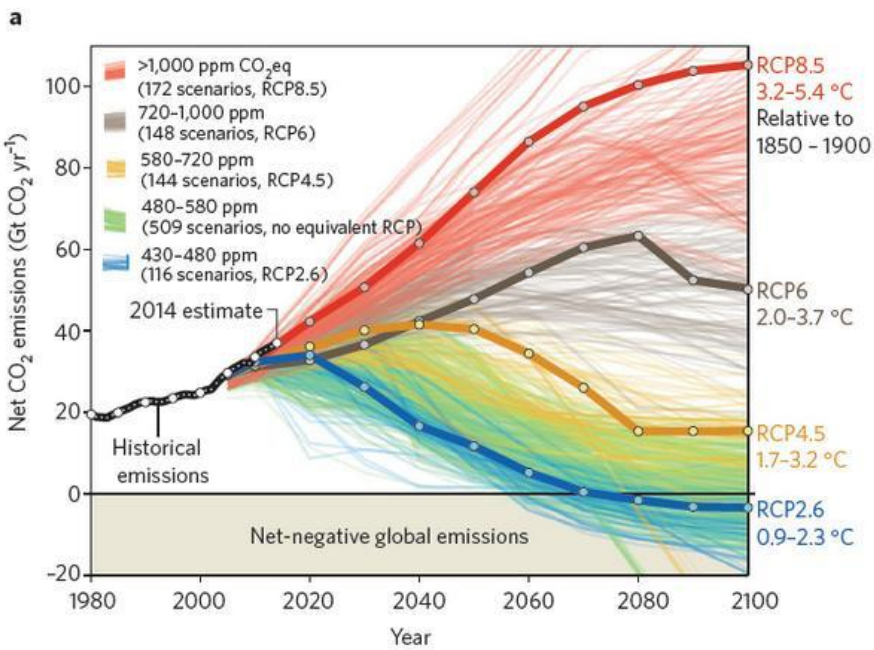


Figure 3.1 The changes of Net CO_2 emission and global surface temperature according to different RCPs used in the CMIP5 simulation experiments (Source: IPCC AR5 /2/).

3.1.1 The Biases of the Climate Projection

It is known that climate simulations output are biases and therefore could affect the subsequent use as modelling input for climate change impact assessment (/10/). Here, we first compare the overall historical distributions of the CORDEX-SEA simulated 10 m wind speed and that of the WRF (Weather Research and Forecast Model, see Section 3.2 for a description of these data) hindcast at 10 selected points as depicted in Figure 3.2.

For this comparison, the historical hindcast distributions were constructed from 2005 to 2016, constrained by the period of data availability; whilst the distributions of the CORDEX-SEA downscaled output were constructed from 1986-2005, constrained by the definition of 'historical period' of the RCP scenarios set. This mismatch in time and data period for distributions comparison is not expected to alter the result as the climate change types of simulations are not constrained by real observations and therefore are not expected to be one-to-one corresponding in time (years) with the observed variations. Also, in the context of climate change, the changes are typically interpreted over a longer period of several decades driven by the changes in GHG in the Earth's climate system, as the signals are apparently more separable from other noises.

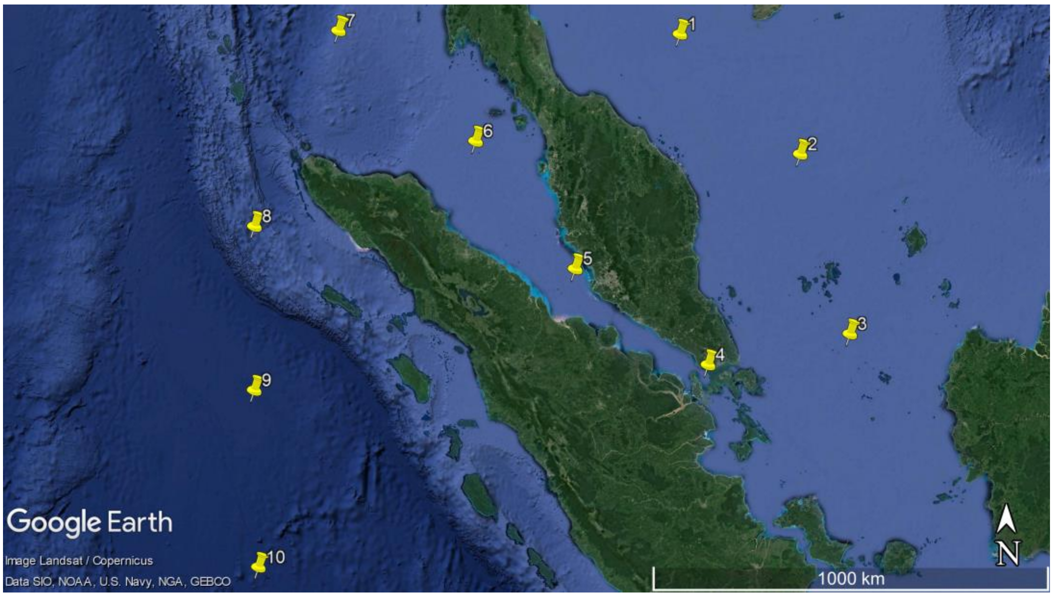


Figure 3.2 Locations of points considered for comparison.

The WRF hindcast winds are available in half-hourly frequency whilst that from the CORDEX-SEA RCMs simulations are in either 3-hourly or 6-hourly frequency. However, the winds output is instantaneous during model integration.

For the distribution comparison, the wind speeds at the selected locations were first computed from the u- and v- wind components. The u- and v-wind components were taken from the grid that contained the selected points. The wind speeds were first fitted to the Weibull distribution and the probability density function (PDF) curves are computed from the fitted distributions. Here, we focus more on comparing the right-tail of the distributions because it characterised high wind events, which presumably has higher relevance to marine operations. Figure 3.3 to Figure 3.5 depict the distributions comparison between the WRF hindcast and the CORDEX-SEA RCMs (refer Table 3.1) simulations over South China Sea, Straits of Malacca and Andaman Sea. For clearer comparison at the right-tail of the distributions, the 95th percentile values of the each of the respective distributions are also overlayed in the plots.

Generally, the RCMs simulated winds tend to skew slightly to the right compared to the hindcast wind speeds. At the Port Klang area (Point 5), the peak of the wind speed distribution is close to 2 m/s but the CORDEX-SEA RCMs simulations tend to produce wind speeds with distribution peak around 3-4 m/s. The positive biases in the CORDEX-SEA RCMs simulations is also apparent at the right-tails of the wind speed distributions. The wind speeds 95th percentile values of the CORDEX-SEA RCMs are also larger compared to that of the hindcast at most of the locations. This indicates that the regional climate model simulations at 25 km grids tend to produce higher wind events compare to that of the hindcast. Overall, the present analysis suggests that the CORDEX-SEA simulations tend to produce positively biased wind surface circulations. Therefore, bias-correction routine is recommended if the datasets are to be used to drive subsequent wave and hydrodynamic models.

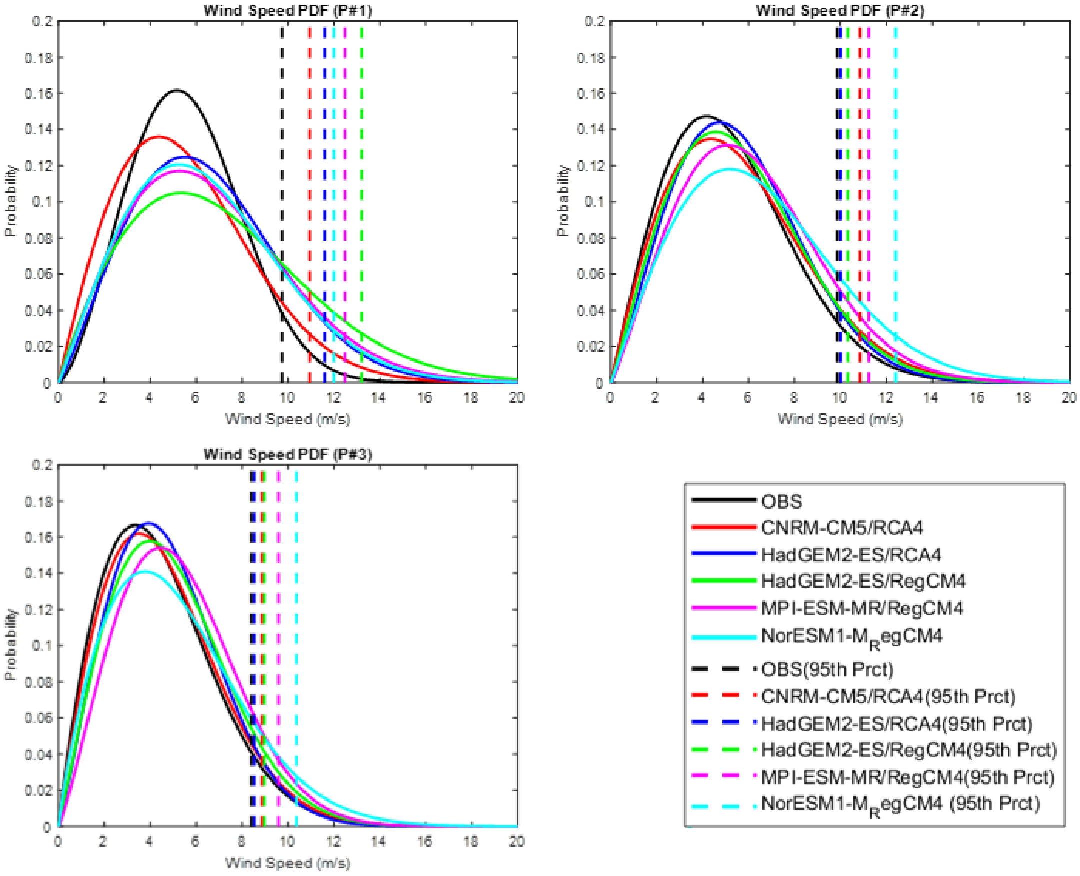


Figure 3.3 The comparison of wind speed distributions between the observation and the RCMs over the South China Sea (point #1, 2 and 3). The vertical dashed lines correspond of the 95th percentile of the data distribution.

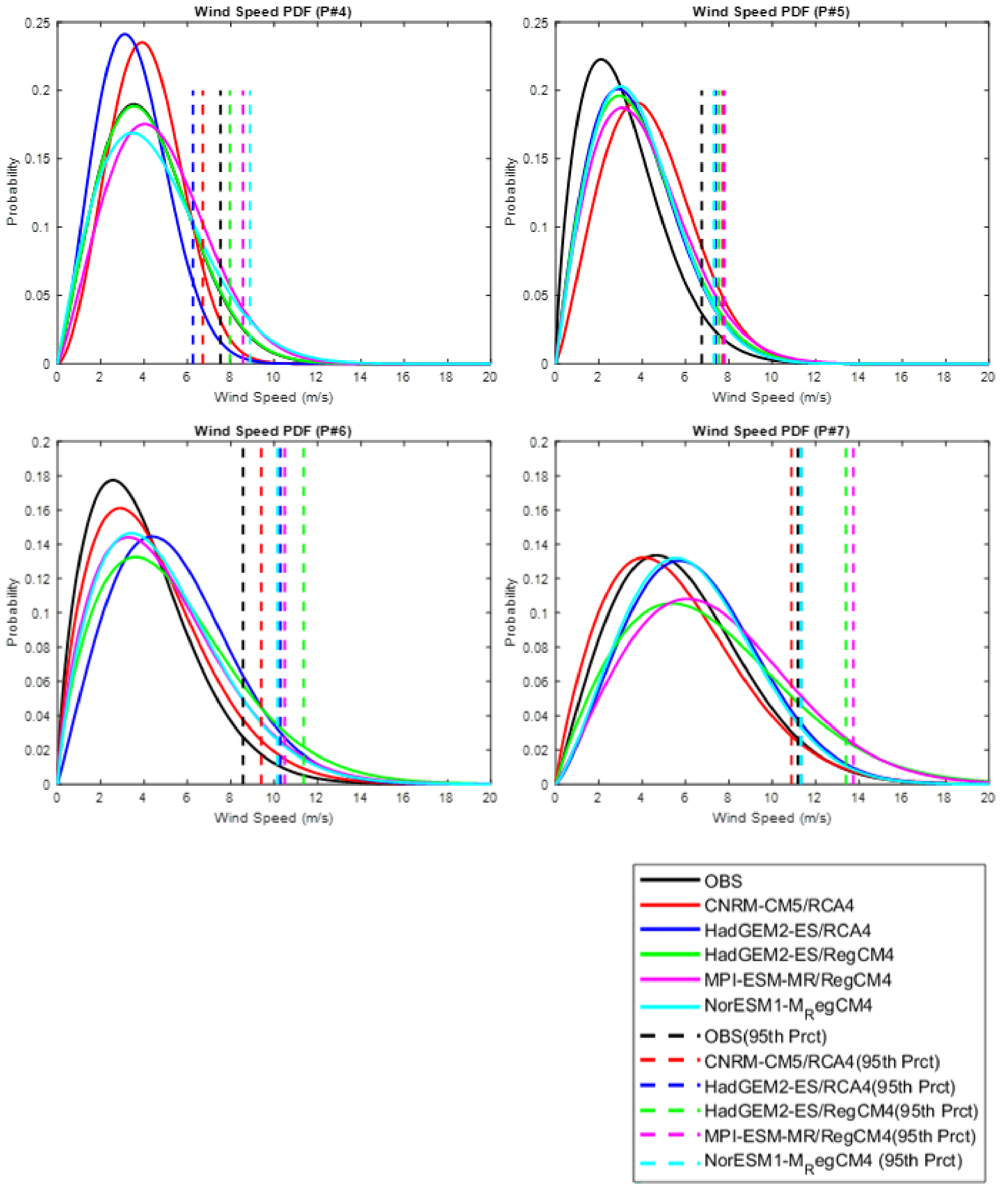


Figure 3.4 The comparison of wind speed distributions between the observation and the RCMs over the Straits of Malacca and Andaman Sea (point #4, 5, 6 and 7). The vertical dashed lines correspond of the 95th percentile of the data distribution.

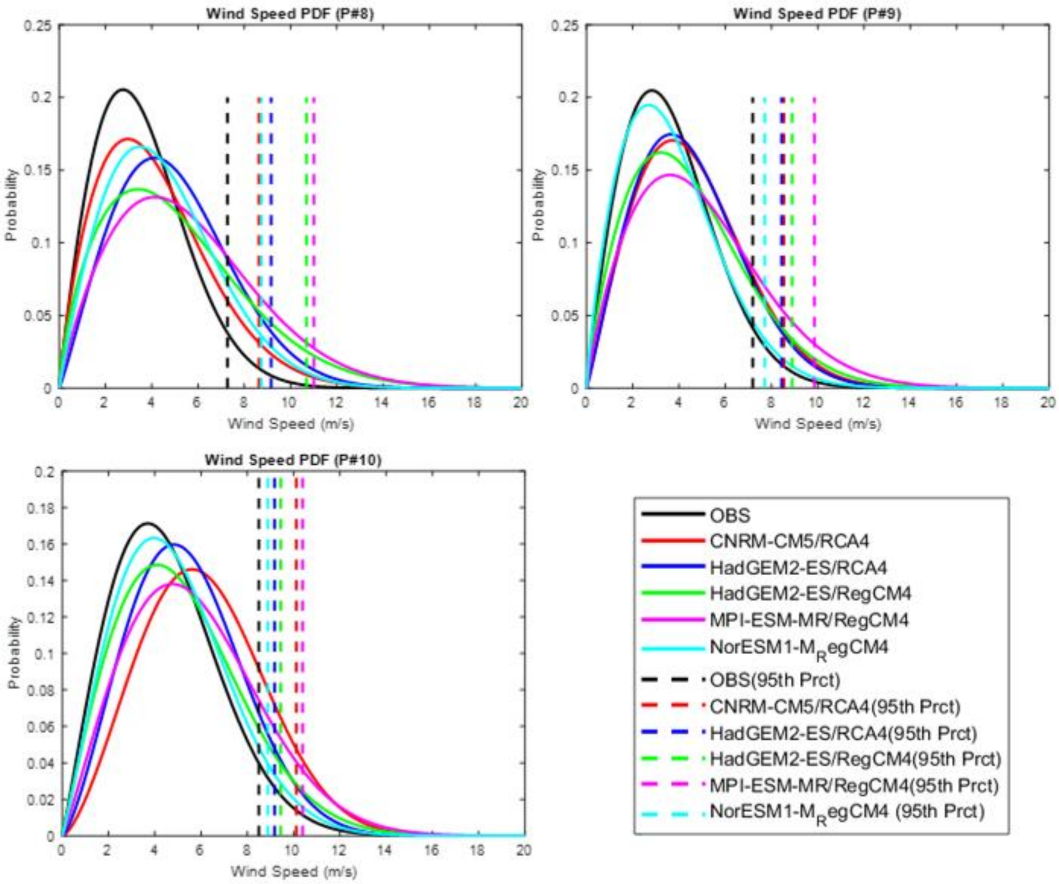


Figure 3.5 The comparison of wind speed distributions between the observation and the RCMs over the eastern Indian Ocean, west of Sumatera (point #8, 9 and 10). The vertical dashed lines correspond of the 95th percentile of the data distribution.

3.1.2 Bias-Correction of the Winds and Sea Level Pressure

Adjusting the biases of climate model simulations output before using it for climate change impact assessment has become a common practice for various sectors e.g., hydrology (/11/), agricultural (/12/), air quality (/13/) etc. The approach, sometimes called bias-adjustment, has been recently adopted in several studies examining the impact of climate change on physical oceanographic properties (/14/).

There are various bias-correction algorithms of different complexity introduced for various applications. In this study, we used the 'delta method' or sometimes called the 'change factor method' to adjust the biases of the 10 m winds and the sea level pressure fields before using them to drive the wave and hydrodynamic models. The delta difference method has been applied for examining the potential changes of physical oceanographic properties under the influence of global warming and driven by IPCC's General Circulation Models (GCMs). Alexander et al. /10/ and Shin and Alexander /15/ used the delta method to bias correct the GCMs simulated winds, sea level pressure and other fluxes to examine the impact of climate change on ocean surface circulations and hydrographic properties over the Atlantic Ocean (/10/ and /15/). Similar approach was adopted by Pozo Buil et al./16/ to examine changes of California current system over the eastern Pacific /16/. Over a smaller area, Goharnejad et al. /17/ applied the delta difference method to examine the impact of climate change on wave energy over the Persian Gulf.

In the delta method, the difference between mean conditions from a future period and the historical of reference period is added to observations that vary with time. In this study, we considered the mean difference (or the 'delta') between baseline (1986-2005) and the 2061-

2080 period. The historical period was selected following the constraint of the RCPs definition where the historical period is up to December 2005 and the scenarios start from 1 January 2006. The 2061-2080 correspond to a period 40-60 years from now. The deltas were computed separately for the 12 climatological months to account for the seasonal variations of the changes.

$$DELTA_{clim} = RCM_{clim\ Future} - RCM_{clim\ baseline}$$

The deltas were then added to the historical (or hindcasted) atmosphere to obtain the 'future atmosphere'. The method was applied separately for the zonal and meridional winds as well as the sea level pressure to obtain the 'future atmosphere'.

$$ATM_{future} = HINDACST_{baseline} + DELTA_{clim}$$

The climate change signals are then interpreted as the differences between the 'future atmosphere' forced conditions and that of the hindcasted atmosphere forced one. Since the historical mean climate and high-frequency variability are retained from observations, this method removes the mean bias and retains realistic unforced climate variability over a range of time scales.

3.1.3 Selecting the Future Scenarios for Wave and Hydrodynamic Modelling Input

There are a total of 10 different future scenarios i.e., three RCP2.6, two RCP4.5 and five RCP8.5 from the CORDEX-SEA archive that can be used to drive the wave and HD models to examine potential changes to the hydrographic conditions driven by climate change.

Limited by the computation resources, we selected 3 scenarios from the 10 different futures, representing 'low', 'medium' and 'upper' bound of the changes. These scenarios encompass all possible changes of the future changes lower atmospheric conditions projected, account for different GCMs, RCMs as well as the GHG scenarios.

To do this we focused on the changes of winds at point No. 5, which is the closest point to our study site. The bias-correction algorithm was applied to the winds time series and the changes driven by the 10 different future scenarios were examined. Figure 3.6 shows the probability density functions (PDFs) of the wind speed of the hindcast (historical) and 10 different futures.

For a clearer comparison, we focused on the right-tail of the distribution and similarly to Figure 3.3 to Figure 3.5, the 99.9th percentile values are displayed. It is noted that the changes of the wind speed at point No. 5 is generally small (<0.5 m/s). However, 7 out of 10 future projections estimated increasing wind speed at this point. The NorESM1/RegCM4 simulation based on RCP8.5 estimated the largest increment of wind speed of ~0.3 m/s. Note also that the HadGEM2-ES/RCA4 simulation based on RCP8.5 also estimate very similar changes of ~0.3 m/s.

Out of 3 projections that estimated a reduction in wind speeds, MPI-ESM-MR/RegCM4 (RCP8.5) projected the largest reduction. Note that both the maximum increment and reduction of wind speed are simulated by the RCP8.5. Therefore, the changes in wind speeds are not a linear function of GHG concentration and may carry considerable uncertainties associated to GCMs sensitivity as well as the downscaling models. However, based on the results, the wind speed is likely (70% chance) to increase in the future, the magnitude of this increase is expected to be small.

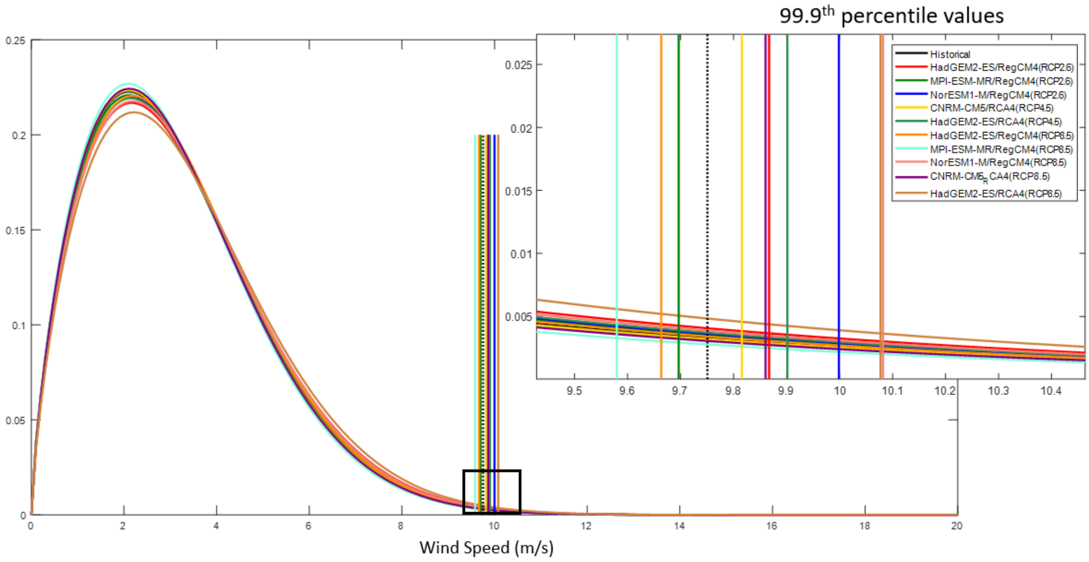


Figure 3.6 The wind speed distributions at point #5 during the historical period and future period 2061-2080 for various GCM/RCM runs driven by different future emission (RCP2.6, RCP4.5 and RCP8.5).

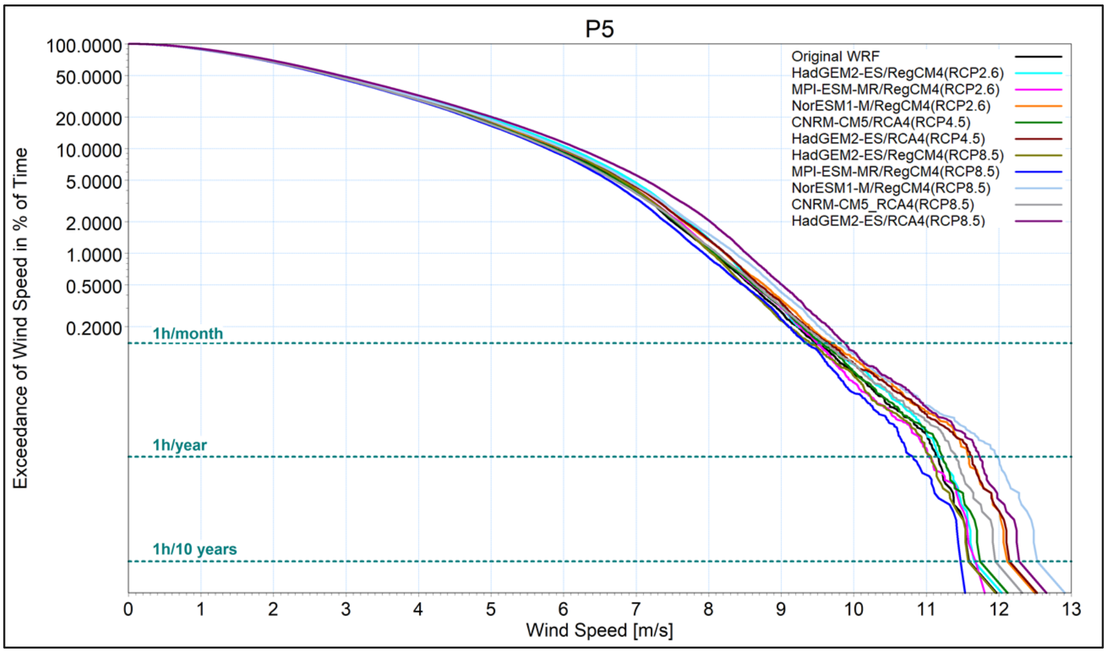


Figure 3.7 The percentage of time the wind speed exceeds a certain wind speed threshold for hindcast (black line) and the 10 different future scenarios (coloured lines).

Figure 3.7 provides the percentage of time the wind speed at point No. 5 exceeds the given thresholds. The high wind event that occurred once in every 10 years has become more frequent in majority of the projected future atmosphere. For instances, the once in 10 years event for the hindcast is ~11.6 m/s. In the NorESM1-M/RegCM4 (RCP8.5) projections, events that exceed 11.6 m/s happen almost every year. Consistent with Figure 3.6, the **NorESM1-M/RegCM4 (RCP8.5)** projected the largest increment of wind speed while **MPI-ESM-MR/RegCM4 (RCP8.5)** projected the largest reduction in wind speed. Therefore, these two scenarios were selected as the 'upper bound' and 'lower bound' of the projected wind changes in the future. The 'deltas' computed from these two projections were applied to the hindcast to produce the 'upper bound' and 'lower bound' atmosphere to drive the wave and hydrodynamic models. For the 'medium' scenario, the averaged changes were used. To achieve this, the averaged ‘deltas’ from the 10 different futures were first computed and these were added to the hindcast fields to provide the ‘medium’ scenario atmosphere for subsequent applications.

While the analysis and selection of the future scenarios were based on the statistics obtained from a single point (point No. 5), the underlying the waves and circulations may also be affected by the adjacent winds and regional pressure gradient. For illustration purpose, the averaged changes (ensemble of 10 future scenarios) of the regional winds and pressure gradients for January, February and March are presented in Figure 3.8. As shown the largest change is projected over the South China Sea and the Andaman Sea. The changes over Strait of Malacca are relatively smaller and magnitude.

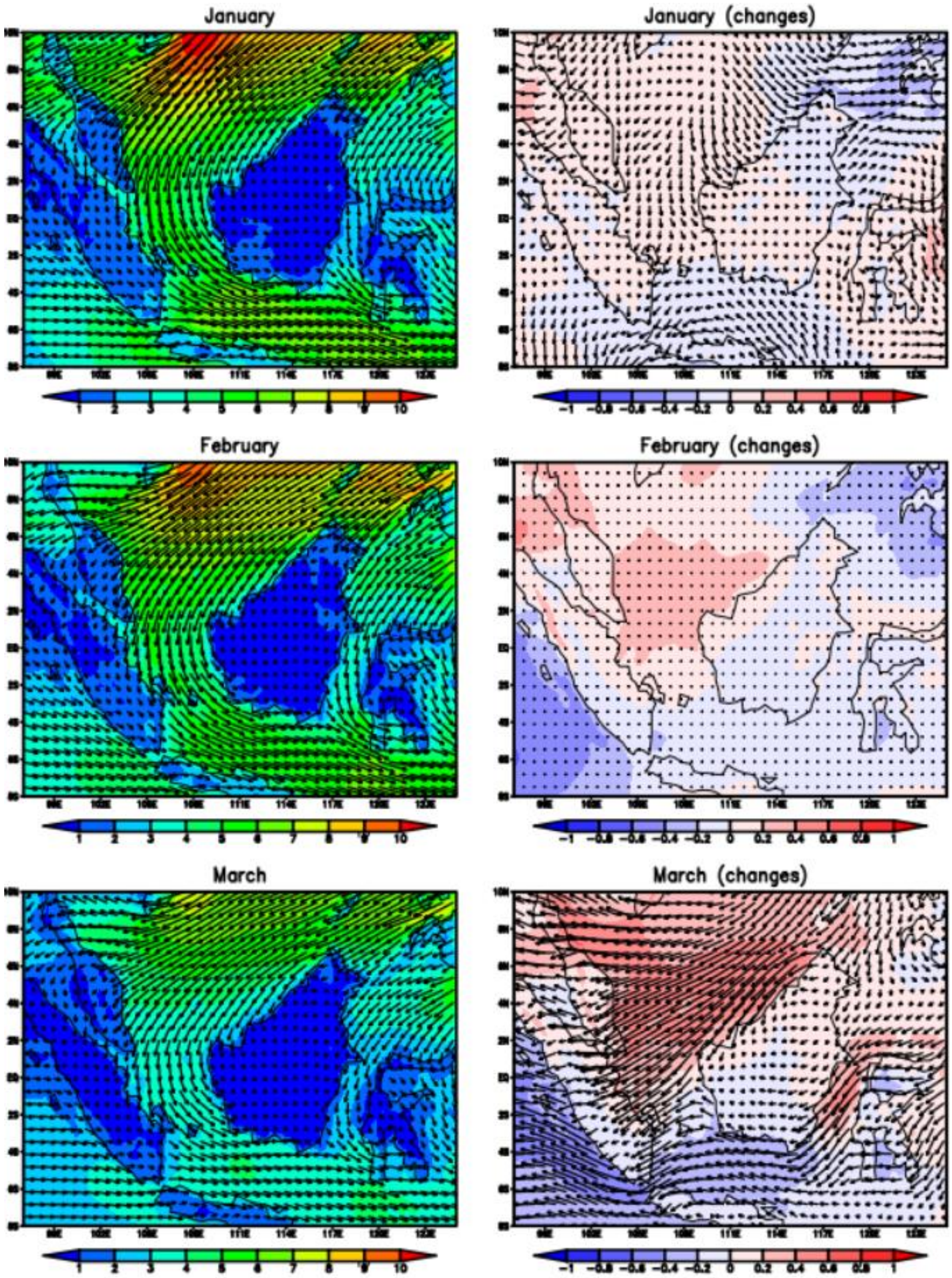


Figure 3.8 The averaged surface winds over Malaysia during January, February and March simulated by the CORDEX-SEA RCMs (left column) and the associated changes during 2061-2080 (right column). Changes of wind speed are contoured (blue and red).

3.1.4 Selected Climatic Scenarios

Based on the assessment in the projection of future conditions - described in section 3.1.3, the selected future climate scenarios (high, medium, and low) are presented in Table 3.2. The assessment is carried out for a period of 40-60 years from now equivalent to the period 2061-2080.

Table 3.2 Selected climate change scenarios to evaluate changes in metocean and meteorological conditions in the Westports area.

Climate Change Scenario	Temperature projections	Wind projections
High NorESM1-M/RegCM4 (RCP8.5)	Averaged temperature increase by 1.7-2.1°C	Increment of wind speed of ~0.3 m/s
Medium Averaged from 10 different futures	Averaged temperature increase by 1.6-2.0°C	No change of wind speed in general.
Low MPI-ESM-MR/RegCM4 (RCP8.5)	Averaged temperature increases by 1.9-2.7°C	Decrement of averaged wind speed ~0.17 m/s

3.1.5 Projection Limitations & Uncertainties

The downscaling projections of future climate involve a significant number of stages with associated uncertainties. The main uncertainties are related to three elements, as described below:

1 **Future emission scenarios.** Future emission of greenhouse gases (GHG) is controlled mainly by the socio-economic development of the world. While the GHG concentrations continue to rise, there is a global effort to reduce the emission via the nationally determined contributions (NDCs) defined by individual countries in the Paris Agreement.
The recent NDCs Synthesis Report 2021 by United Nations Framework Convention on Climate Change (UNFCCC) and The Emission Gap Report 2021 by UN Environment Programme have indicated that the current updated NDCs only reduce the projected 2030 emissions by 7.5% relative to previous unconditional NDCs. This is far below the emission reduction of between 30% and 55% required to achieve the Paris Agreement's goals to limit global warming to 2.0°C and 1.5°C. While many governments have updated their current 2030 NDCs and set their new 2050 'Net Zero Targets', a recent study by FTSE Russell (2021) /27/ indicates that the targets are not aligned with the current Paris Agreement.
Furthermore, current policies of some advanced economies appear to be off track from that of the NDCs. The future pathways of emissions and warming remain uncertain as future climate scenarios depend critically on the world's commitment in reducing the GHG within the next decade.

2 **Climate sensitivity of the climate models.** Given similar GHG increment and radiative forcing, different GCMs will produce different future anthropogenic climate responses. This is mainly due to the different mathematical representation of the dynamical, physical and chemical processes prescribed in the models that result in different feedback mechanisms, particularly that associated with the response and impact of ocean circulation.
Therefore, climate change impact assessment can be affected by the GCMs used to provide the future climate projection. It is imperative to consider multiple GCMs projection to account for the associated uncertainties.

3 **RCMs used for downscaling.** Similar to the GCMs, the regional climate models (RCMs) used to downscale the GCMs projections have different mathematical representations of the regional climate processes. Hence, they response differently to similar boundary condition. A study by Suzuki-Parker (2018) /31/suggested that the magnitude of the uncertainties contributed by the RCMs can be comparable to that of the GCMs.

Given the sources of uncertainty, the future climate projections need to consider multiple emission scenarios, GCMs and RCMs. In the present study, we consider 10 different future projections constructed from the 5 combination of GCMs-RCMs couplets and 3 different future emission scenarios (RCP2.6, RCP4.5 and RCP8.5).

One of the key parameters analysed in the present assessment is wind, this is an important driving mechanism for the generation of waves and currents in the Malacca Straits. The analysis of winds in this area showed that changes of wind speed do not linearly follow the GHC emission patterns and seven out of ten future scenarios projected increment in the mean wind speed indicating a likely increment of wind speed, with moderate possibilities that the projection is erroneous in the direction of changes. It should be mentioned, however, that the predicted increments are expected to be minimal.

For extreme wind conditions, the applied approach assumes the changes as a shift of the mean wind speed, however this approach may not capture the actual changes in the extreme winds driven by warmer environment. In addition, the RCMs downscaling was conducted with a resolution of 25 km × 25 km that is unable to explicitly resolve extreme events driven by local forces where scales are smaller than the RCMs' resolution. These events include the Sumatra squall events which are crucial for the shipping activities over the Strait of Malacca and is often characterized by very narrow rain-band.

A limitation of the present assessment is that there is limited measured data at the site and measurements provide an in-depth understanding of the site conditions. It is recommended that Westports establishes a data monitoring programme to gather valuable climatic and metocean data at their existing facilities to support future climate change assessments. It is recommended that a weather station is placed at the site as well as a wave recorder. With the advent of new hardware and software solutions as well as digital services, data acquisition has become easier and more affordable to carry out environmental observations that can provide valuable information to Westports.

3.1.5.1 IPCC data used

The climate scenarios produced in the present study are based on the CORDEX-SEA downscaled GCMs projections used within the IPCC's 5th Assessment Report (AR5). The latest IPCC 6th Assessment Report (AR6) released in August 2021, updated the climate models and scenario sets in AR5. The climate models used in the AR6 are obtained from the 6th Phase of the Coupled Model Intercomparison Project (CMIP6) that includes a new and better representation of physical, chemical, and biological processes, as well as higher resolution, compared to climate models considered in AR5.

The CMIP6 climate models show higher and a wider range of climate sensitivity that provide better assessment compared to its predecessors. The higher CMIP6 climate sensitivity compared to CMIP5 can be traced to an amplifying cloud feedback in CMIP6 by about 20% (IPCC, 2021). This resulted in increased certainty in the projected climatic effects of increasing greenhouse gases forcings, particularly on the potential range of global temperature rise. Also, different sets of emission scenarios with new radiative forcing pathways (shared socioeconomic pathways) were used in AR6 projections. In general, AR6 estimates a more rapid increment of global temperature and more intense heat and precipitation extremes as well as the compounded effect in both the historical observations and the future projections.

Within the past decades and before the release of AR5 (i.e 2003-2015), observations have shown a warming of 0.78°C compared to the pre-industrialization era. This warming increased to 1.09°C from 2011-2020, indicating a more rapid warming rate in the most recent decade. The assessment in AR6 projected even higher warming rates with higher certainty compared to the projections in AR5. For instance, AR5 projected that the warming is 'likely' to exceed 2°C for RCP6.0 and RCP8.5. AR6 projected that it is 'very likely' that the warming will be between 2.1-3.5°C for the SSP2-4.5 (intermediate) scenario.

For rainfall, AR5 projected 'likely' intensification of El Nino Southern Oscillation (ENSO) modulation on rainfall under the warming climate but for AR6, the ENSO-rainfall association is 'very likely' to amplify in the coming decades, even according to the SSP2-4.5 emission.

Due to higher increment of temperature, the projection global sea level rise is also higher in the AR6. In AR5, the projection estimated 'likely' global mean sea level by the end of the 21st century increase in the ranges of 0.26-0.55m for RCP2.6, 0.32-0.63m for RCP4.5, and 0.45-0.82m for RCP8.5.

For AR6, the sea level rise projection was revised to 0.28-0.55m under the very low GHG emissions scenario (SSP1-1.9), 0.32-0.62m under the low GHG emissions scenario (SSP1-2.6), 0.44-0.76m under the intermediate GHG emissions scenario (SSP2-4.5), and 0.63-1.01m under the very high GHG emissions scenario (SSP5-8.5). The differences between the two IPCC assessment reports appear to be larger (~19 cm) for the very high emission scenarios but lower for the low to intermediate emission scenarios. Predicted sea level rise estimations in AR5 and AR6 reports by the end of 21st century are presented in Table 3.3.

Table 3.3 Predicted global sea level rise (SLR) by the end of 21st century for AR5 and AR6 assessments.

Climate Change Scenario	**Predicted Global Sea Level Rise (m)**	
	AR5 Assessment	**AR6 Assessment**
SSP1-1.9		0.28-0.55
RCP2.6 / SSP1-2.6	0.26-0.55	0.32-0.62
RCP4.5 / SSP2-4.5	0.32-0.63	0.44-0.76
RCP8.5 / SSP5-8.5	0.45-0.82	0.63-1.01

The current assessment based on the data produced during the AR5 timeline, may underestimate the projected impact of climate change at the study area particularly for temperature warming rate and the sea level rise. However, no detailed information along the Malaysian waters is available for AR6. Given the recent release of the IPCC AR6, the high-resolution downscaled climate projection products are not yet available and will only be released in the next 1-2 years within the AR6 timeline.

Overall, the change in future climate in the Malacca Straits is estimated to be minimal and dominated by uncertainties which could affect the climate change impact assessment. These uncertainties should be considered in the adaptation planning, and it is recommended that an updated assessment should be carried out once the AR6 (or more recent) downscaled high resolution projection data are made available.

3.2 Winds

One of the key sections of this project is the capability of providing wind field and its changes in future climate over the Straits of Malacca. The winds were used as input forcing in the hydraulic models to estimate future changes in waves and currents.

Meteorological variables are normally released in low resolution from global forecast models. However, the weather forecasting model (WRF) is being used in this assessment as a basis of the "Present or historical" wind scenario to further develop and increase the accuracy of predictions particularly in the Strait of Malacca area.

To assess the future and changes of wind and hydraulic conditions over the Strait of Malacca areas, the future climate projections signal (as described in Section 3) are added to the hindcast WRF forcing fields to make the future climate models. Details of the "Present/historical" and "Future" wind model used in this study are briefly explained in Section

3.2.1. The wind model results were subsequently analysed with the future changes in wind climates is discussed in Section 3.2.2.

3.2.1 Wind Data Sources

Mesoscale weather data has been sourced from DHI's regional Southeast Asia (SEA) wind hindcast database. The DHI's SEA wind database is based on the Weather Research and Forecast (WRF) model, which is a state-of-the-art atmospheric model. The WRF model has been used and adapted by DHI to dynamically downscale atmospheric fields such as surface pressure and wind from the established Climate Forecast System Reanalysis (CFSR) project. The hindcast data covers a period of 11 years between 2006 and 2016 with a 30-minute temporal resolution, this period is defined to represent baseline "2020" conditions. The data consists of wind velocities at 10 m above mean sea level and the atmospheric pressure at surface level. The WRF data is given with a spatial resolution of 10 km, which is notably higher than other global hindcast meteorological models. Example of the wind field and the extent of the model coverage is shown in Figure 3.9.

The winds at the project site are likely to be governed by a combination of the monsoonal winds, orographic influences and diurnal land-sea breeze effects which are generally perpendicular to the overall shoreline orientation and blowing landward during day (sea breeze) and seaward during night (land breeze). This occurs due to the temperature differences between land and sea. Depending on the temperature difference and strength of regional winds, the land-sea breeze may occasionally be lacking. During calmer periods, the winds in the coastal regions are likely to be dominated by sea breeze.

With the limited spatial and temporal resolution of the wind fields it should be mentioned that these do not capture the detailed local effects from land and topography or the effects of for high intensity low duration events such as for instance local squalls, see Section 3.2.3.

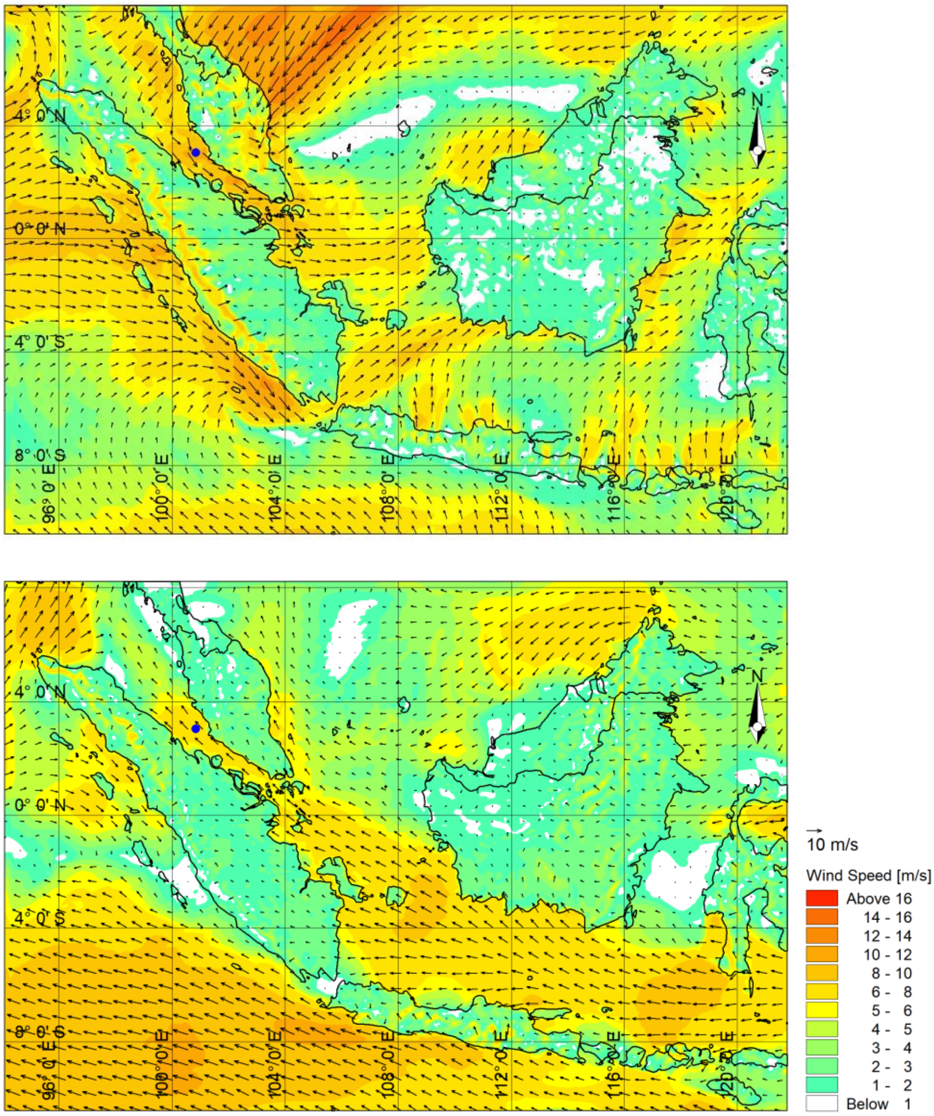


Figure 3.9 Overview of the model extent and sample wind field during NE (top) and SW (bottom) monsoon. The black vectors represent the wind directions given as direction where the wind is blowing from. The blue dot denotes the location of wind data extraction.

Wind speed and direction have been extracted from WRF database at an offshore point of Port Klang for the period 2006 to 2016. The All-year and monthly wind roses showing the prevailing wind speed and wind direction at Westports location are presented in Figure 3.10.

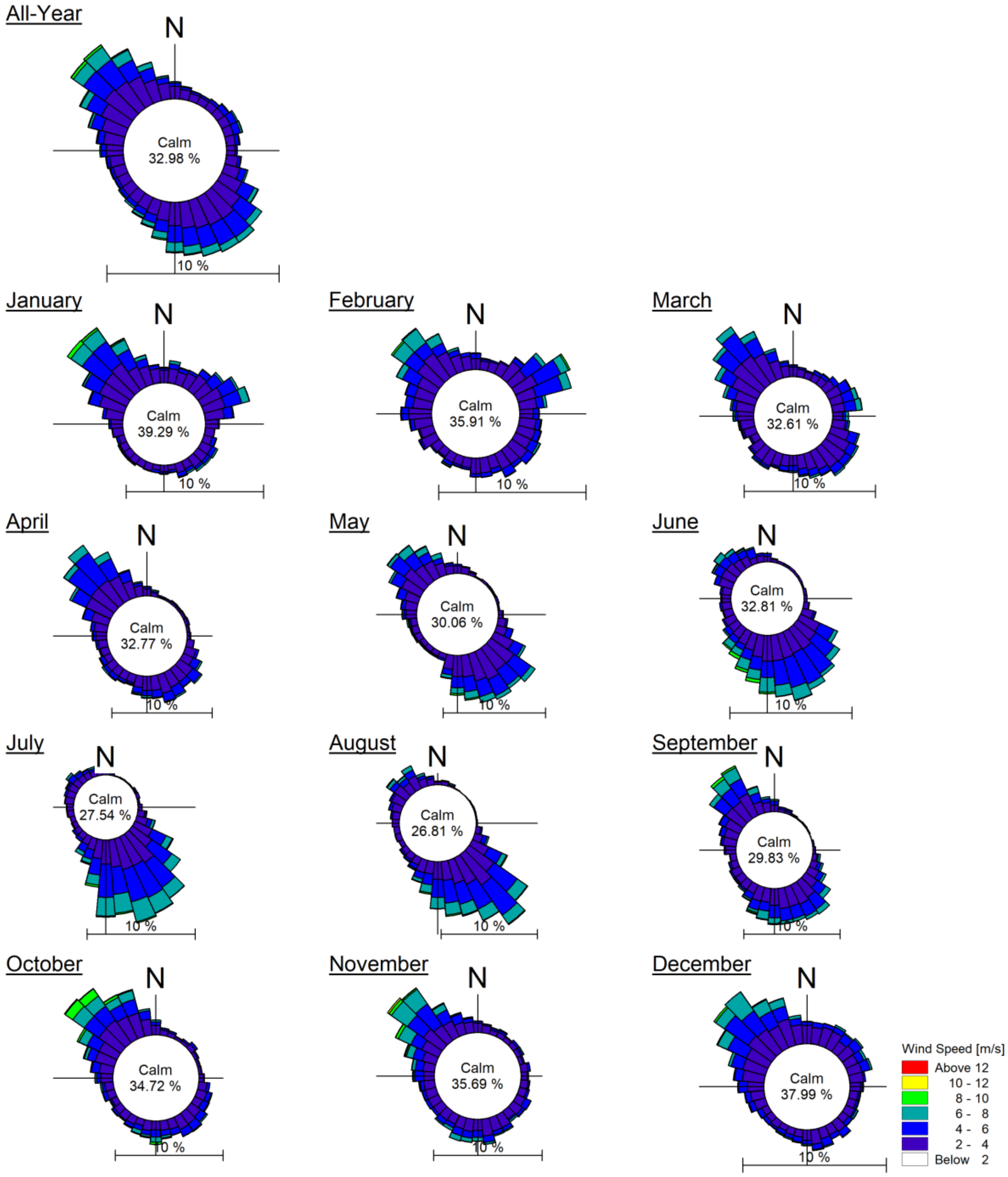


Figure 3.10 Annual and monthly wind roses (2006-2016, 10 years hindcast data - Present Scenario) extracted at Westports.

The monthly wind roses show the NE monsoon have a prevailing wind coming from NW and NE direction and occurs during November to March. Generally, the northeast (NE) monsoon is characterised by strong persistent winds reaching up to 10 m/s from the north-westerly sector. Between April and May, the wind direction is largely variable, indicating the formation of an unsteady wind field during the inter-monsoon.

The SW monsoon during June to August is characterized by prevailing winds from S and SE sectors. The south-easterly and southerly wind directions are generally observed with wind speeds of above 8 m/s during the southwest (SW) monsoon. The withdrawal of the SW monsoon between September to October is showed by the wind shifting towards a more northerly direction at the onset of the NE monsoon.

3.2.2 Future Changes in Wind Climate

Based on the selection of future scenario analysis in Section 3.1.4, the three (3) selected future "Low", "Medium" and "High" scenarios scenario were merged with the ambient WRF to generate "total" future climate wind and pressure maps. The important characteristics of future projection are not only extreme wind climate (i.e. during storm) but also average conditions. Before discussing the extreme climate change in winds - See Section 3.2.2.1, the mean changes are first addressed. Examples of the wind field map during the NE monsoon months between November and February for the future climate scenarios (Low, Medium and High) are shown in Figure 3.11 to Figure 3.13. The average difference between the future and present for each of the scenario during the NE monsoon is as well included in the plots.

The offshore winds in South China Sea Basin are generally 5 – 10 m/s from the North-easterly sectors, whereas the winds inside the Malacca Straits are from the North-westerly sectors with mean winds of less than 5 m/s - significantly lower intensity. These plots illustrate the much weaker winds during the NE monsoon along the Straits of Malacca compared to areas in the South China Sea basin.

The strongest and consistent north-easterly winds occurring during the month of January and predicted future wind changes during the peak NE monsoon month are low. The largest differences are usually observed during the beginning of the NE monsoon in November, with the future low and high wind speed seen to decrease and increase, respectively by up to 2m/s in the South China Sea. However, the changes in wind speed magnitude observed inside the Malacca Straits are relatively smaller compared to the other area.

No significant changes are observed between the future Medium conditions. Further to investigate the changes near Westports, time series of wind extracted from the present and all three future climate models were analysed and compared in Section 3.2.2.1

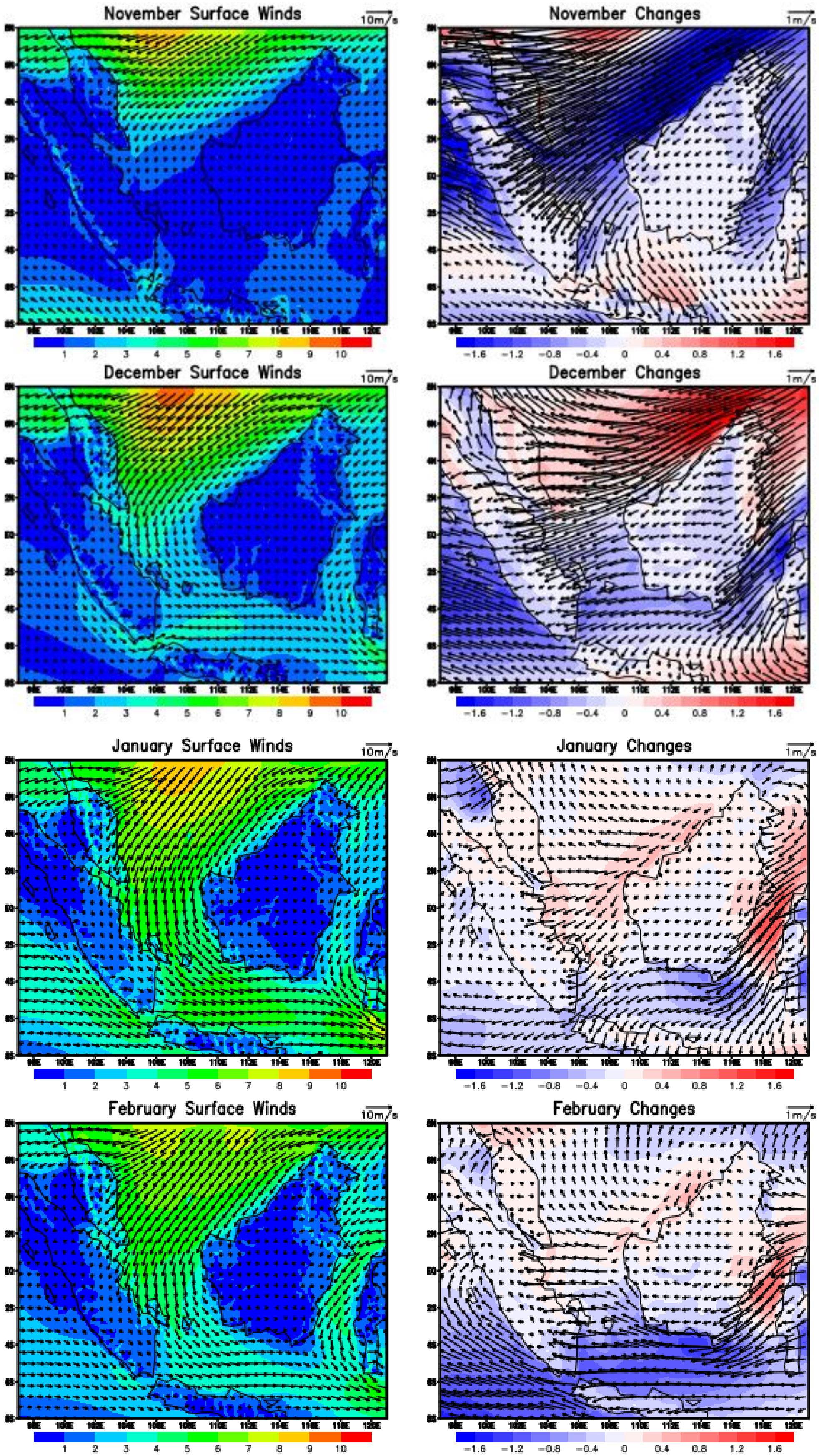


Figure 3.11 Example of average future Low Scenario wind field (left) and its difference between the future and present (right) during NE monsoon months (November to February).

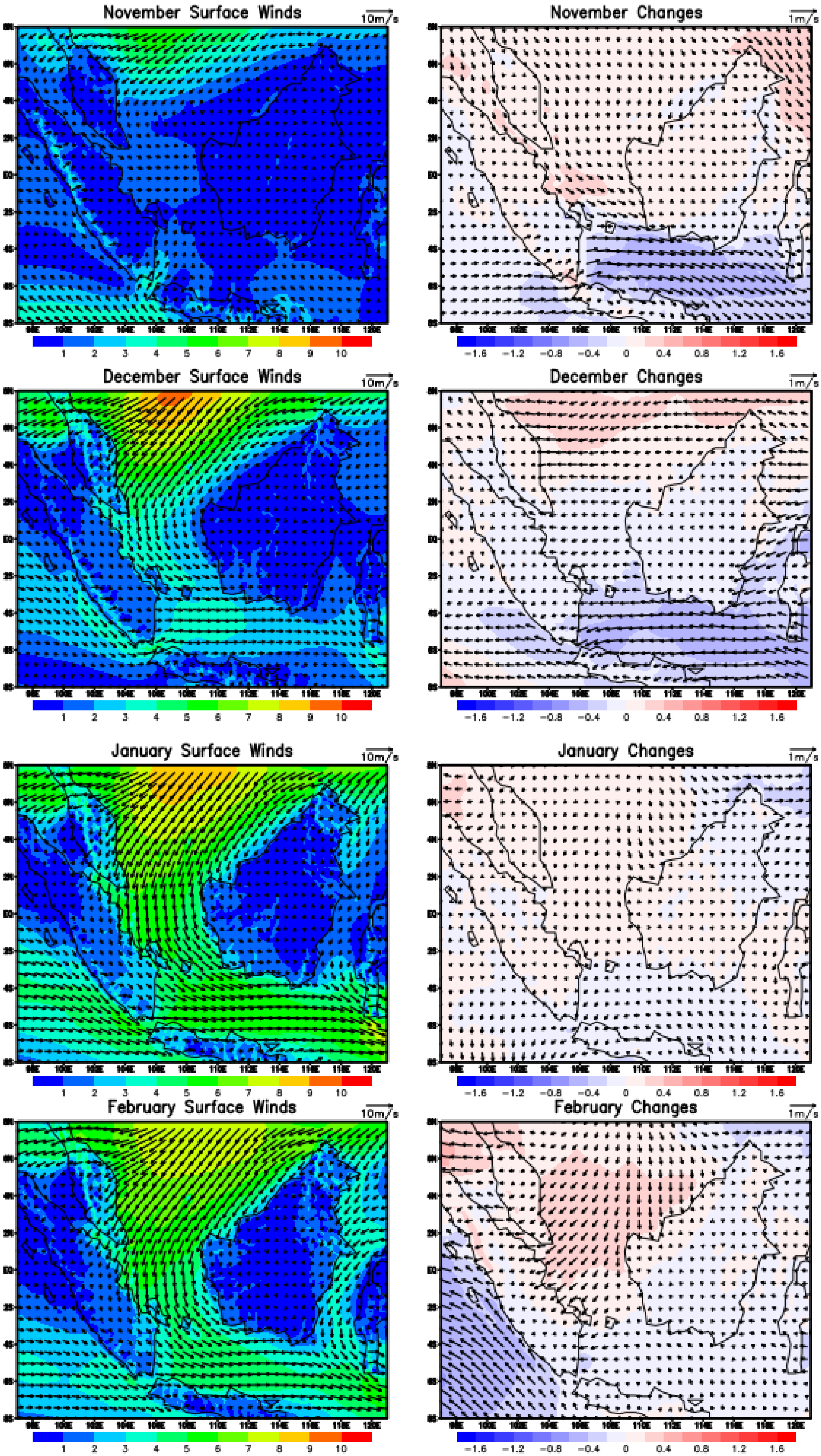


Figure 3.12 Example of average future Medium Scenario wind field (left) and its difference between the future and present (right) during NE monsoon months (November to February).

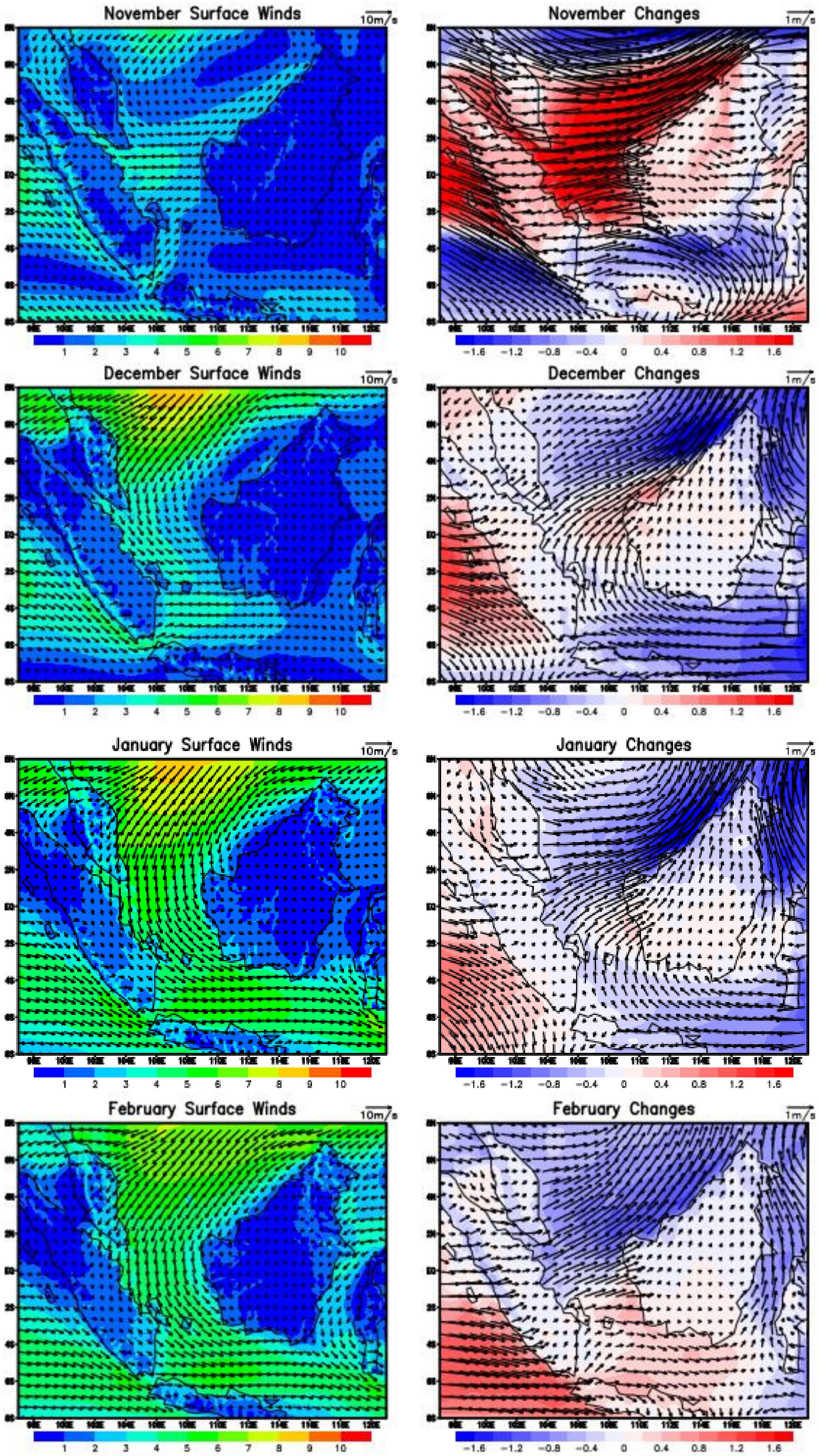


Figure 3.13 Example of average future High Scenario wind field (left) and its difference between the future and present (right) during NE monsoon months (November to February).

3.2.2.1 Changes in wind speed and direction

In this section, the future wind climate at Westports modelled under Low-Medium-High scenarios were analysed and compared against the present wind climate condition. Annual percentage of exceedances for omni-directional winds as function of the time of the year for the present and future climate scenario has been provided in Figure 3.14. The scatter comparison for all scenarios (Low to High) between future climate and baseline condition wind speeds at Westports for the 10 years dataset simulated between 2006 and 2016 are given in Figure

From the results, minimal changes are observed for the future Medium climate scenario. For the future Low and High climate scenarios, it was found that the wind speed will decrease and increase, respectively. Based on the peak ratio (PR) agreement found in scatter plot, on average the future Low scenario generally predicts a decrease by 3%; while the future High scenario predicts increase of wind speed by 4% in respect to the historical wind conditions. The agreement between the future-Medium and present scenario on the other hand show good quantile alignments with PR being closed to 1, indicating only small changes is expected between the two datasets.

The average of monthly peak wind speed (WS_{max}) at Westports for the three future climate scenarios are compared in Figure 3.16. The similar results for the present scenario are also shown in the same plot. Based on this, the percentage of difference between the future and present climate were also calculated and provided in Figure 3.17.

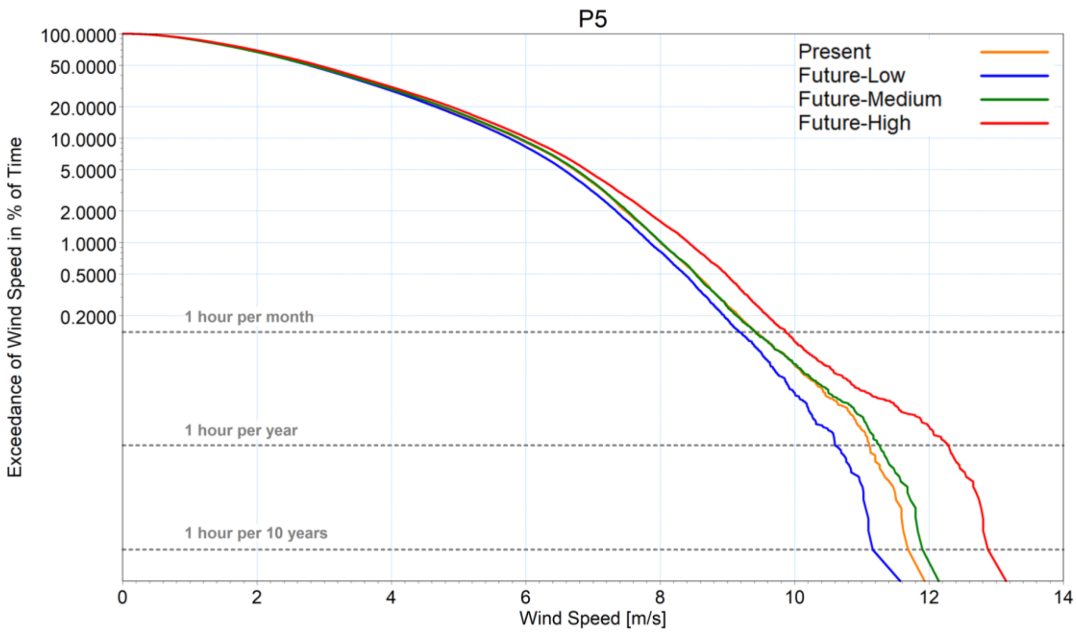


Figure 3.14 Percentage of exceedance for all-year wind speed at Westports based on 10 years dataset for the present (Baseline) and future (Low-Medium–High) climate scenario.

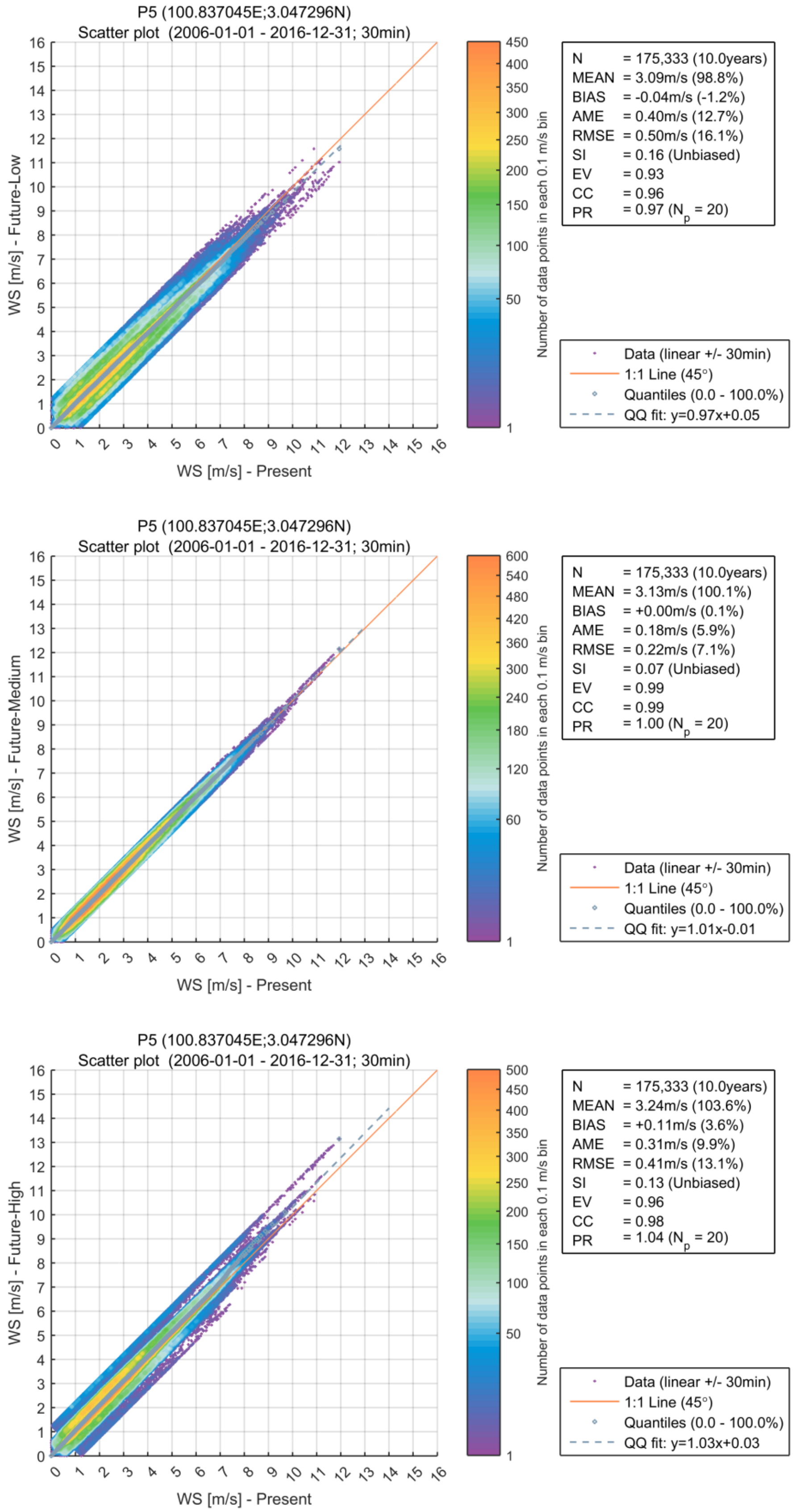


Figure 3.15 Scatter comparison of wind speed between Future climate scenarios (Low - top, Medium - middle and High - bottom) and Present condition at Westports.

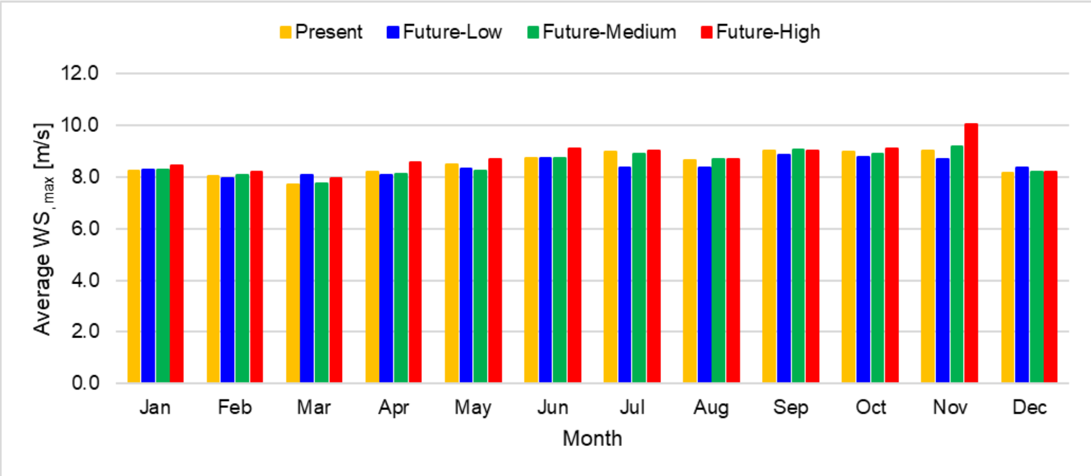


Figure 3.16 Comparison of the present (Baseline) and future (Low-Medium–High) averaged monthly peak wind speed WS_{max} at Westports.

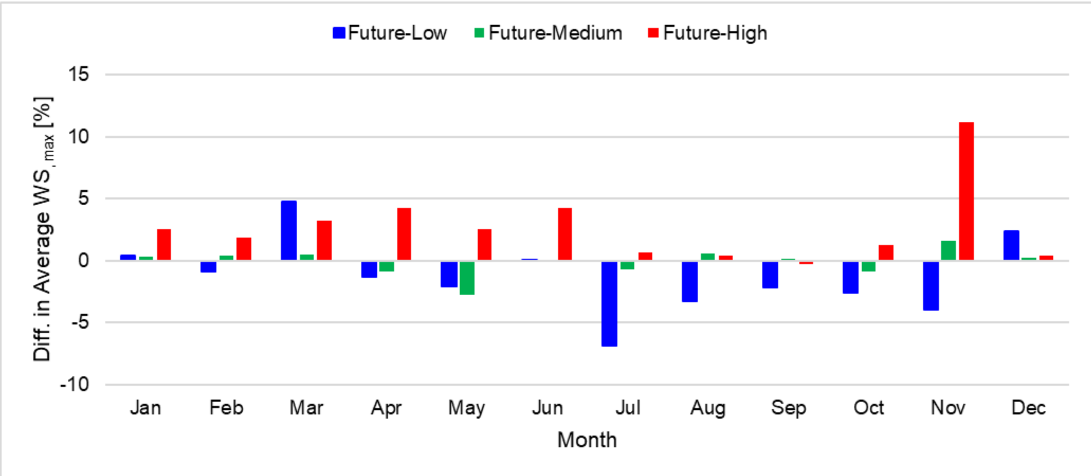


Figure 3.17 Percentage of difference in averaged monthly wind speed, WS_{max} event obtained between the present (Baseline) and future (Low-Medium–High) at Westports.

The directional winds rose plot comparison in Figure 3.18 shows that the future high scenario projected an increase dominancy from the SW to NW sector accompanied by a generalized decrease of wind events from NE to SE sector. The future Low and Medium scenario both contrarily shows increased influenced by the wind blowing from the NE to SE sector.

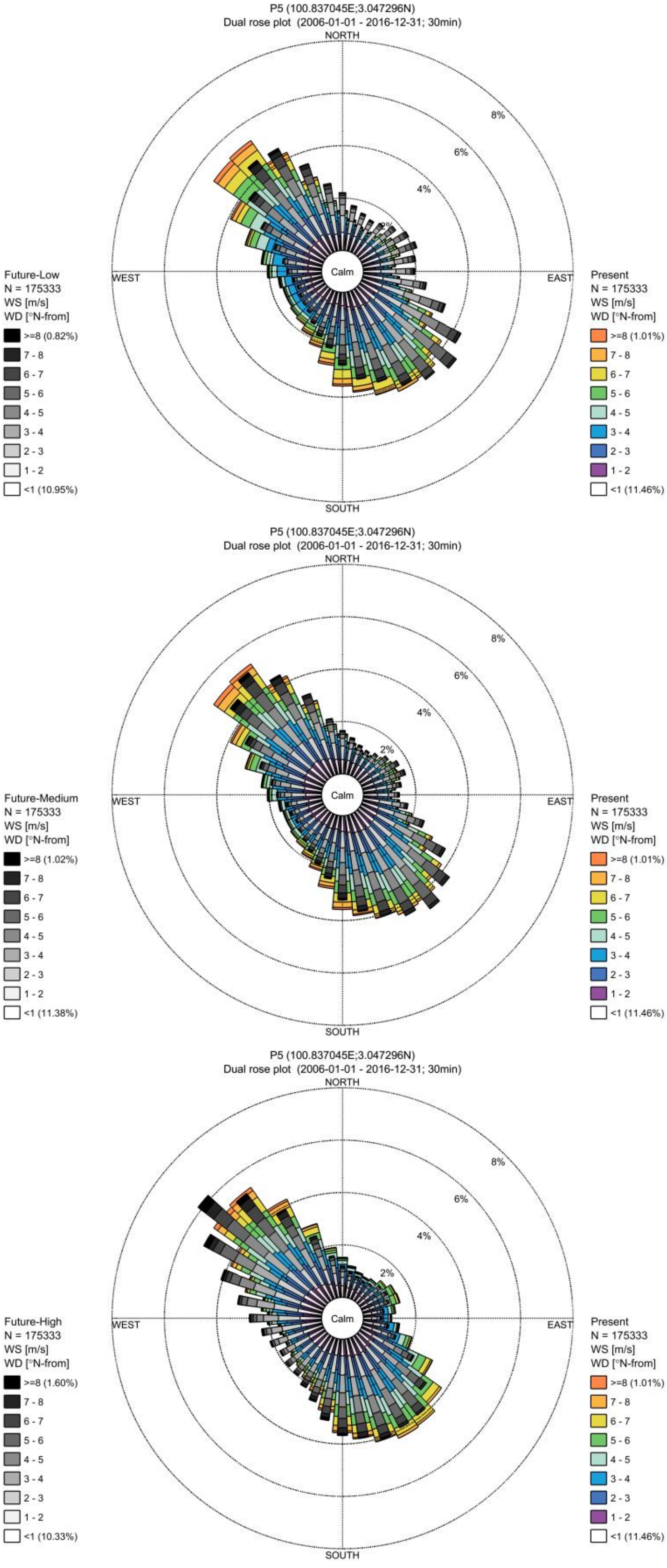


Figure 3.18 Directional Changes observed in between Future (Low-Medium–High) scenario and Present condition at Westports

3.2.3 Extreme Conditions and High Intensity Events

Due to the coarse spatial and temporal resolution of both the hindcast model (WRF) and the climate models considered, the simulations are not expected to capture local scale, high intensity events such as squalls. In addition, there is limited information and/or measurement on squalls in the Strait of Malacca, particularly at the site. This makes the assessment of future squall characteristics changes due to warmer climate extremely difficult.

The "Sumatra squall" is a high intensity and short-duration winds weather system in the Strait of Malacca. It typically forms in the Strait of Malacca and propagate from west to east as a narrow band of thunderstorm toward the western coast of Malay Peninsula (Yi and Lim, 2007).

The squalls usually form in the morning hours and have life span longer than single cell thunderstorms (Lo and Orton, 2016). Their formation is usually followed by onset of strong gusty surface winds exceeding up to 25 m/s and usually accompanied by heavy rain over Peninsular Malaysia, lasting 1 to 2 hours. To date, the onset, structure and dynamic of the squalls are still not very well understood (Koh and Teo 2009), and the modelling of the squalls is extremely difficult (Chan et al. 2019). Ultra-high resolution numerical simulations coupled with advance initialization treatment are required to simulate the onset of squall events (Yi and Lim, 2007; Chan et al. 2019), and their evolutions are generally not well simulated. The same scheme was used to compute the annuals cycle of squalls proxy frequency in the future period (2061-2080).

Projected changes during the southwest monsoon i.e the peak of squalls season show considerable uncertainties. It is noted that these uncertainties are mainly related to the regional climate models used in the downscaling. Future changes of squall events during the peak season are uncertain, hindered by the modelling technological shortage outlined earlier.

3.2.4 Summary of Predicted Wind Changes

A summary of the predicted wind changes for the three scenarios is presented in this section.

- For the low scenario a decrease in the future wind speed most of the months except for March and December is predicted. July displays large deviations with average peak storm wind speed, WS_{max} decreases by ~7% between the future low with respect to present condition. March predicts largest increment of close to 5%.
- The medium scenario shows changes in the order of ±2% is observed so changes are minor.
- The high scenario shows increase in wind speeds throughout the year. It is observed in that higher average peak storm wind speed to be increased in the order of 5-10% observed from November and June.
- The directional winds roses show that the future high scenario projects an increase of winds from the SW to NW sector accompanied by a generalized decrease of wind events from NE to SE sector. Conversely, the future Low and Medium scenario show increase influence by winds blowing from the NE to SE sector.
- The evaluation of the change of future squalls occurrences season shows considerable uncertainties, which are mainly related to the regional climate models used in the downscaling. Future changes of squall events during the peak season are uncertain, hindered by the modelling technological shortage outlined earlier.

3.3 Waves

Changes in future wave climate can impact port assets or operations that could impact on coastal structures, change operation conditions during navigation and berthing and/ or safety procedures, etc. This section provides an overview of changes in wave conditions. To investigate potential future changes on wave conditions corresponding to a future in 60 years a comprehensive numerical modelling exercise was carried out. The waves were driven by "present or historical" and "future" scenario wind conditions. Details of the wave model description and data used are briefly described in Section 3.3.1 with the model limitation discussed in Section 3.3.2. The model results are subsequently analysed and the predicted future changes in wave conditions are discussed in Section 3.3.4.

3.3.1 Modelling Approach and Data Sources

Future variations in wind fields may alter waves conditions over the Straits of Malacca, changing the wave energy transmission along with fetch generation. The annual averaged and extreme waves undergo changes in the future when exposed to different climate change scenarios which can affect the generation and propagation of waves. Due to limited knowledge about how future climate changes may affect the wave climate in the Strait of Malacca particularly at the project site, a three-steps approach was adopted:

1. **Hindcast wave climate models applying historical wind and pressure fields**

   To develop an overview of the wave condition in the Straits of Malacca region, a regional wave model covering SW_{SOM} using DHI's Spectral Wave modelling software (MIKE21 SW) was established. The model is based on an unstructured triangular mesh having a characteristic element length about 5 km within the whole domain. The model resolution is illustrated in Figure 3.19. The 10 years hindcast model driven by wind forcing derived from the WRF historical wind fields (described in Section 3.2.1) that provides baseline conditions that represent the "Present/historical" wave climate scenario.

2. **Future wave climate models under various global warming emission scenarios**

   Based on the selection of future scenario analysis in Section 3.1.4, the three relevant future climates representing the future "Low", "Medium" and "High" scenarios were modelled. The 10 years **Step 1** wave modelling were adapted to represent an estimate of the wave conditions, including the effect of future climate changes. These were done by applying the three (3) future wind and pressure fields as input for the wave models via an ensemble method.

   Although the period used in the wave model covers the period between 2006 and 2016, it should be noted that the established future wave database was based on wind and pressure fields obtained from the adopted future 60 year predicted climate models.

3. **Estimation of future changes in wave climate at Westports**

   Having modelled the conditions for a present (**Step 1**) and a future (**Step 2**) scenario, it was possible to estimate the relative change in wave variables (i.e. H_{m0} and T_p) from the present to future climate, quantitatively and the results are discussed.

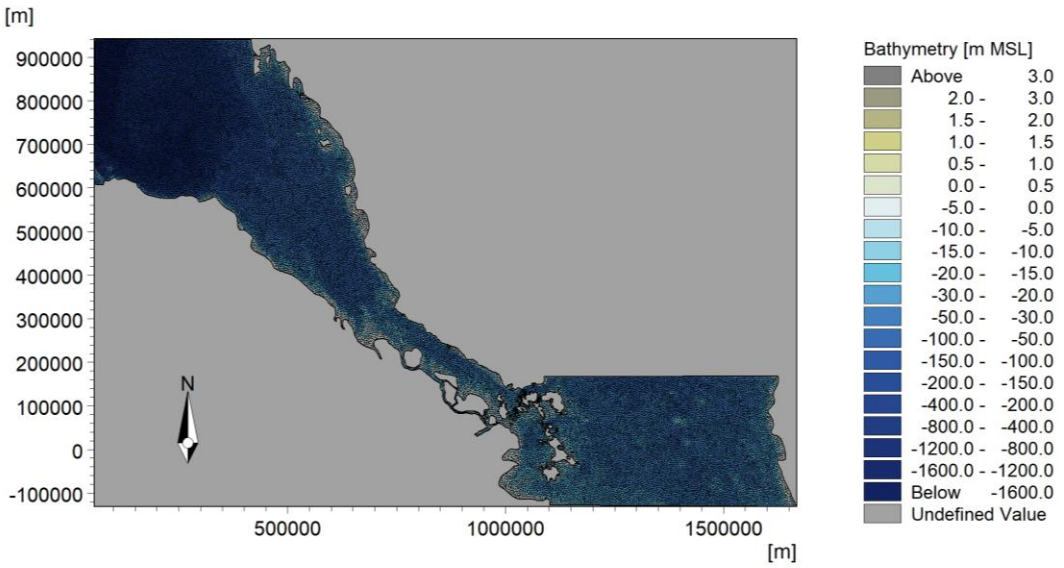


Figure 3.19 SW_{SOM} wave model coverage and bathymetry with vertical datum corresponding to MSL.

3.3.2 Model Limitations & Uncertainties

In the Straits of Malacca, WRF wind data is not able to properly describe small scale land-sea and short-term high intensity wind gusts and squalls. These winds can produce gusts exceeding 25 m/s. Comparison between the present regional SW_{SOM} and storm based local wave model (SW_{LOC}) used in /22/ shows that, the average annual maximum H_{m0} produced in SW_{SOM} model will tend to underestimate the wave in the study area. The discrepancy between the two datasets may largely attributed to the underestimated nearshore wind field where a spatially and temporally varying prescribed in the modelling SW_{SOM}. Whereas the SW_{LOC} in /22/ uses time series WRF winds extracted well offshore from the site to get a better representation of the likely winds over the sea.

The error in the computed SW_{SOM} “present” and “future” is expected to be in the same order of error, therefore the analysis of changes in wave patterns is designed to be used to estimate the ratio of wave climate change from the present to future climate scenarios quantitatively.

3.3.3 General Wave Patterns

The offshore wave climate is composed of locally generated wind waves and swells waves approaching the area from the Indian Ocean and the Andaman Sea. Due to the shoreline orientation along the Straits of Malacca, waves are predominantly coming from between the north-westerly and south-easterly sectors only. Example of the wave field in the study and surrounding areas the predicted wave field during NE and SW monsoons are shown in Figure 3.20 and Figure 3.21 respectively.

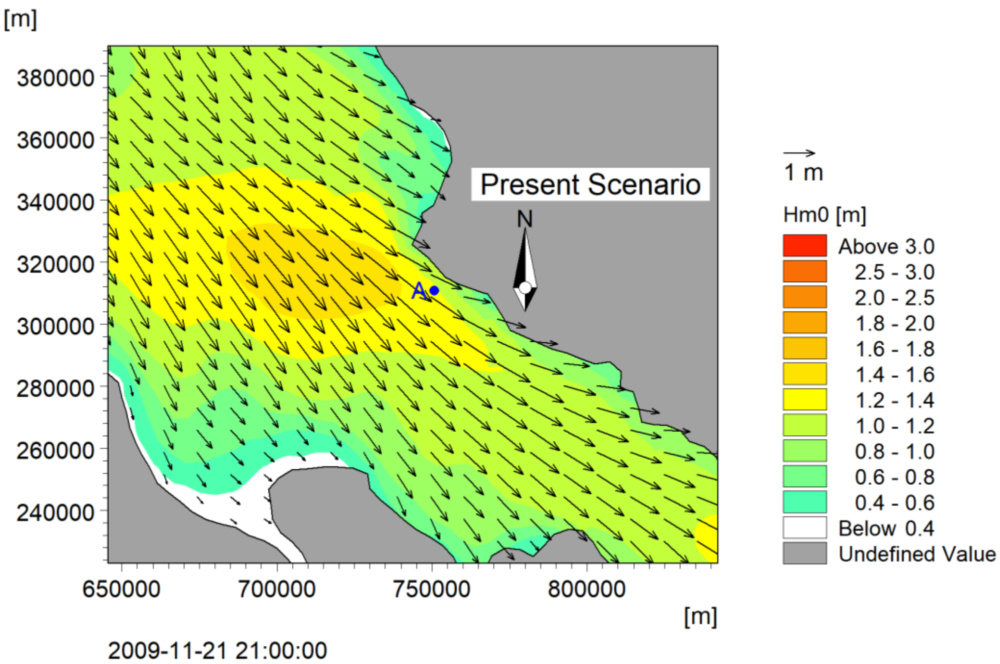


Figure 3.20 Overview of the wave field corresponding to NE-monsoon, the blue dot denotes the extraction site location.

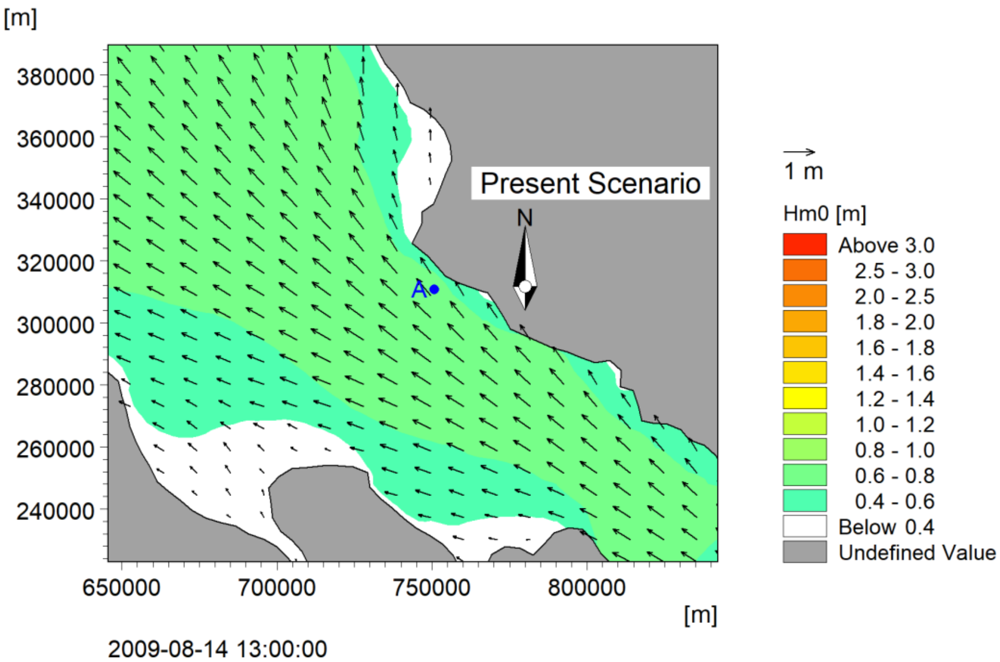


Figure 3.21 Overview of the wave field corresponding to SW-monsoon, the blue dot denotes the extraction site location.

To illustrate the temporal wave patterns at the project site, waves were extracted from the 10 year hindcast database (Present Scenario) offshore of the approach channel to Westports. The annual and monthly wave roses provided in Figure 3.22 to Figure 3.24 show higher waves reaching up to 1.2 m are predominantly coming from the Northwest sector during the NE monsoon occurring between October and February, these waves are influenced by swells generated over the Andaman Sea. With the limited fetch, wind-wave conditions during the SW monsoon between June to August are generally benign with significant wave heights below 1 m for most of the time and are generally propagate from Southeast to Southwest sectors.

The monthly rose plots in Figure 3.23 show that the waves at the site are consistent with the north-westerly wave conditions dominating throughout the year, particularly during the NE monsoon. During the SW monsoon (June-August) the wave climate is influenced by south-easterly winds resulting in more dominance of SE waves.

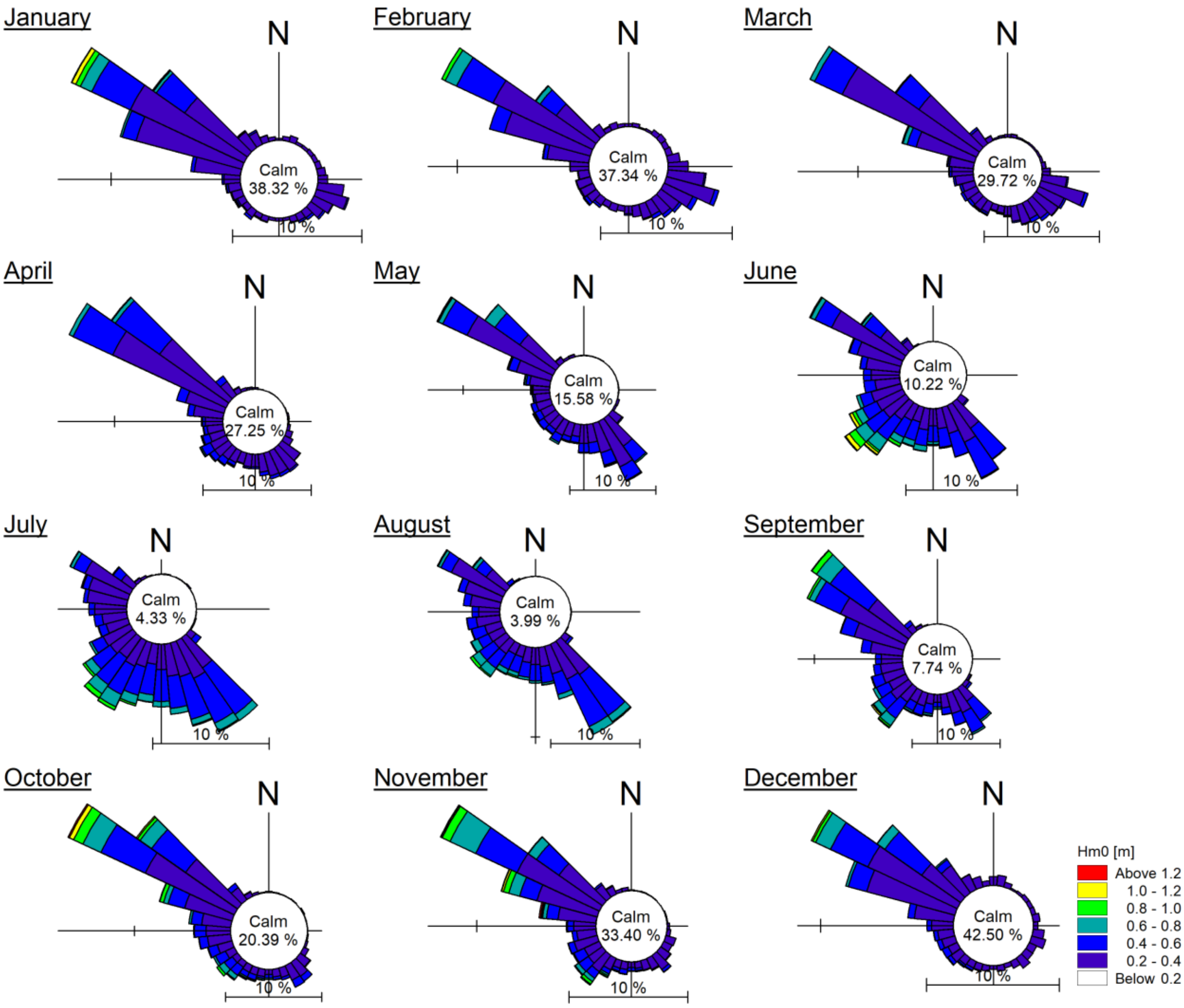


Figure 3.22 Monthly significant wave height roses (2006-2016, 10 years hindcast data – Present/Historical) extracted at Westports.

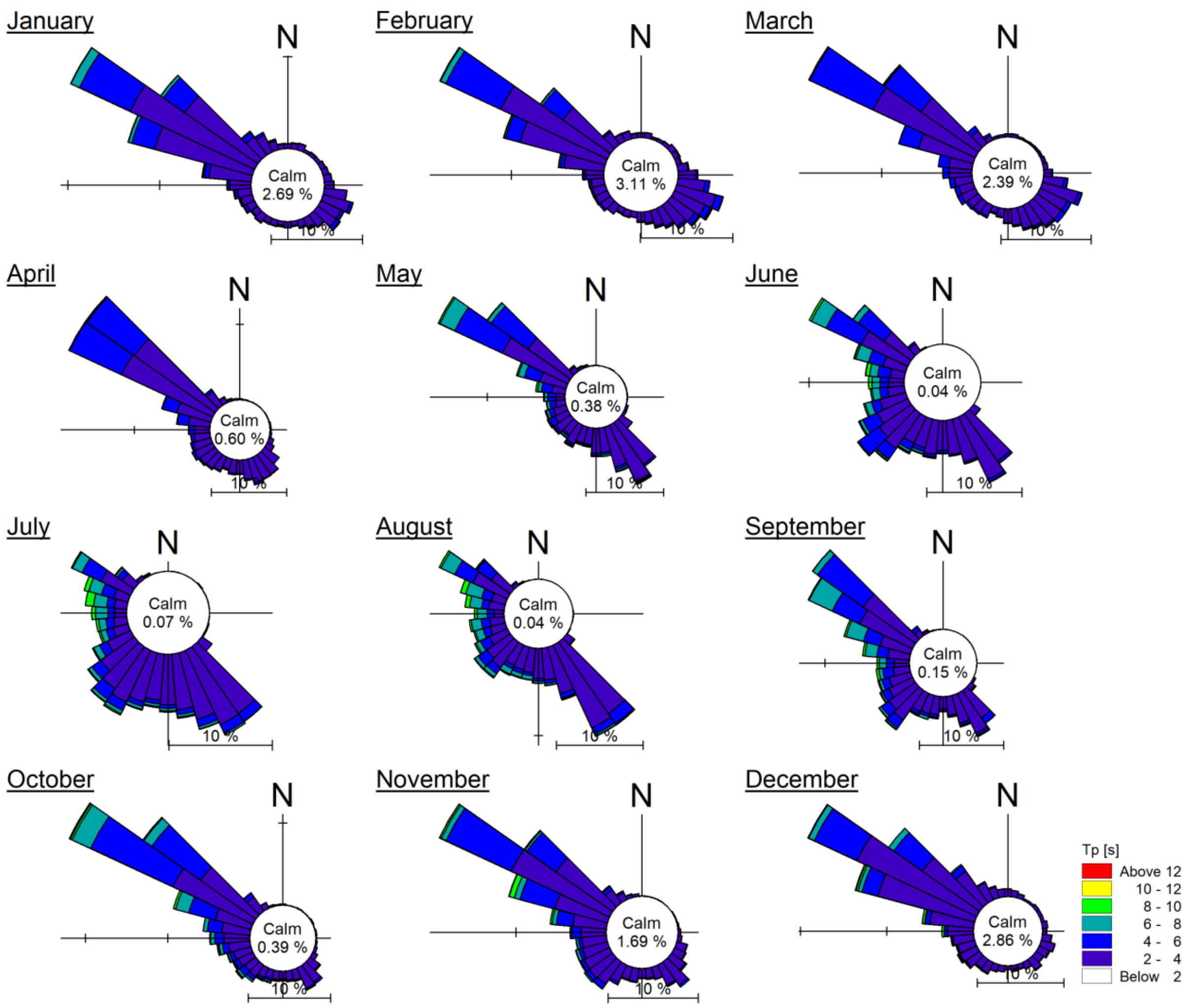


Figure 3.23 Monthly peak wave period roses (2006-2016, 10 years hindcast data – Present/Historical) extracted at Westports.

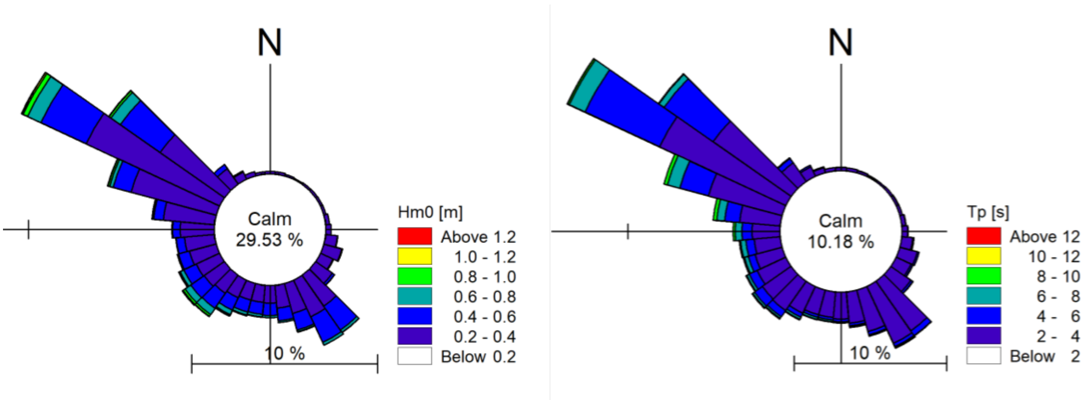


Figure 3.24 All-year significant wave height (left) and peak wave period (right) roses at Westports from year 2006 to 2016, present/historical conditions.

3.3.4 Future Changes in Wave Climate

Annual percentage of exceedances for omni-directional waves as function of the time of the year for the present and future climate scenario has been provided in Figure 3.25. The scatter comparison for all scenarios (Low to High) between future climate and baseline/present conditions for significant wave heights offshore of the approach channel to Westports for the 10 years dataset simulated are given in Figure 3.26.

From the results, minimal changes are expected for the future Medium climate scenario, indicating that it is in good agreement with the present scenario. While for the future Low and High climate scenario, it was found that the waves will decrease and increase, respectively.

Figure 3.27 was mapped to illustrate the normalized average difference between the future and present climate within the model domain, respectively. The future changes of wave heights are most prominent in the northern areas of the Malacca Straits with percentage of average difference observed in the order of ± 15 to 20% (decreases in Low scenario and increases in high scenario). To the south of the Strait of Malacca, average differences observed gradually being reduced with changes observed less than ± 10%.

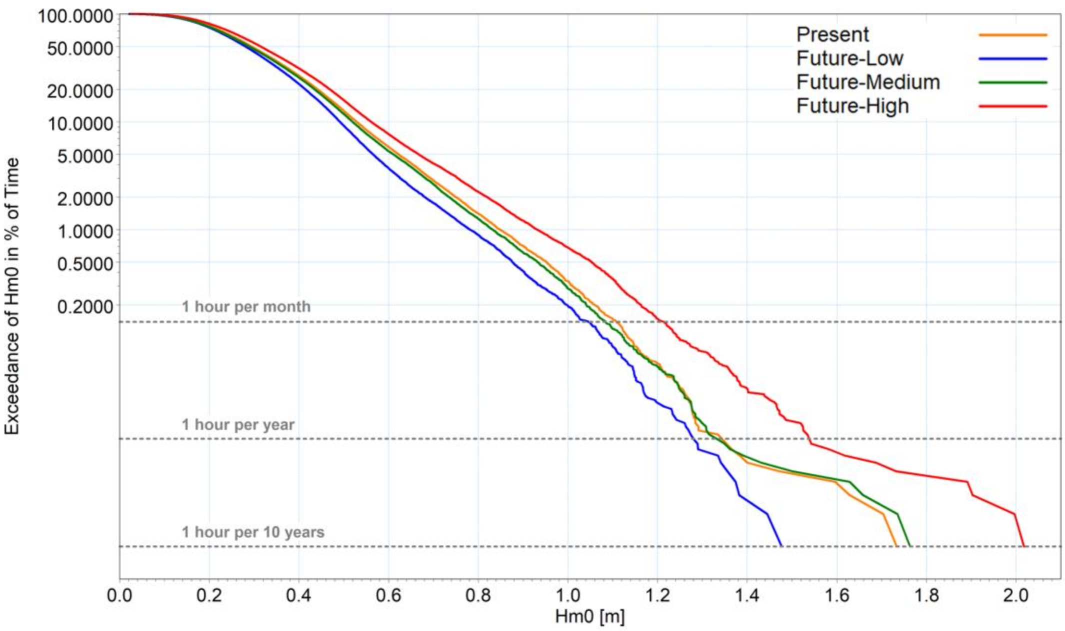


Figure 3.25 Percentage of exceedance for all-year significant wave height at Westports based on 10 years dataset for the present (Baseline) and future (Low-Medium–High) climate scenario.

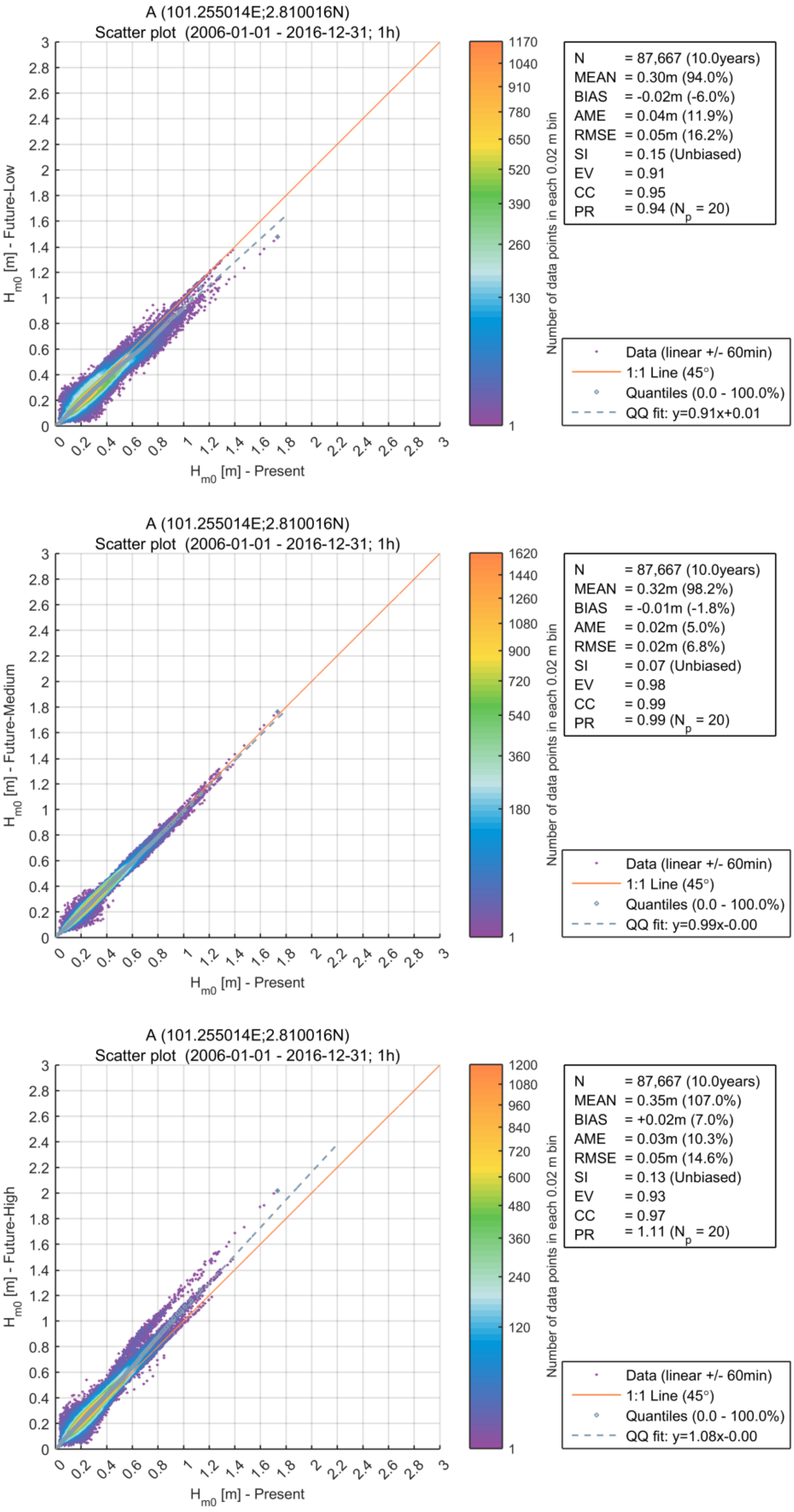


Figure 3.26 Scatter comparison of SW_{SOM} Significant wave height between Future climate scenarios (Low - top, Medium - middle and High - bottom) and Present condition offshore of the approach channel to Westports.

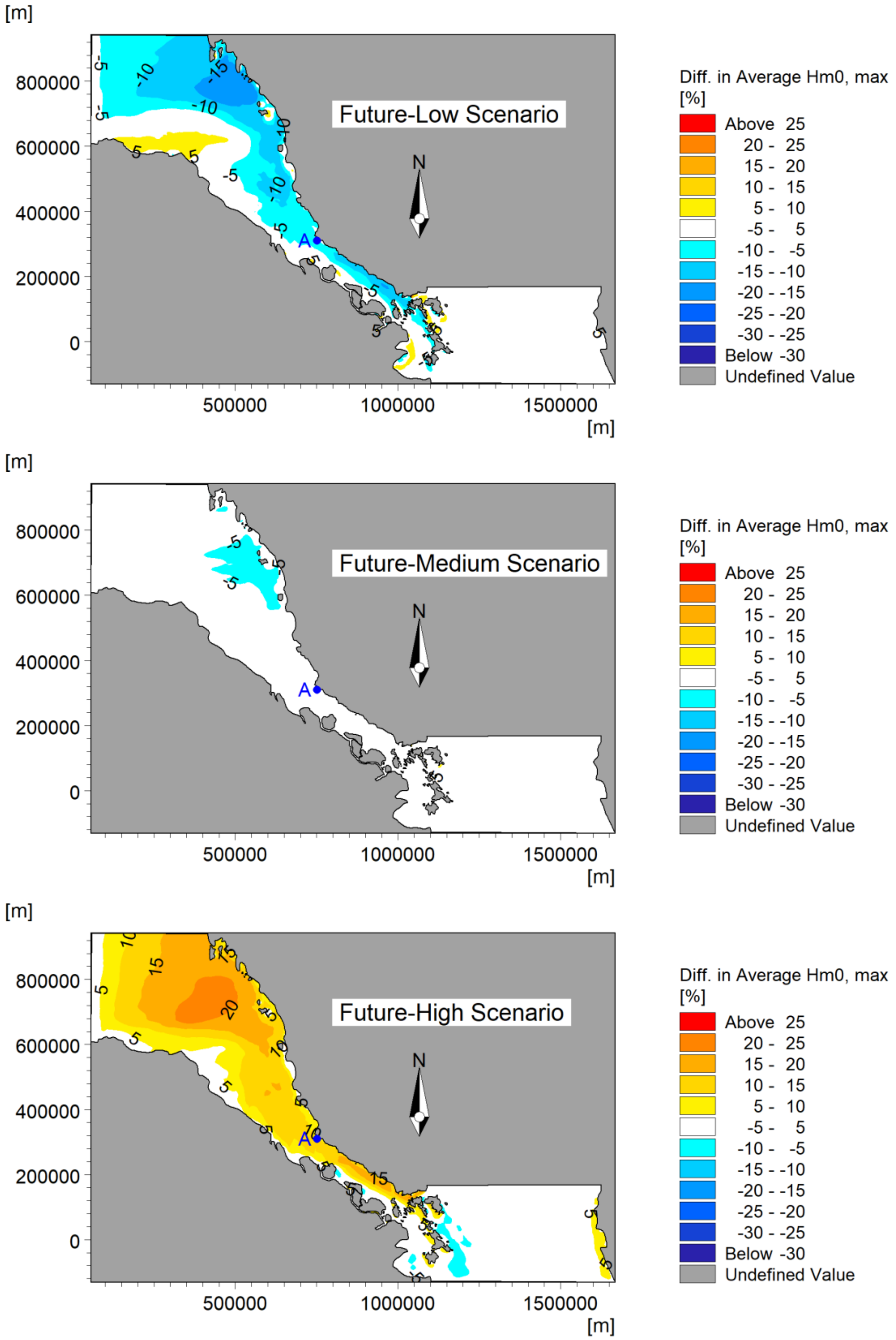


Figure 3.27 Percentage difference of average $H_{mo\ max}$ between future (Low-Medium–High) and present climate normalized by present climate.

Changes in future storm climate are further inferred through the comparison of the average monthly statistics of modelled data for the “present” and “future” climate scenarios. Mean and maximum differences are expressed as the following:

$$Difference\ (i) = Future(i) - Present$$

$$Mean\ Difference = \sum_{i=1}^{3}(Difference(i)\ /3$$

$$Max\ Difference = \max(\ Difference\ (i)) - \min\ (\ Difference(i))$$

The averaged of monthly peak significant wave height ($H_{m0\ max}$) at Westports for the three future climate scenarios are compared in Figure 3.28. The similar result for the present scenario is also shown in the same plot. Based on this, the percentage of differences between present and future scenario were also calculated and provided in Figure 3.29. Table 3.4 present the variation in peak storm wave height together with the mean and maximum differences of future changes.

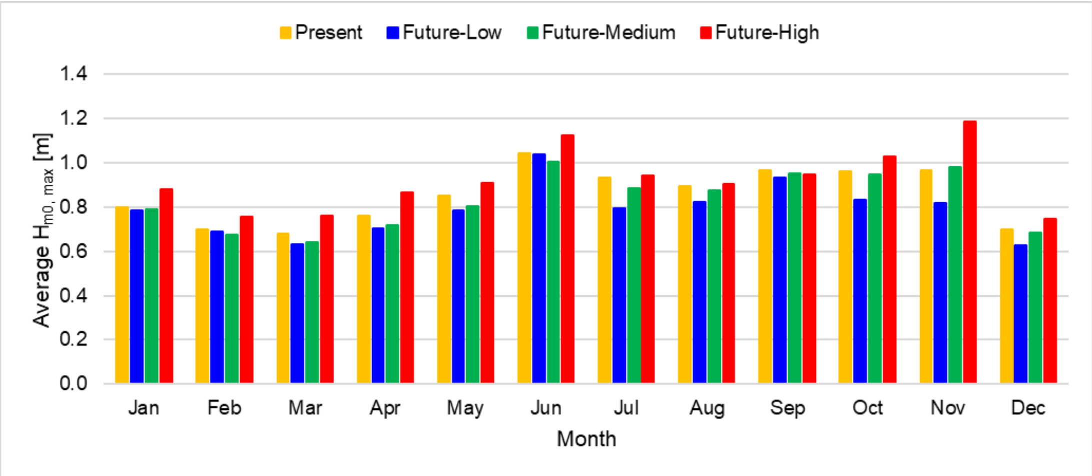


Figure 3.28 Comparison of the present (Baseline) and future (Low-Medium–High) averaged monthly storm significant wave height $H_{mo\ max}$ at Westports.

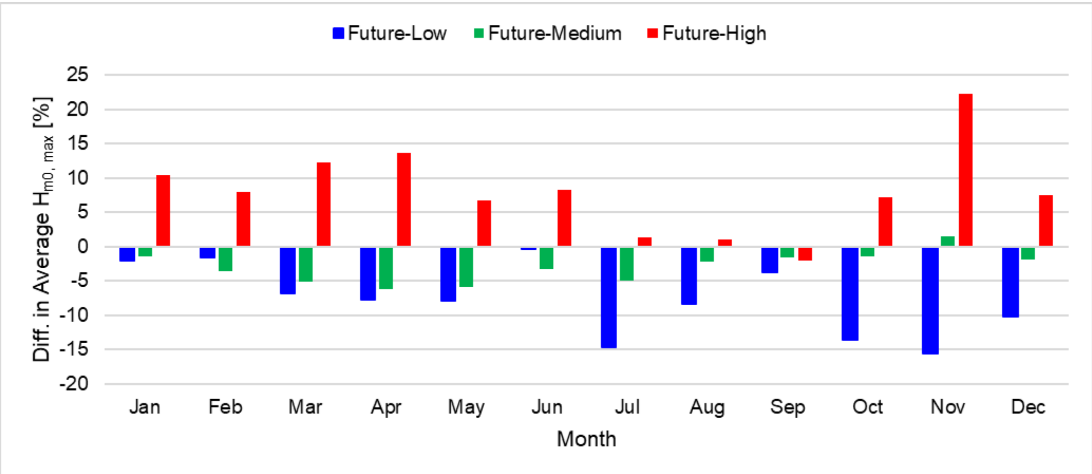


Figure 3.29 Percentage of difference in averaged monthly storm significant wave height $H_{mo\ max}$ obtained between the present (Baseline) and future (Low-Medium–High) at Westports.

Table 3.4 Westports - Comparison of present (Baseline) and future (Low-Medium–High) $H_{m0\ max}$.

Month	Present	Future-Low		Future-Medium		Future-High		Mean Difference [m]	Max Difference [m]
	Avg [m]	ΔAvg [m]	ΔAvg [%]	ΔAvg [m]	ΔAvg [%]	ΔAvg [m]	ΔAvg [%]		
Jan	0.80	-0.02	-2.0	-0.01	-1.4	0.08	10.4	0.02	0.10
Feb	0.70	-0.01	-1.6	-0.03	-3.6	0.06	8.0	0.01	0.09
Mar	0.68	-0.05	-6.8	-0.04	-5.2	0.08	12.2	0.00	0.13
Apr	0.76	-0.06	-7.7	-0.05	-6.2	0.10	13.6	0.00	0.16
May	0.85	-0.07	-7.9	-0.05	-5.9	0.06	6.8	-0.02	0.13
Jun	1.04	0.00	-0.4	-0.03	-3.3	0.09	8.3	0.02	0.12
Jul	0.93	-0.14	-14.7	-0.05	-4.9	0.01	1.3	-0.06	0.15
Aug	0.90	-0.07	-8.2	-0.02	-2.1	0.01	1.1	-0.03	0.08
Sep	0.97	-0.04	-3.7	-0.02	-1.5	-0.02	-2.1	-0.03	0.02
Oct	0.96	-0.13	-13.6	-0.01	-1.4	0.07	7.2	-0.02	0.20
Nov	0.97	-0.15	-15.5	0.01	1.4	0.22	22.3	0.03	0.37
Dec	0.70	-0.07	-10.2	-0.01	-1.9	0.05	7.5	-0.01	0.12

3.3.4.1 Changes in peak wave period, T_p and mean wave direction, MWD

Figure 3.30 shows the normalized difference in frequency of peak wave period occurrence obtained between the present and future climate scenarios offshore of the approach channel to Westports. The results show an indication of a potential change in peak wave period range due to climate change.

Similar to the changes observed in wave height, variability in trend is seen between different future scenarios. The future Low and Medium scenario mostly shows decreased in occurrence of longer period wave (i.e T_p > 4 sec) by 2.3% and 1%; while the occurrence of shorter period wave (i.e T_p < 4 sec) shows an increase of 2.3% and 1%, respectively. The future High scenario on the other hand shows an opposite trend with accumulated 2.7% increase in longer period wave (i.e T_p > 4 sec) incident followed by a reduction in occurrence of the shorter period wave (i.e T_p < 4 sec).

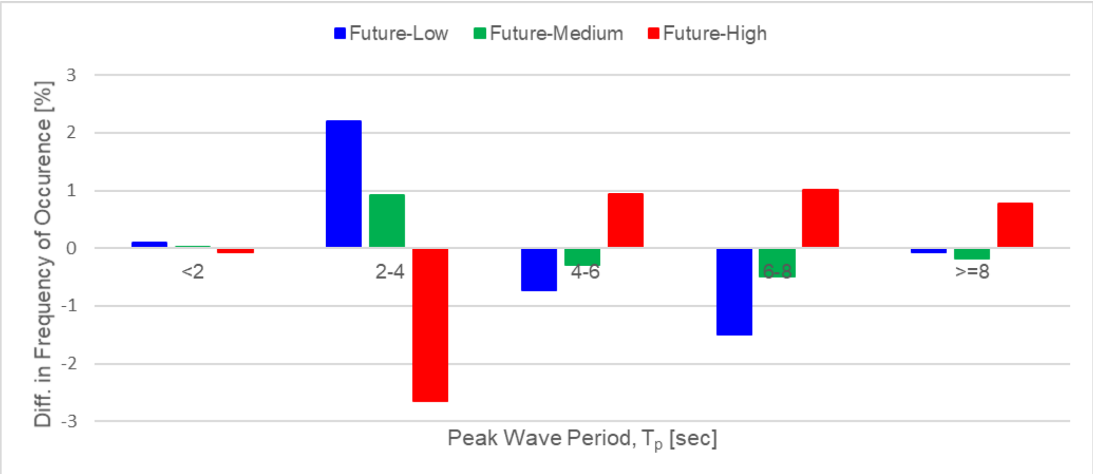
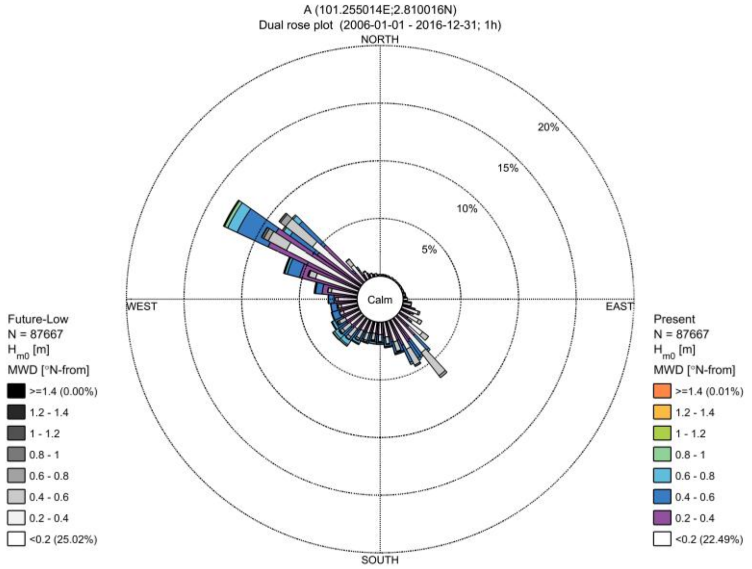


Figure 3.30 Percentage of difference in frequency of T_p occurrence obtained between the present (Baseline) and future (Low-Medium–High) offshore of the approach channel to Westports

The directional waves rose plot comparison in Figure 3.31 and Figure 3.33 confirmed that the future high scenario projected an increase of the waves that are strongly dominated by swells from the NW sector accompanied by a generalized decrease in SE sector. The future Low and Medium scenario both contrarily shows increased influenced by the locally generated wind wave from the SE sector.



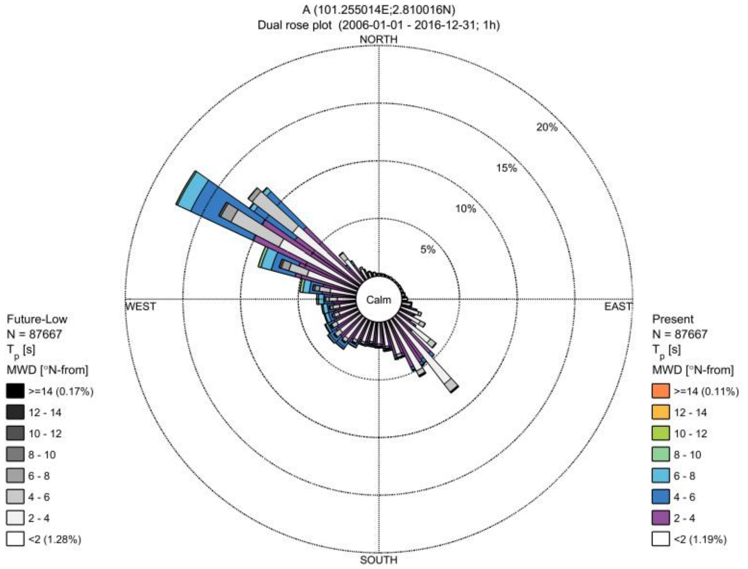
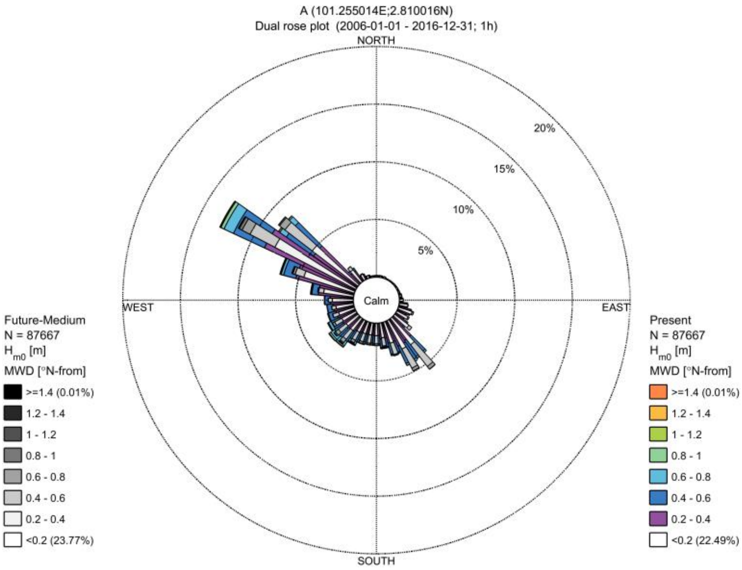


Figure 3.31 Directional Changes observed in H_{m0} (top) and T_p (bottom) between Future Low scenario and Present condition offshore of the approach channel to Westports



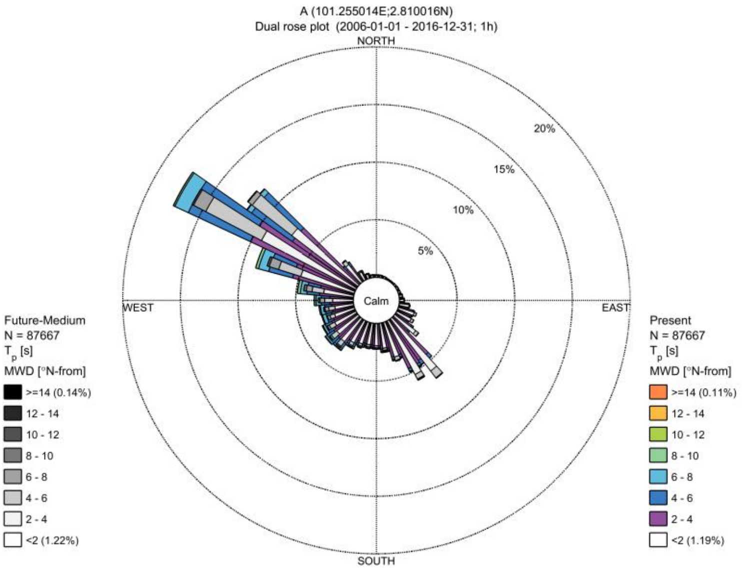


Figure 3.32 Directional Changes observed in H_{m0} (top) and T_p (bottom) between Future Medium scenario and Present condition offshore of the approach channel to Westports

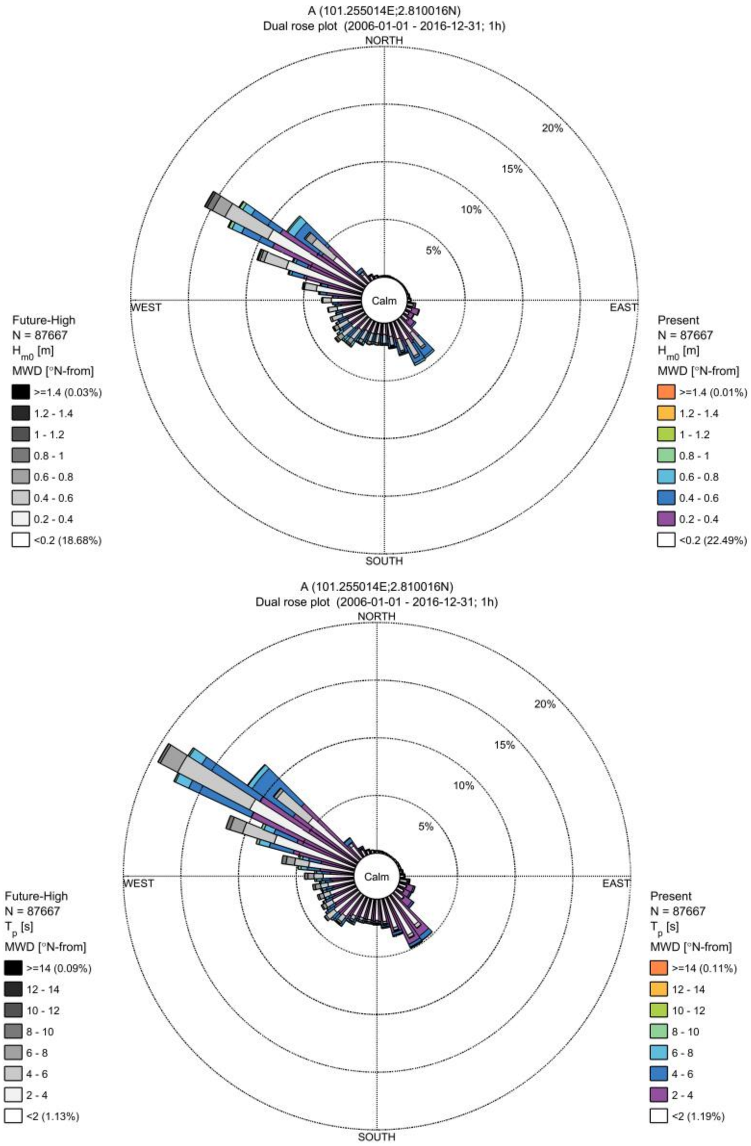


Figure 3.33 Directional Changes observed in H_{m0} (top) and T_p (bottom) between Future High scenario and Present condition offshore of the approach channel to Westports

3.3.5 Summary of Predicted Wave Changes

A summary of the predicted wave changes for the three future scenarios is presented below.

- **For the low scenario** a decrease in the wave height throughout the year. July, October and November show larger changes with average $H_{m0\ max}$ approximately 15% decrease.
- **The medium scenario** shows no apparent overall difference in peak storm wave heights with changes below 5%.
- **High scenario** provides the most consistent change from the present with clear seasonal signature in peak storm wave heigh. It is observed that higher average peak storm wave heights increase in the order of 10-20% during NE monsoon season while the SW monsoon season show changes in wave heigh less than 3%.
- Overall, no clear and consistent trend is observed in the change of peak wave height within the three future scenarios, with some months showing both decrease and increase peak wave heights. The largest uncertainty in the projected wave height is found particularly in the month of November. The projections of wave climate showed inconsistent future changes in wave climate among the future climate models, the wave height changes in Westports are observed to be minor.

- In terms of extreme conditions induced by high intensity squalls, the wind predictions show significant uncertainty and therefore it is not possible to derive conclusive quantification of changes in extreme wave conditions.

3.4 Water Levels

The definition of future water levels is important to support the climate adaptation plans. Combining the various water level components to a design total water level corresponding to a given return period or design life is not straightforward statistically as some of the components are independent while others are semi-dependent. To evaluate the water level conditions, the nearest available long-term water level records in the proximity are utilised, which are at Pelabuhan Klang tidal gauge station /22/. The water level records are subjected to a harmonic tidal analysis used to separate the tidal and non-tidal (residual) components. The “de-tiding” is conducted based on harmonic analysis. The tidal stages at the site will be derived from tidal constituents derived from the harmonic analysis of the measurement.

In short, the extreme water levels consist of various components which broadly can be separated into harmonic (tidal) and stochastic (related to climatic events) components as well as sea level rise due to climate change.

3.4.1 Present Tidal and Extreme Water levels

Tidal level in Port Klang are published by the RMN and the characteristic tidal values are presented in Table 3.5. These values represent typical tidal conditions.

Table 3.5 Tidal level characteristics at Pelabuhan Klang in m CD.

Tidal Level	Published RMN 2020 [m CD]
Highest Astronomical Tide (HAT)	5.82
Mean High Water Spring (MHWS)	5.09
Mean High Water Neap (MHWN)	3.72
Mean Sea Level (MSL)	3.03
Mean Low Water Neap (MLWN)	2.35
Mean Low Water Spring (MLWS)	0.99
Lowest Astronomical Tide (LAT)	0.00

To derive extreme water levels, the measurements at Pelabuhan Klang (1984 to 2015) were applied as they cover a sufficiently long period and therefore can be used to estimate the extreme water levels. The long term total measured water levels were analysed using Extreme Value Analysis (EVA) to provide design criteria for variation return period without separating the tide and surge component, which can be deemed more realistic (i.e. the measurement itself is taking into account the joint probability or combination effect of high/low tidal and positive/negative residual during its 32-year measurement). Testing against different candidate distributions has shown that truncated Weibull and 2-p Weibull distributions using a threshold corresponding to an average of 3 annual peaks and 2 annual peaks with least square parameter estimates provides a good fit to the extreme high and low water level, respectively. The results of the extreme value analysis for total high and low water level are shown in Figure 3.34.

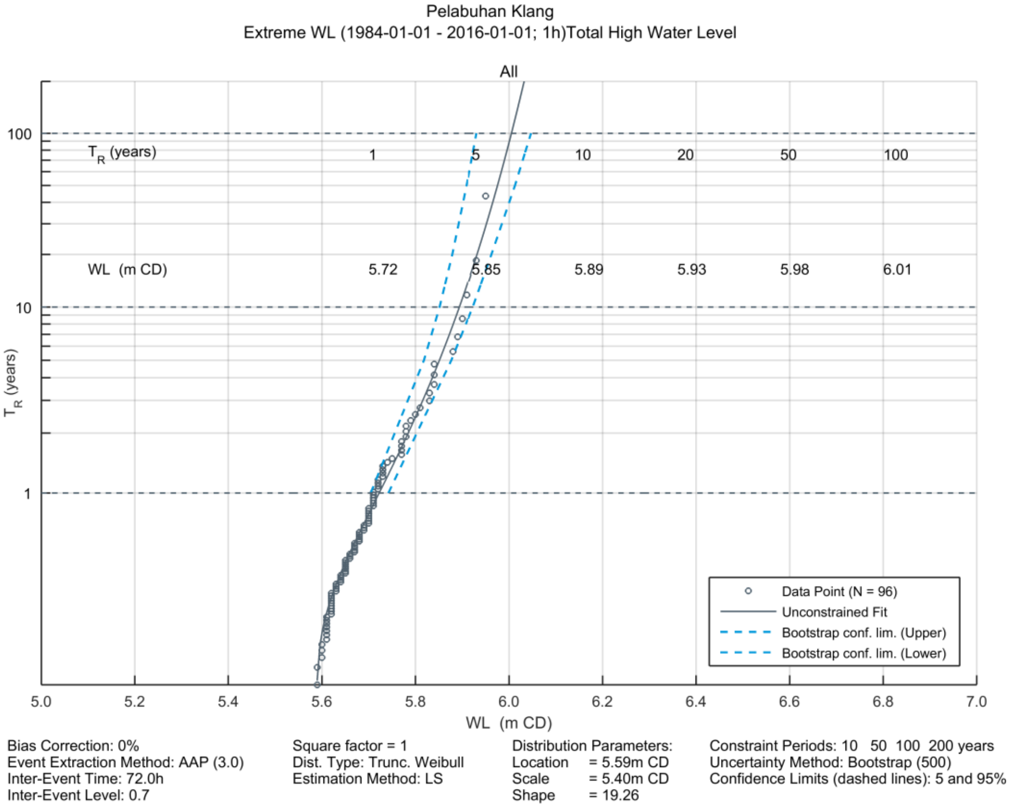


Figure 3.34 Historical extreme values for total high water level at Pelabuhan Klang. The full line represent the central estimate and dashed lines correspond to 5% and 95% confidence limits respectively.

3.4.2 Sea Level Rise

For design of coastal structure with service life more than few years or decades, it is important to take into account the climatological and secular variation of sea level rise from global warming. A study of Malaysia Sea Level Rise (/23/) has been carried out by CSIRO with collaboration with NAHRIM and government agency in year 2017. It is an updated study from 2010 NAHRIM Malaysia Sea Level Rise study (/24/) that aims to provide the latest, reliable and acceptable projection of sea level rise in Malaysia which uses Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models.

Based on the study, projection of central estimates and 83% confidence limit of sea level rise (SLR) to Year 2080 for Pelabuhan Klang are set out in Figure 3.35 and Table 3.6.

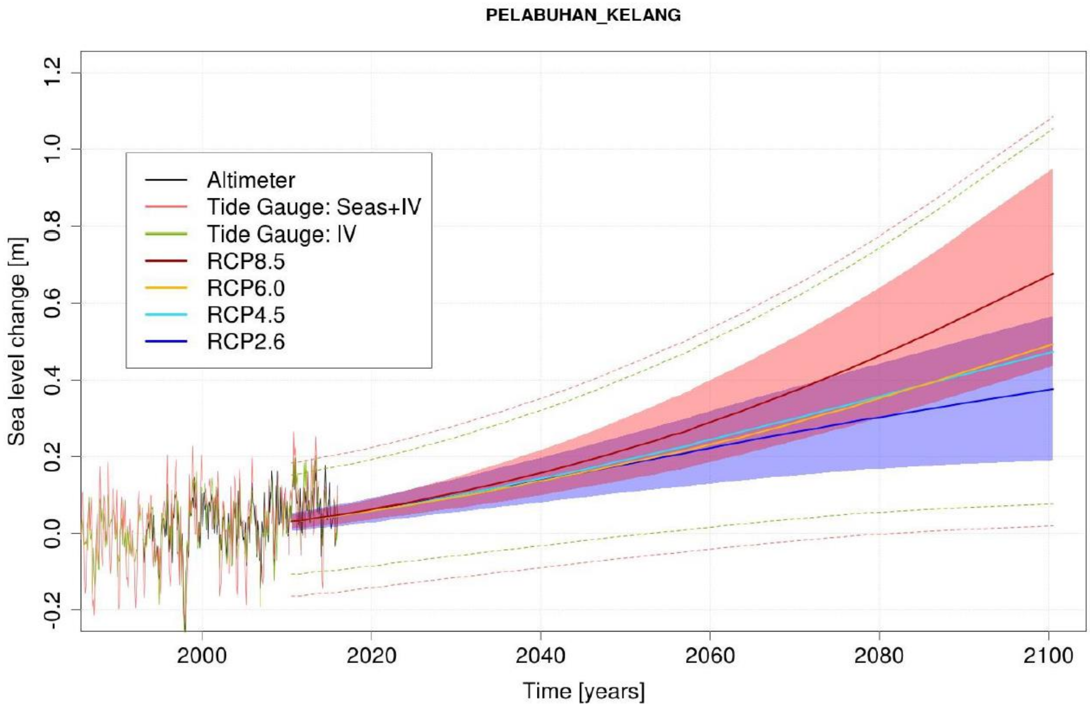


Figure 3.35 Projected sea level rise to 2100 for RCPs 2.6, 4.5, 6.0 and 8.5. Shading indicates the 17-83 % uncertainty range for RCPs 2.6 and 8.5 for Pelabuhan Klang.

Table 3.6 Value of projected sea level rise of RCP 8.5 at Pelabuhan Klang from year 2020 to 2100 relative to a historical baseline of 1986-2005.

Year	**RCP 8.5 Sea Level Rise [m]**	
	Central Estimate	**83% Confidence Limit**
2020	0.07	0.09
2030	0.11	0.15
2040	0.16	0.22
2050	0.22	0.31
2060	0.29	0.41
2070	0.38	0.52
2080	0.47	0.65
2100	0.68	0.95

Based on the analysis of tidal levels and SLR prediction it is expected that higher tidal levels will occur more frequently. For example the 1hr per year event is now 5.6 MSL whereas the for the central estimate 6.1 and for the 83% percentile 6.3m.

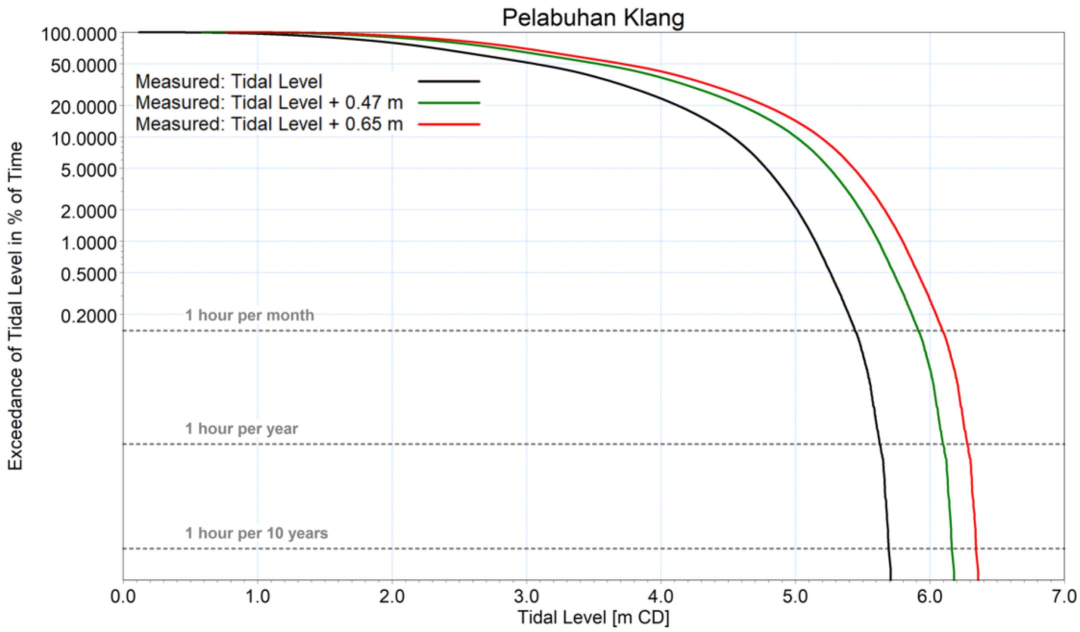


Figure 3.36 Exceedance tidal levels for the period 2061-2080 including SLR values central estimate and 83% percentile mCD.

The extreme total water level analysis, the present total high-water level for a 100-year return period at the site is 6.01 m CD. To support the climate adaptation assessment future sea level rise is added to the extreme water level, the estimated 100-year return period water levels for the period 2061-2080 is presented in Table 3.7.

Table 3.7 Estimated 100-year return period water levels for various years. These values are referred to historical data.

Parameter	Historical	2061 -2080
Total High-Water level for a 100-year Return Period [m CD]	6.01	6.01
Sea Level Rise Central / 83% confidence [m]		0.47 / 0.65
Extreme Water Level Central / 83% confidence [m CD]	6.01	6.48 / 6.66

3.4.3 Summary Sea Leve Rise

The analysis of the sea level rise show water level increase of 0.47 m to 0.65m representing central and 83% confidence levels. The predicted extreme water levels for 100-year return period are 6.48 and 6.66 mCD for central and 83% confidence values. The predicted increase in sea level rise are considered to be significant.

3.5 Currents

Currents in Westports as well areas within the Strait of Malacca are strongly influenced by the tidal effects. To establish a basic understanding on the prevailing current conditions at the project site, current and water level in the areas have been simulated based on the application of the MIKE21 FM hydrodynamic (HD) model for one (1) year period. The 1-year HD model was also established for the different “future” climate conditions to assess the potential changes on currents in response to climate change and future sea level rise at Westports.

Details of the HD model description and data used are briefly described in Section 3.5.1 with the model limitation discussed in Section 3.5.2. The model results were subsequently analysed with the future changes observed in currents are discussed in Section 3.5.4.

3.5.1 Modelling Approach and Data Sources

A depth-averaged 2-dimensional (2D) hydrodynamic model complex has been established using DHI's MIKE 21 HDFM. The bathymetry has been constructed based on C-MAP electronic database for the regional area, supplemented with local survey data from DHI's in-house database.

A rather large model coverage is required to capture the current flow within the narrow Straits of Malacca. The HD model domain extends are shown in Figure 3.37. The model is based on an unstructured mesh with resolutions ranging from 300 m in the vicinity of the project area to 3 km throughout the straits. The resolutions of the mesh have been tailored to be able to resolve the tidal propagation and physical processes at the project site. At the open sea boundaries, the "Present" HD scenario is forced by the WRF's winds described in Section 3.2.1 and tidal variation retrieved from the KMS global tide model. The performance of the "Present/historical" HD model was assessed by comparing to water level measurements sourced by JUPEM. Comparisons between the modelled and measured water levels at Pelabuhan Klang stations were performed for a one (1) month period and the time series are presented in Figure 3.38. In general, a reasonably good agreement between the modelling results and the water level measurement has been obtained. The comparison indicates that the HD model able to capture the water levels pattern and is found reliable for the present hydraulic studies.

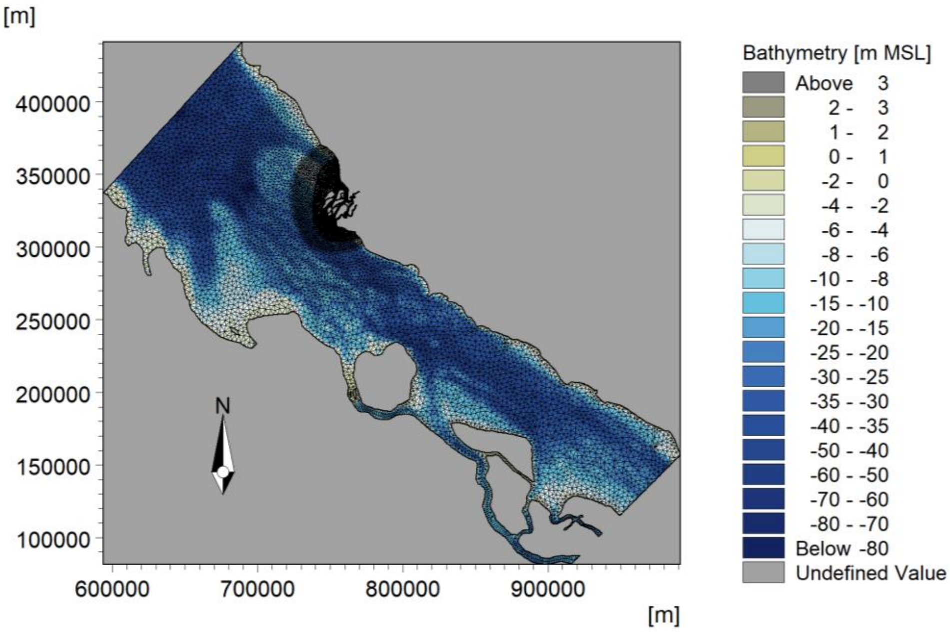


Figure 3.37 HD model coverage and bathymetry with vertical datum corresponding to MSL.

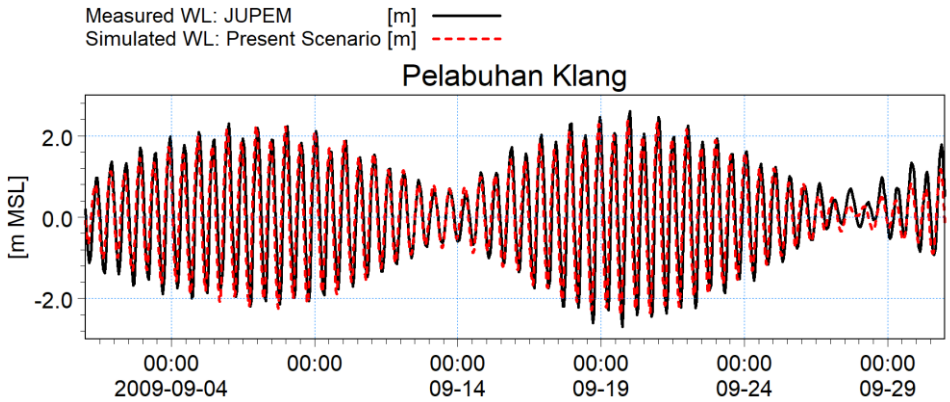


Figure 3.38 Time series comparison between measured and modelled water levels at Pelabuhan Klang

For the future “Low”, “Medium” and “High” 1-year HD models, allowance of the 60 years (by 2080) projection of sea level rise is introduced by adding the following constant value (obtained from Section 3.4.2) to water levels at the open boundary of the shelf model:

- **“Future Low Scenario”**: SLR of 0.21m, obtained from lower bound based on RCP 6.0
- **“Future Medium Scenario”**: SLR of 0.43m, the mean value obtained between the future low and high scenarios
- **“Future High Scenario”**: SLR of 0.65m, obtained from the highest emission scenarios based on RCP 8.5

In this study, the future climate model assumed that tidal forcing is not significantly changed in response to the considered 2080 sea level rise (i.e. SLR changes of range between 0.21m and 0.65m). This was supported by tidal amplitude changes developed by Pickering et al. /26/ where the semidiurnal M2 and S2 constituents in the Straits of Malacca changes are only in the order of 4 and 6 cm, respectively, whereas changes in the diurnal tidal response (K1 and O1) are found to be limited for a significant sea level rise of 2 m scenario. Compared to the “future” scenario adapted in Westports study, changes to the tidal forcing are therefore expected to be marginal and therefore the tidal constituent for generation of boundary information has not been bias-adjusted.

In addition to the sea level rise effect, the wind and air pressure forcing over the model domain has also been prescribed by the three (3) future wind and pressure fields that are briefly described in Section 3.2.2.

3.5.2 Model Limitations & Uncertainties

The choice of model, model setup and data availability affect the ability of the model to capture the identified contributions to the total current fields.

In this study, the effects of sea level rise to potential current changes in the Westports has only been analysed using a depth-integrated model rather than a full 3D model. This adds limitations to the modelling of the ocean circulation as well as potential stratification in response to temperature, salinity and vertical density variations due to climate change.

3.5.3 General Current Patterns

Currents along the straits of Malacca are influenced predominantly by tidal flows and to a lesser degree by wind driven currents. Overviews of peak flood and ebb currents during spring tides the project site to the sea are presented in Figure 3.39 and Figure 3.40, respectively. The dominant current direction sector along the shore is generally observed moving towards the northwest direction during flood tide while currents move to the southeast during ebb tide.

Crafted by the complex marine topography of the Klang area, strong flow is as well observed along the Selat Klang channel due to the relatively larger water depth of the navigation channel and particularly milder current flows along the nearshore area.

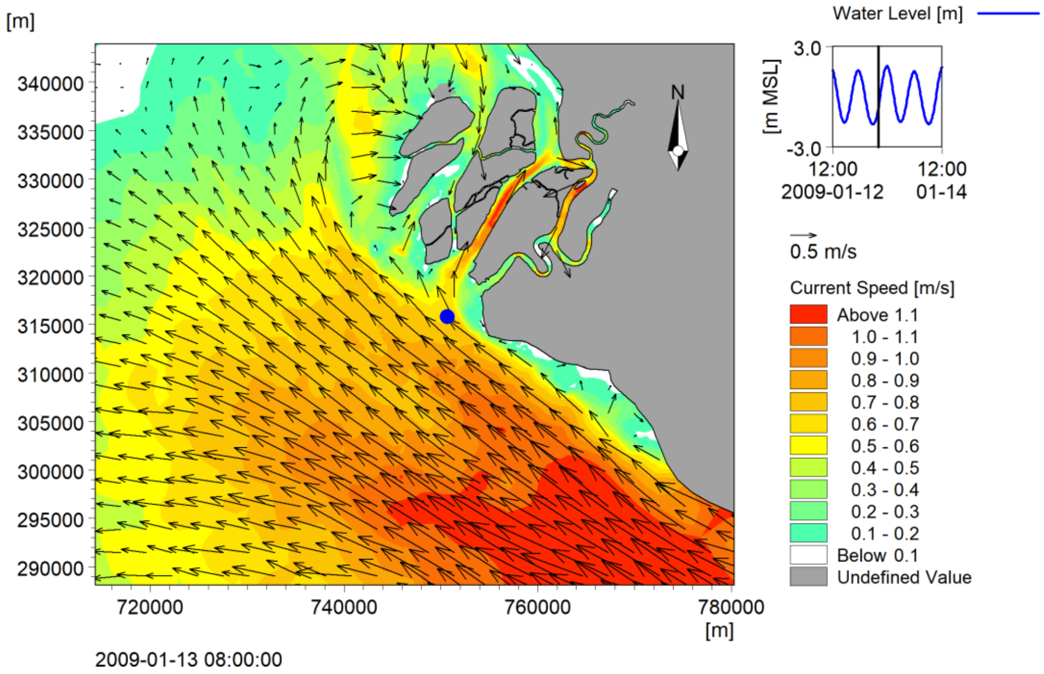


Figure 3.39 Instantaneous current condition during a spring flood tide at Westports and around Klang Delta. The blue dot denotes the location of current data extraction.

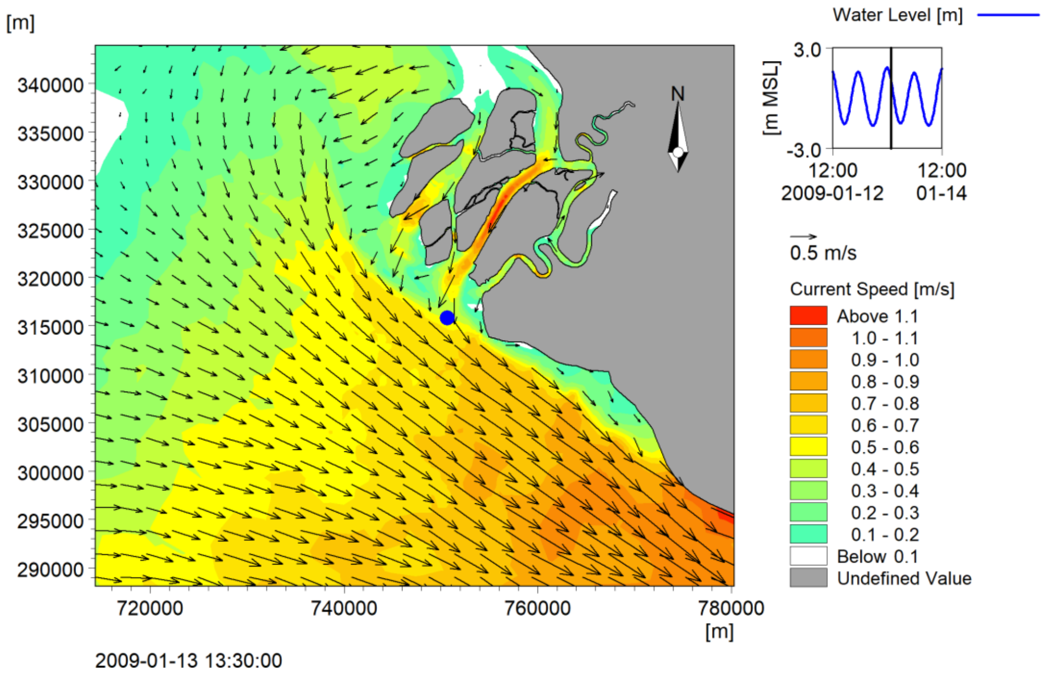


Figure 3.40 Instantaneous current condition during a spring ebb tide at Westports and around Klang Delta. The blue dot denotes the location of current data extraction.

Figure 3.41 further illustrates predicted current speeds (black) and separated into harmonic constituents (blue) and residuals (red). The separation into the harmonic and residual components has been carried out through a harmonic analysis. The dominant currents correspond to the dominant tidal forces that governs the current flow at the site. Both flood and ebb tides during spring tide generate strong flows in front of the project site with peak current reaching up to 1.0 m/s.

There is no significant difference between the modelled NE and SW climatic conditions in terms of the overall current patterns. The predicted residuals in front of the project site are quite uniform and in the order of up to 0.3 m/s.

The current directions and speeds at the extraction points have further been illustrated through current roses in Figure 3.42.

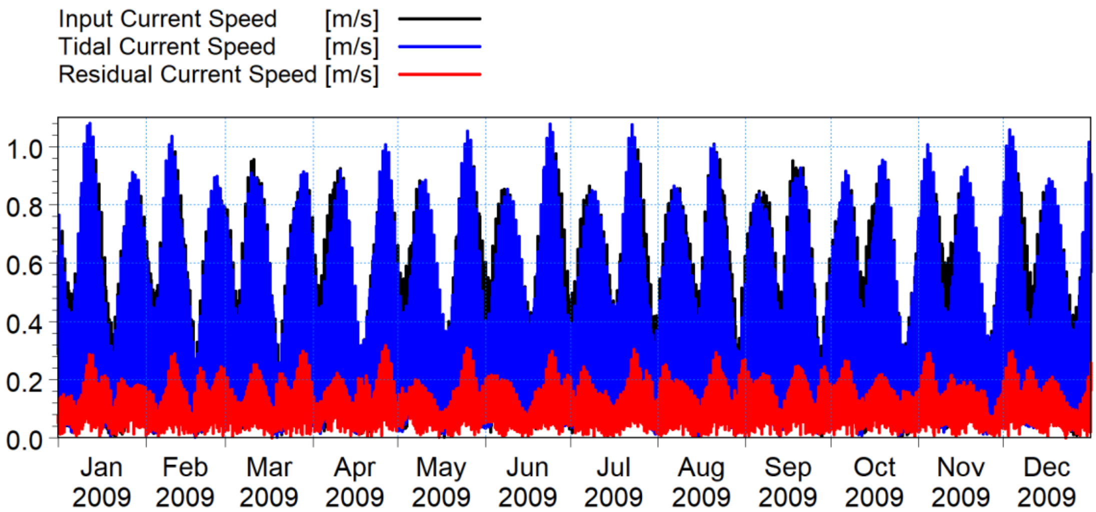


Figure 3.41 Predicted total (black), harmonic (blue) and residual (red) current components at seaward of Westports.

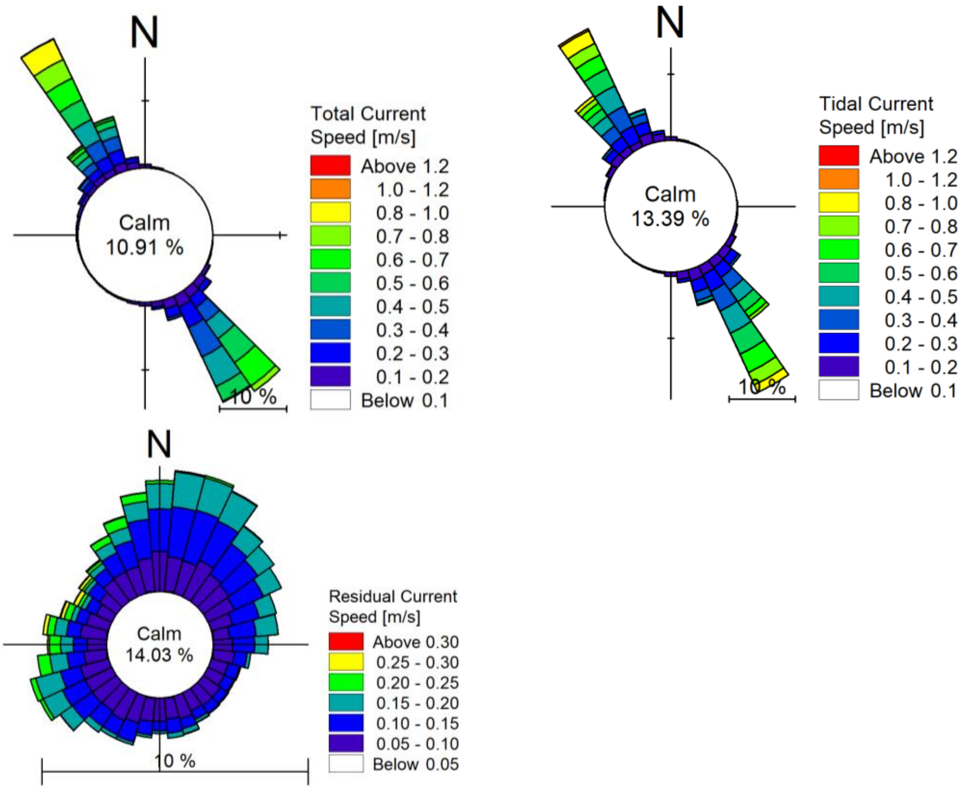


Figure 3.42 All-year total (top-left), tidal (top-right) and residual (bottom) current speed roses at Westports for the “Present” scenario.

3.5.4 Future Changes in Currents

The future current climate at Westports modelled under Low-Medium-High scenarios were analysed and compared against the present wave climate condition. Figure 3.43 and Figure and illustrates the statistical mean and maximum current speeds for the baseline conditions. The plots are complemented with differences in mean and maximum current speed between the future and present for each of the scenario were as well included.

Currents on a regional scale are not affected by the climate change while impacts in speeds due to all three future scenarios at the nearshore are found limited. The changes of ±0.025 m/s in mean current speeds up to ±0.1 m/s to the maximum current speeds can extend up to a kilometre radius from the project site are observed for all three future scenarios.

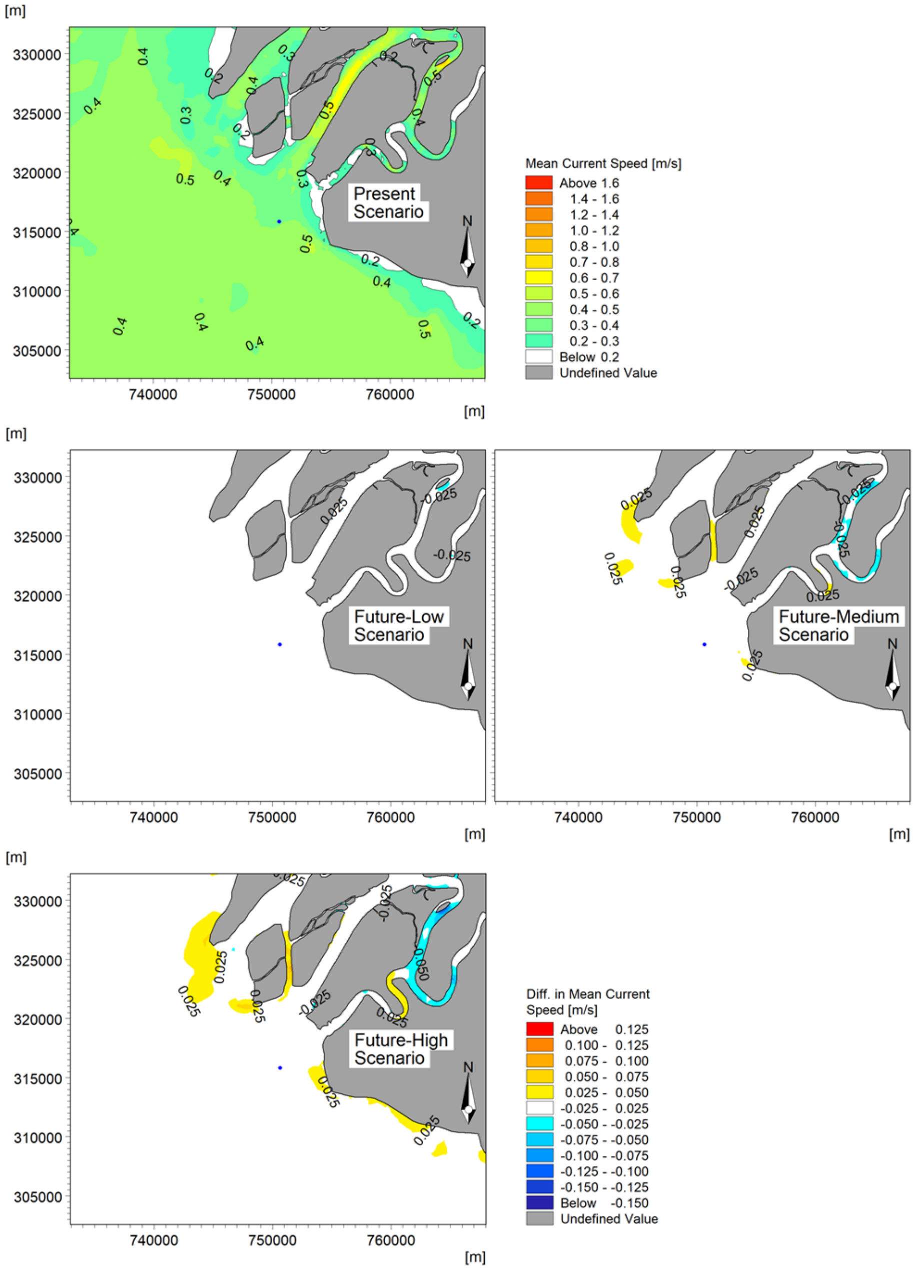


Figure 3.43 Mean current speed plot for the present condition (top) with difference (bottom) in mean current speed over 1-year modelled period for historical and future climate conditions.

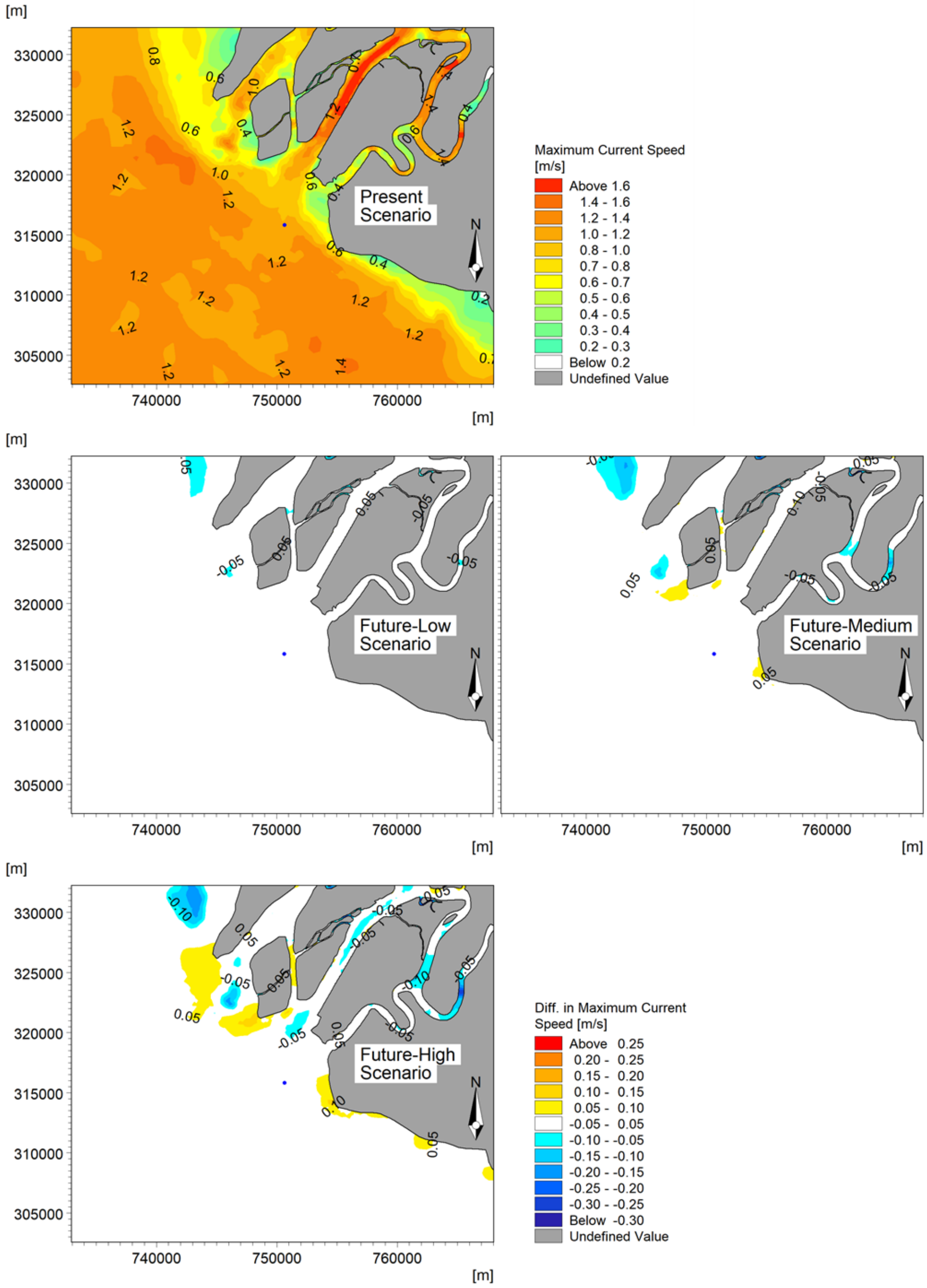


Figure 3.44 Maximum current speed plot for the present condition (top) with difference (bottom) in maximum current speed over 1-year modelled period for historical and future climate condition.

Annual percentage of exceedances for omni-directional currents as function of the time of the year for the present and future climate scenario has been provided in Figure 3.45. The scatter comparison for all scenarios (Low to High) between future climate and baseline condition significant wave heights at Westports for the 1-year dataset simulated are given in Figure 3.46. The comparison indicates the future and present currents at Westports show good statistical scores with bias value of the current speed close to zero and good quantile alignments with the Q-Q line slope being close to 1.

The directional currents rose plot comparison in Figure 3.47 shows that the all three future (low-medium-high) scenario projected an increased dominancy from both the NW and SE sector due to the dominance of tidal current flows at the project site.

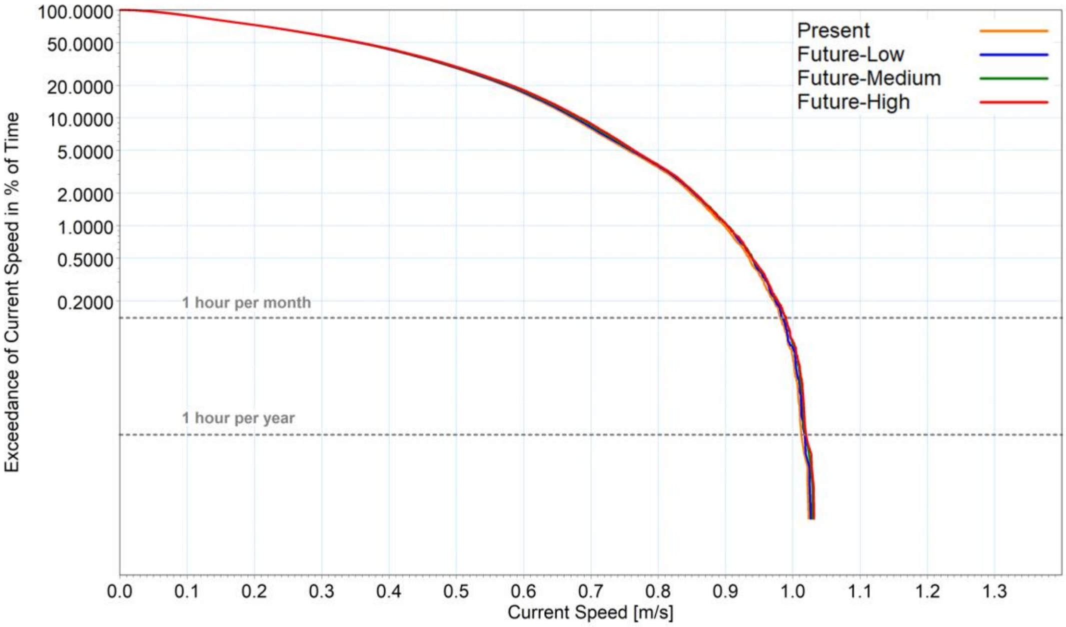


Figure 3.45 Percentage of exceedance for 1-year current speed at Westports for the present (Baseline) and future (Low-Medium–High) climate scenario

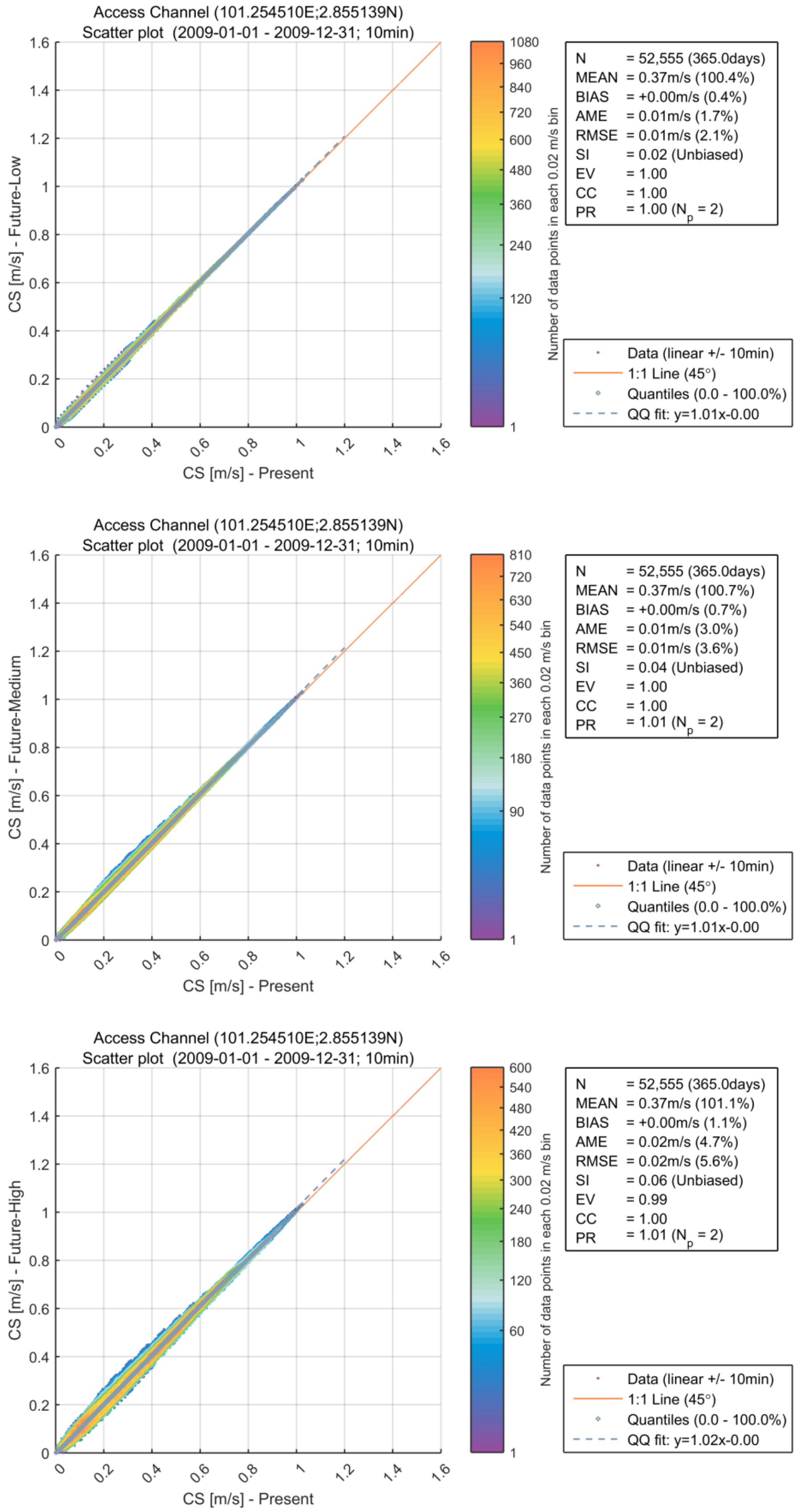


Figure 3.46 Scatter comparison of current speeds between Future climate scenarios (Low - top, Medium - middle and High - bottom) and Present condition at Westports

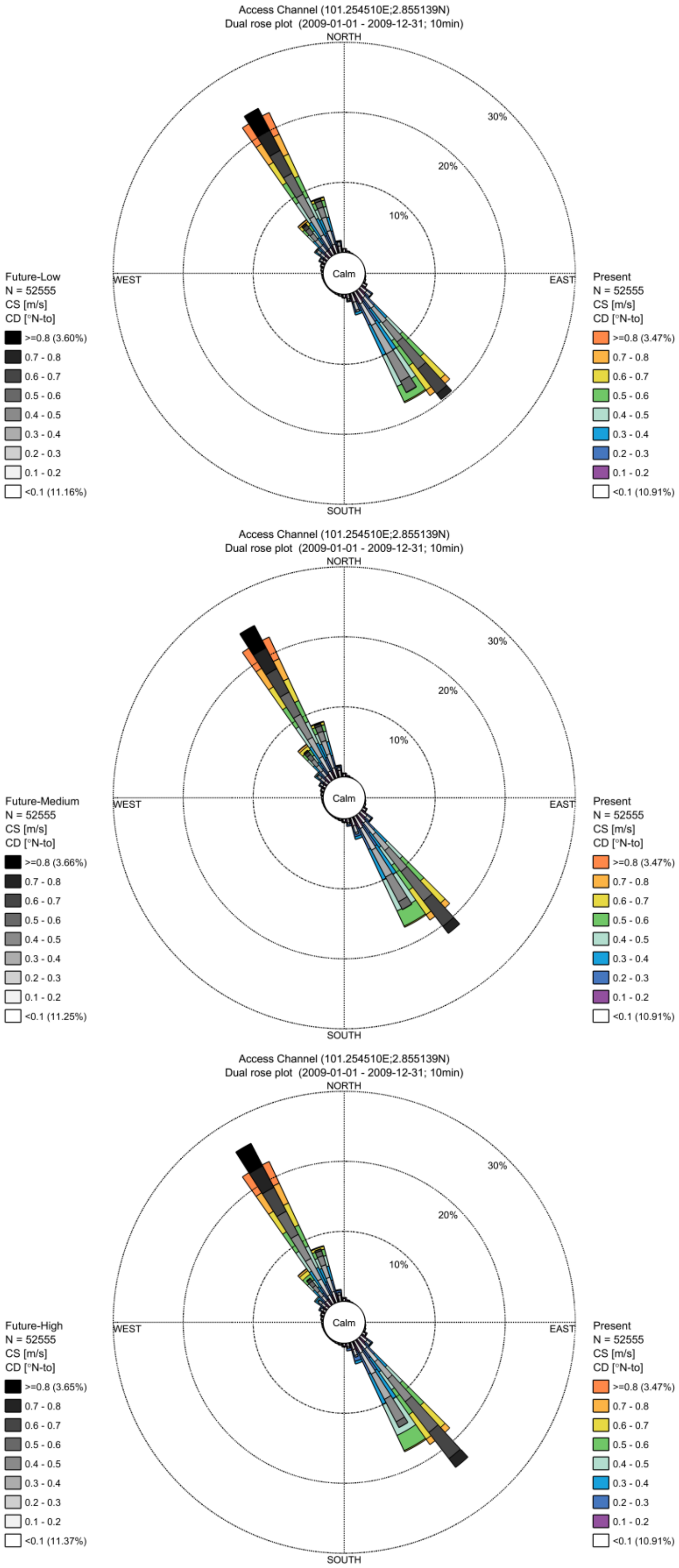


Figure 3.47 Directional Changes observed in current speed Future climate scenarios (Low - top, Medium - middle and High - bottom) and Present condition at Westports

3.5.5 Summary of Predicted Current Changes

The results indicate minimal changes with the present scenario are predicted for all three future climate scenarios and therefore the future projection of currents in Westports are found to be very minor.

3.6 Rainfall

Changes in future precipitation patterns can impact port assets and operations leading to damage to structures, change operating conditions due to hazards related to flooding and visibility.

To investigate future changes in rainfall characteristics, the projection of future rainfall characteristic changes can be obtained from the similar set of CORDEX-SEA simulations (refer Table 3.1). Details of bias-correction of daily rainfall are described in Appendix B of this report and future changes in precipitation patterns are discussed in Section 3.6.2.

A few rainfall indices that are commonly used to characterize hydrological extremes were computed. The rainfall indices and their definitions are listed in Table 3.8. These indices are a subset of the CLIMPACT indices used to calculate indices related to daily climate extremes. The indices selected for use in this study have been identified by the Expert Team on Sector-Specific Climate Indices (ET-SCI) (Ref /18/).

Table 3.8 The rainfall indices used in current study.

Indices	Remark
PRCPTOT	Total annual precipitation on wet days. Let RR_{ij} be the daily precipitation. If *i* represents the number of days in *j* year, then: $$\mathrm{PRCPTOT}_j = \sum_{i=1}^{I} RR_{ij}$$
SDII	Simple Precipitation Intensity Index Let RR_{wj} be the daily precipitation amount on wet days, *w* (*RR* ≥1 mm) in period *j*. If *W* represents number of wet days in *j*, then: $$\mathrm{SDII}_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$$
Rx1day	Monthly maximum 1-day precipitation Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. The maximum 1-day value for period *j* is $Rx1day_j = \max(RR_{ij})$.
R95pTOT	Contribution to total precipitation from very wet days. $$\mathrm{R95pTOT} = \frac{100 \times R95p}{\mathrm{PRCPTOT}}$$ Where R95p is the total precipitation where the daily rainfall values >95th percentile of the rainfall.
CDD	Maximum length of dry spell: maximum number of consecutive days with RR <1 mm. Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. Count the largest number of consecutive days where RR_{ij} <1 mm.

3.6.1 Historical Changes in Rainfall Indices

Before examining the potential changes of rainfall characteristic over the study side, the observed historical changes were first examined. Daily rainfall data were obtained from a

Malaysia Drainage and Irrigation Department's (DID) station (ID 2913122) located at 101° 19' 20" E; 02° 56' 30"N. The rainfall record spans a period of 46 years from 1975 to 2020. The location of the daily rainfall station relative to the project site is shown in Figure 3.48.

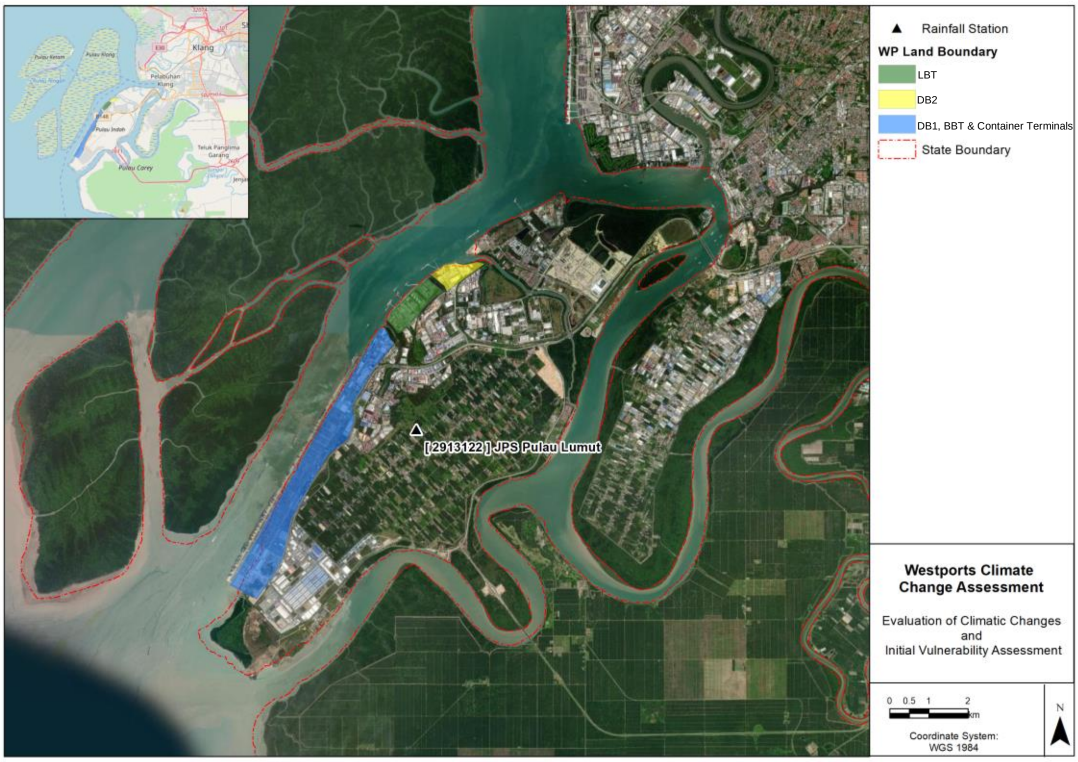


Figure 3.48 Location of rainfall station relative to Westports

The rainfall indices have been computed on an annual basis. As some of the indices (e.g., PRCPTOT, CDD) can be sensitive to missing values, only the years with at least 95% of the daily rainfall record were considered when computing indices. As we focus on the long-term trend in the yearly indices, a few missing years are not expected to alter the general findings. Figure 3.49 shows the yearly time-series of the computed indices. Note that there are some missing years due to gaps in the rainfall record.

A linear trend analysis based on the simple linear regression and the Student-t test was used to assess the significant of the trends. The result suggests that there are no significant monotonic changes in the rainfall indices at the station over the past 46 years. Monotonic changes are those that show a persistent positive or a persistent negative trend through time. The historical rainfall data showing no evidence of monotonic changes is likely due to the large rainfall variabilities (both interannual and decadal). It is noted that the station experienced a particularly wet epoch during 1990 to 2000 when the annual rainfall exceeded 4,000 mm while the average rainfall (over 46 years) was ~2,500 mm. During this wet epoch, there was an increase in the simple rainfall intensity (SDII) with reduced monthly maximum 1-day precipitation (Rx1day) and a reduced contribution to total rainfall from very wet events (R95pTOT). Therefore, the increase in total rainfall is associated with a slight increase in rainfall intensity and rainfall days but not the increment of rainfall that has occurred in the heavy rain days. During this wet epoch, the dry spells (CDD) generally reduced in length.

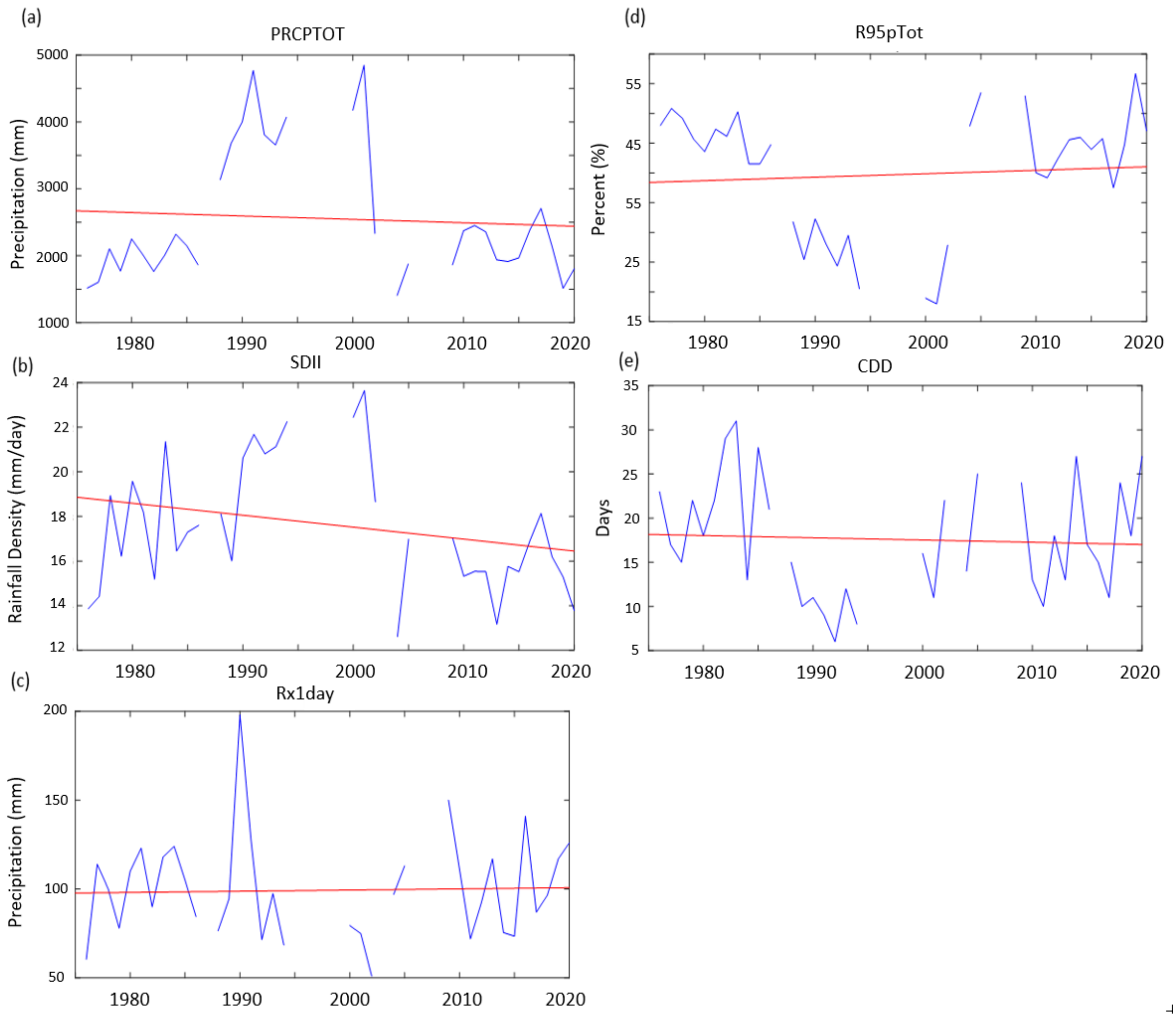


Figure 3.49 The yearly time series of the rainfall indices computed at DID station 2913122 (101°19'20"E; 02°56'30"N).

3.6.2 Future Changes of Rainfall Indices

In this current study, the future changes of the rainfall indices are examined based on the CORDEX-SEA downscaling simulations (refer Table 3.1). Nevertheless, simulated rainfalls from climate models are known to be biased (Ref /11/) and bias-corrections are usually carried out before the data is used for analysis of changes in extreme events (Ref /19/). The quantile mapping bias correction algorithm developed by Ngai et al. (Ref /20/ and Ref /21/) has been employed to bias correct rainfall data for this study. Bias correction of the rainfall data is described in further detail in Appendix B.

Using the bias-corrected time-series we examined the changes of the rainfall indices in the future. The changes were defined as the differences between the 2061-2080 and 1986-2005. Before using the projection data for assessing the future rainfall changes, the bias-corrected rainfall distribution from the historical period was compared to that of the station observed. Figure 3.50 shows the probability of the daily rainfall intensity exceeding a certain threshold of the station observed and the climate model simulations. It is noted that the bias-corrected climate models simulated rainfall distributions are generally consistent with the observation. However, the climate models generally produced slightly lower probability for low to moderate rainfall (<40mm) events but slightly higher chance for high intensity rainfall events.

Using the bias-corrected time-series from the climate models simulations, we examined the changes of the rainfall distributions in the future. Figure 3.51 shows the quantile-to-quantile comparisons between the historical rainfall and the future rainfall driven by the 10 different future scenarios (refer Table 3.1). It is noted that the projected future changes in daily rainfall events show large uncertainties, except for the heavy rainfall events. For rainfall < 70mm, four out of ten simulations projected reduction and for events 70mm to 125mm, three out of ten projections expected reduction whilst the rest are projecting increment in the chances of these rainfall categories. For extremely heavy rainfall (>125mm), all the projections are expecting increased likelihood. Therefore, moderate to heavy rainfall is likely increased, and the extremely heavy rainfall is extremely likely to increase in the projected future period. Note that the future changes of rainfall are not sensitive to the emission scenarios.

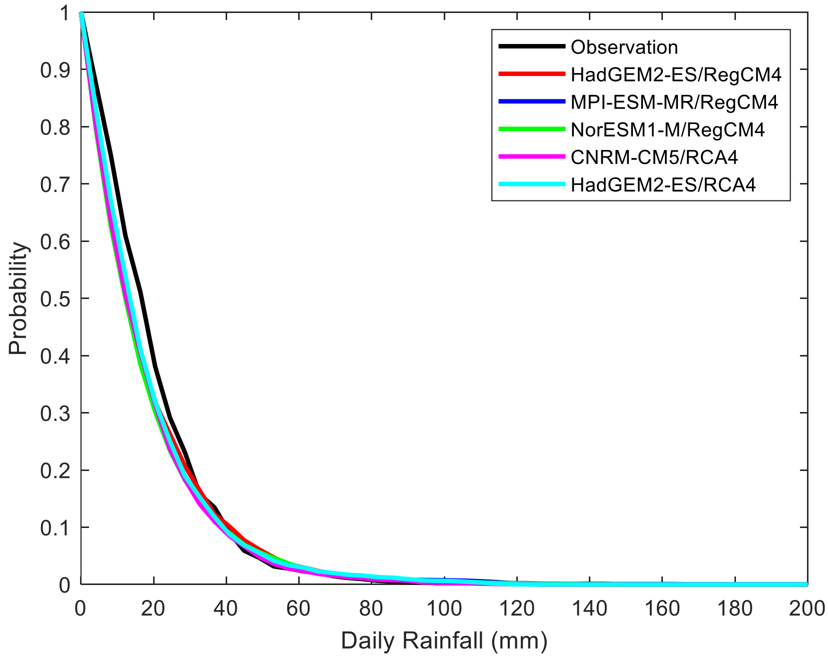


Figure 3.50 The exceedance probability of daily rainfall intensity

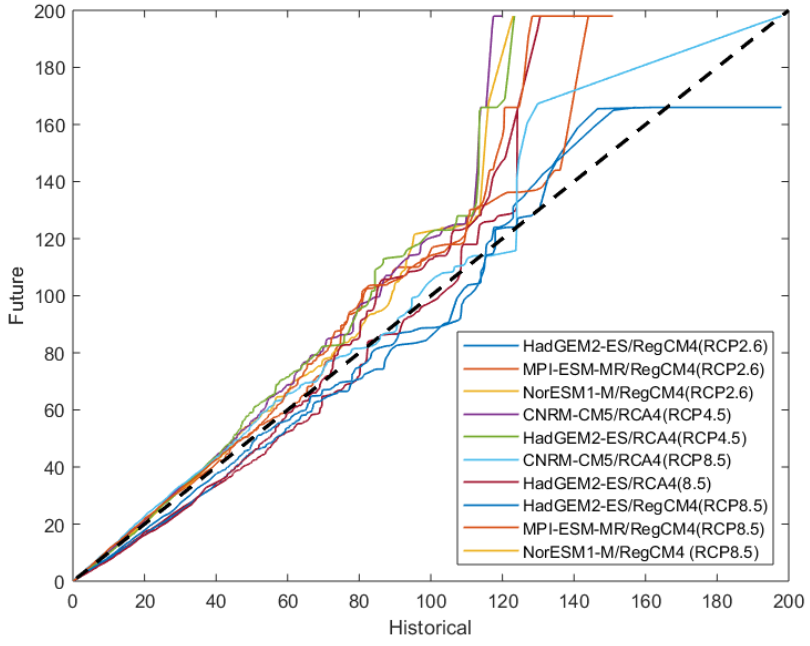


Figure 3.51 The Q-Q plot comparing future and historical daily rainfall distribution

Future changes in the extreme tails of the rainfall distribution are expected to be reflected in the changes shown in the rainfall indices. Figure 3.52 shows changes in rainfall indices (refer Table 3.8) as projected by the different future scenarios and climate models. The indices were computed for each of the years in the considered historical and future period and changes were taken from the multi-years averaged of the computed indices. First it is noted that the changes of total rainfall (PRCPTOT) are very uncertain as four out of ten projections suggested decrement whilst the rest projected an increasing trend in the total rainfall. Also, the projected reductions show larger magnitude. Similar projections are expected for the simple daily rainfall intensity. On the other hand, the extreme rainfall associated indices, i.e Rx1day and R95pToT show higher agreement amongst the different models and scenarios. Seven out of ten projections have suggested increasing of averaged Rx1day between 5-25 mm. Nine out of ten projections have suggested increasing contribution (by 1-5%) of very wet days to the total annual rainfall. The CDD, a representation of dryness, is also projected to increase in the future period. Seven out of ten projections have estimated increment of 1- 4 days to the dry spell length. Hence, from the climate projection result, it is likely that both the dry and wet extremes will increase in the considered future period.

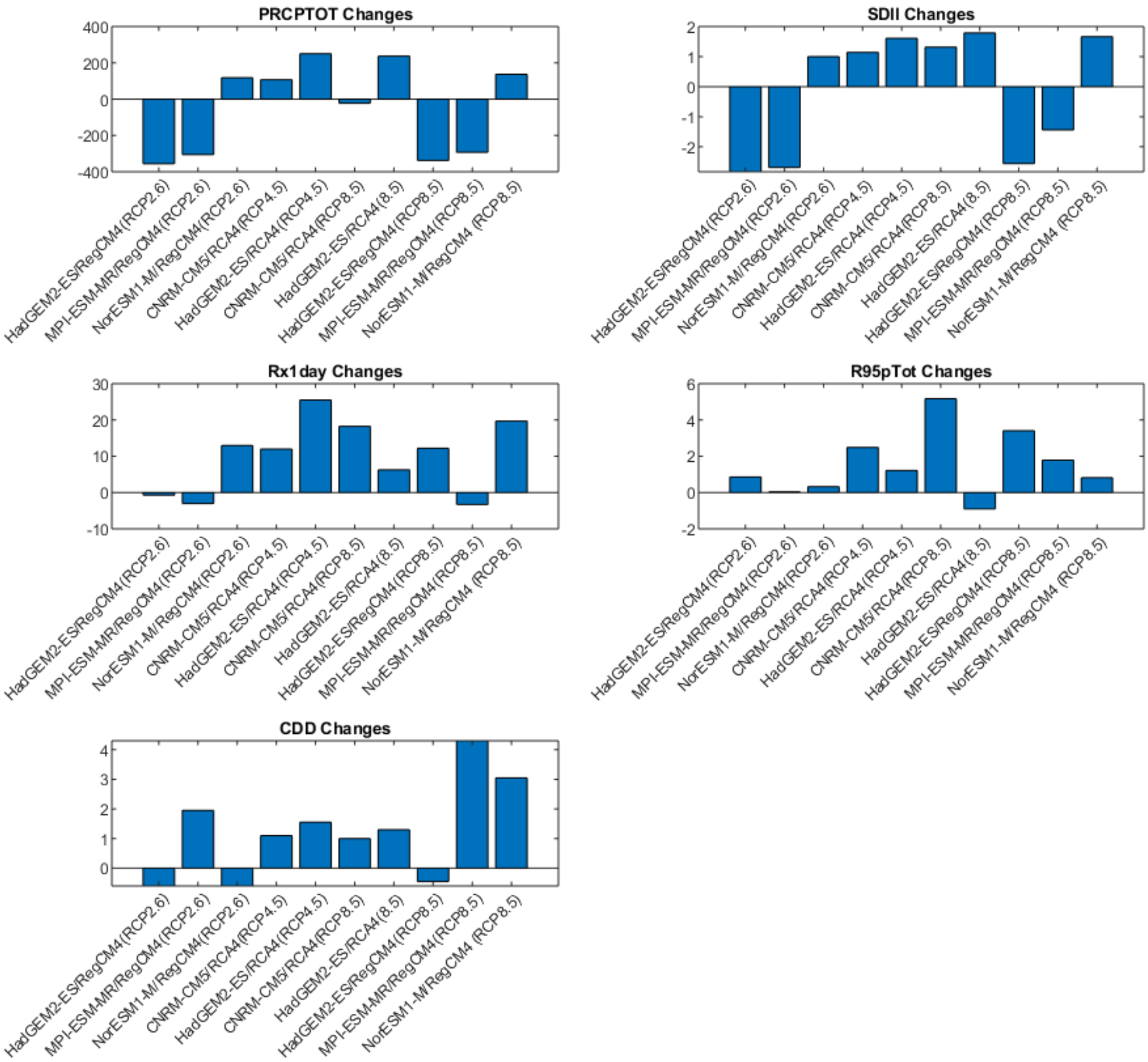


Figure 3.52 The projected future change (2061-2080) of the rainfall indices

3.6.3 Summary of changes in rainfall conditions

The key finds related to changes in rainfall conditions at site can be summarised as follows:

- With respect to the total annual change in rainfall (PRCPTOT) experienced at the site there is no clear evidence of a trend with some half of the models showing increased in annual rainfalls and the remaining half showing a reduction in annual precipitation totals. Projected changes in annual rainfall totals range from a decrease by as much as 400mm to increases of 200mm.
- The simple precipitation intensity index (SDII) which calculates the typical rainfall occurring on wet days shows four of the ten models projecting a decrease in rainfall intensity in the order of 1 to 2 mm per day and six of the ten models projecting an increase in rainfall intensity in the order of 1 to 2 mm per day.
- Monthly maximum 1-day precipitation (Rx1day) show more evidence of a pronounced increasing trend with seven of the ten models showing increases in the monthly maximum 1-day rainfall event ranging from 5 to 25mm and only three models finding only a minor decrease in the range 1 to 3 mm.
- Contribution to total precipitation from very wet days (R95pTot) shows an increasing trend in nine out of ten models. Very wet days are defined as days when the total precipitation are above the 95th percentile of daily precipitation. This indicates that future storm intensities for more severe events are anticipated to change by as much as 5 mm/day.
- Maximum length of dry spell (CDD) which is defined as the maximum number of consecutive days where rainfalls are less than 1mm again shows predominately a positive trend with seven of the ten climate models showing dry spells increasing in length by between 1 and 4 days. Models showing a decrease in the duration of dry spells only show decreases of a single day.

In summary while there is not yet clear evidence as to how annual rainfalls will change there are evident trends when extreme rainfall is examined with the intensity of severe storms expected to increase, and the duration of dry spells increasing.

3.7 Temperature

3.7.1 Historical Changes in Temperature

Daily mean temperature data of the nearest location (Mardi Klang 101° 29' E and 2° 59' N) to the study site was obtained from Malaysia Meteorology Department. The data spans for a period of 7 years from 2010 to 2016 and this short period of data coverage is insufficient to detect long term climate change signals and the time-series will be dominated by shorter variations such as annual and interannual cycles. Nevertheless, the data was applied to verify the climate models simulations in term of the temperature annual cycle.

Figure 3.53 shows the comparison between the monthly averaged observed daily mean temperature and that of the regional climate models (refer Table 3.9) simulations in the historical period. The shade indicates the differences between the five different models. It is noted that there are considerable variations (<2°C) between the climate models. In general, the regional climate model simulations are slightly colder compared to observed temperatures (<1.5°C) although the simulated temperature annual cycles are consistent with the observations. Nevertheless, in addition to the cold bias, this inconsistency is also due to the different averaging period of the observation and the regional climate models simulations.

Also noted is that the simulated temperature annual range is rather small below 2°C, consistent with the observation. In addition to the mean temperature, the annual cycle of the minimum temperature and the maximum temperature also juxtaposed for visual comparison although the observation of maximum and minimum temperature is not readily available. Both the minimum and maximum temperature show similar annual patterns with the mean temperature with highest values in the middle of the year. Comparatively, the simulations of both maximum and minimum temperature show larger inter-model variations (>2°C) compared to the mean temperature.

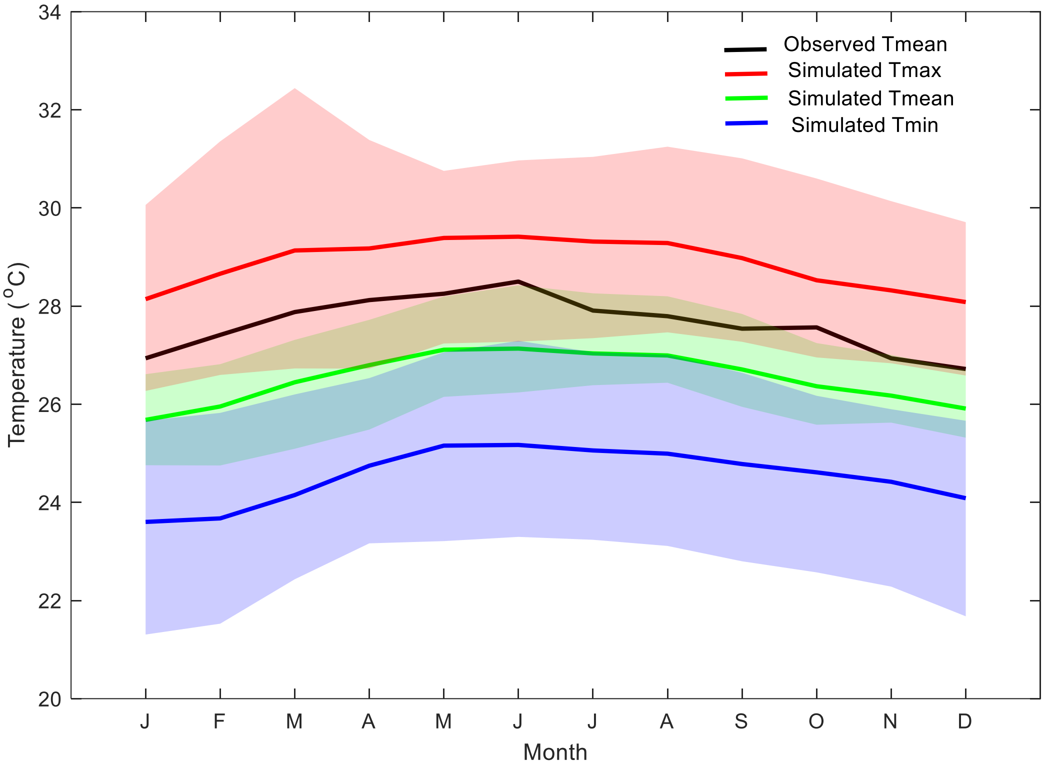


Figure 3.53 The comparison between the observed daily mean temperature climatology (black line) (2010-2016) and that simulated by the CORDEX-SEA RCMs (green line/shade) (2086-2005). The averaged maximum and minimum temperature of the CORDEX-SEA RCMs were juxtaposed for comparison.

3.7.2 Future Changes in Temperature

Figure 3.54 shows the mean, minimum and maximum temperature changes simulated by the regional climate models under different emission scenarios at the station location. Overall, the patterns of changes across the different temperature variables show high similarity. The future change of temperatures ranged between 0.6°C to 2.6°C, depends on the scenarios considered. The difference between the mean minimum and maximum temperatures are minimal. Unlike the rainfall, the projected temperature change is very sensitive to the emission scenarios. The temperature change for RCP 8.5 is ~2.2-2.6°C whilst that for RCP 2.6 is ~0.7-0.8°C. For easy comparison the numerical values of the changes are shown in Table 3. Overall, the projected change of temperature is rather consistent over the climatological months. However, the increment of temperature in April-June is expected to be slightly higher. Some individual climate models simulated much higher temperature changes. For instance, in RCP 8.5, the projected changes of minimum temperatures it can be as large as 4°C with reference to the historical period. Therefore, the projections of minimum and maximum temperature show large ensemble spreads between the scenarios.

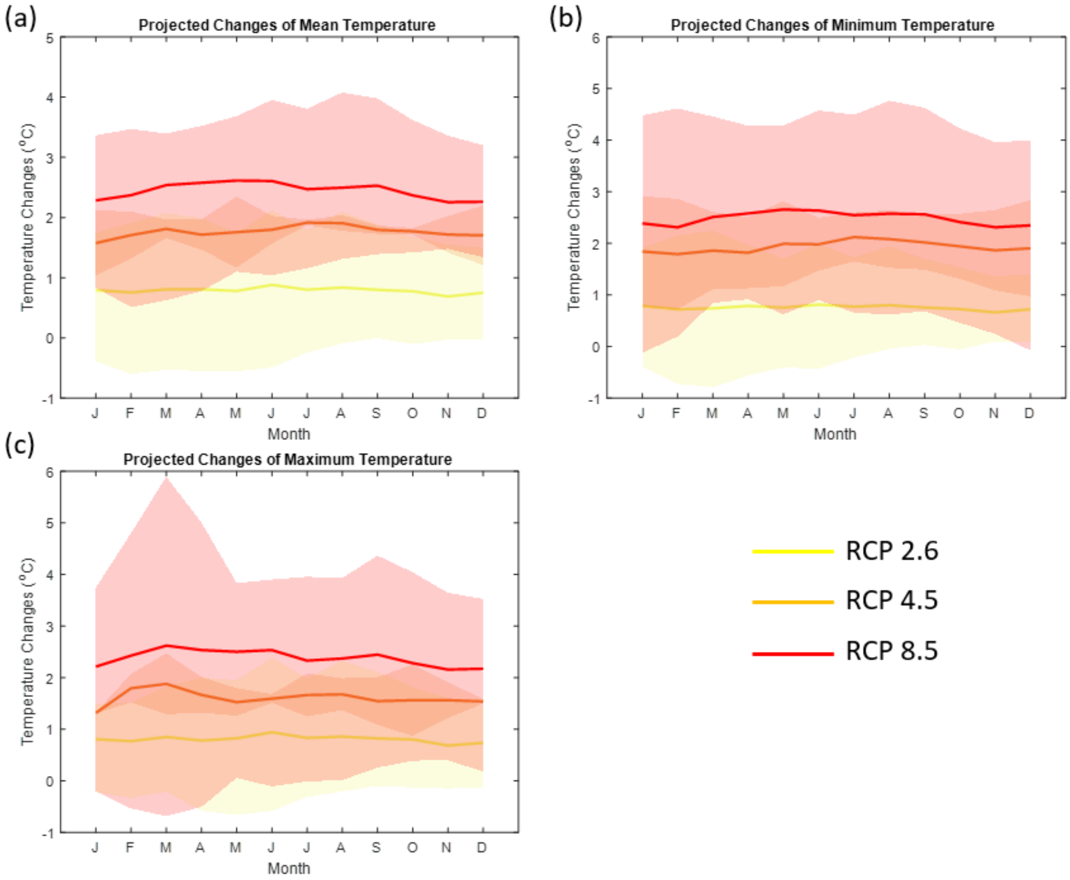


Figure 3.54 The projected changes of (a) mean temperature, (b) minimum temperature and (c) maximum temperature for different RCPs.

Table 3.9 The projected changes of minimum, mean and maximum temperature for each month in 2061-2080 w.r.t 1986-2005 (historical data).

Month	**Minimum Temperature**			**Mean Temperature**			**Maximum Temperature**		
	RCP2.6	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**
January	0.8	1.8	2.4	0.8	1.6	2.3	0.8	1.3	2.2
February	0.7	1.8	2.3	0.8	1.7	2.4	0.8	1.8	2.4
March	0.7	1.9	2.5	0.8	1.8	2.5	0.9	1.9	2.6
April	0.8	1.8	2.6	0.8	1.7	2.6	0.8	1.7	2.5
May	0.8	2.0	2.7	0.8	1.8	2.6	0.8	1.5	2.5
June	0.8	2.0	2.6	0.9	1.8	2.6	0.9	1.6	2.5
July	0.8	2.1	2.5	0.8	1.9	2.5	0.8	1.7	2.3
August	0.8	2.1	2.6	0.8	1.9	2.5	0.9	1.7	2.4
September	0.8	2.0	2.6	0.8	1.8	2.5	0.8	1.5	2.4
October	0.7	1.9	2.4	0.8	1.8	2.4	0.8	1.6	2.3
November	0.7	1.9	2.3	0.7	1.7	2.3	0.7	1.6	2.2
December	0.7	1.9	2.3	0.8	1.7	2.3	0.7	1.5	2.2

3.7.3 Changes in Temperature Indices for both the Baseline and Future Climate

The changes of heat extremes can be carried out based on several heat indices commonly used in the literature such as that for the rainfall. Here, we examined the changes of heatwave characteristics, namely the averaged heatwave number, heatwave duration and heatwave amplitude (refer Table 3.10). Similar to the rainfall indices, these heat indices are subset of CLIMPACT indices identified by the Expert Team on Sector-Specific Climate Indices (ET-SCI) (Alexander and Herold, 2016).

Note that the Malaysia Meteorological Department uses a threshold of 35°C for the definition of heatwave event. Here, we used the 90th percentile of the daily maximum temperature as the threshold instead of pre-setting a constant threshold value because the climate models tend to produce cold biases due to the models' resolution as well as the parameterization of surface processes, which may result in zero events in a given period. The observation temperature dataset is too short in duration for bias-adjustment to be carried out. Hence using the percentile thresholds eliminates the inherited biases issue when defining the heat indices.

Table 3.10 Table 4. The heat indices considered in current study.

Indices	Remark
HWN	Heatwave number. The number of individual heatwaves that were identified in a given period. A heatwave event is defined as 3 or more days where maximum temperature, Tmax > 90th percentile of Tmax, calculated from a given base period (1986-2005).
HWD	The length of the heatwave identified by HWN.
HWA	The peak daily value in a heatwave event identified by HWN.

Figure 3.55 shows the climate models produced heatwaves characteristics during the baseline period. Based on the heatwave number definition, the averaged heatwave number is ~4 and the averaged duration of the heatwave is around 4-6 days. The averaged amplitude is 30-36°C. Figure 3.56 shows the future changes of the heatwaves characteristics projected by the different climate models driven by different RCPs scenarios. All the climate models projected an increase in the heatwave numbers. The heatwave number appears to be less sensitive to the future emission scenarios, but rather dependant on the regional climate models used for the downscaling. The downscaled climate by RCA4 tends to produce a higher increment of heatwave number compared to the RegCM4. In generally, the result suggests that the chance of a heatwave event occurrence in the future is slightly more than twice that during the baseline period. The heatwave duration is also projected to increase in the future. Nevertheless, the larger increments (>10days) are projected by higher emission scenarios i.e RCP 8.5 compares to the RCP2.6 and RCP4.5 in which the projected increment of duration is generally < 5 days. On the other hand, the heatwave amplitude is also projected to increase more in the RCP 8.5 scenario, but less so in the RCP 2.6 and RCP 4.5 downscaled projections. The amplitude changes projected by RCP 8.5 driven simulations are ~0.5°C to >1.0°C whilst that projected by RCP 2.6 and RCP4.5 are generally <0.5°C.

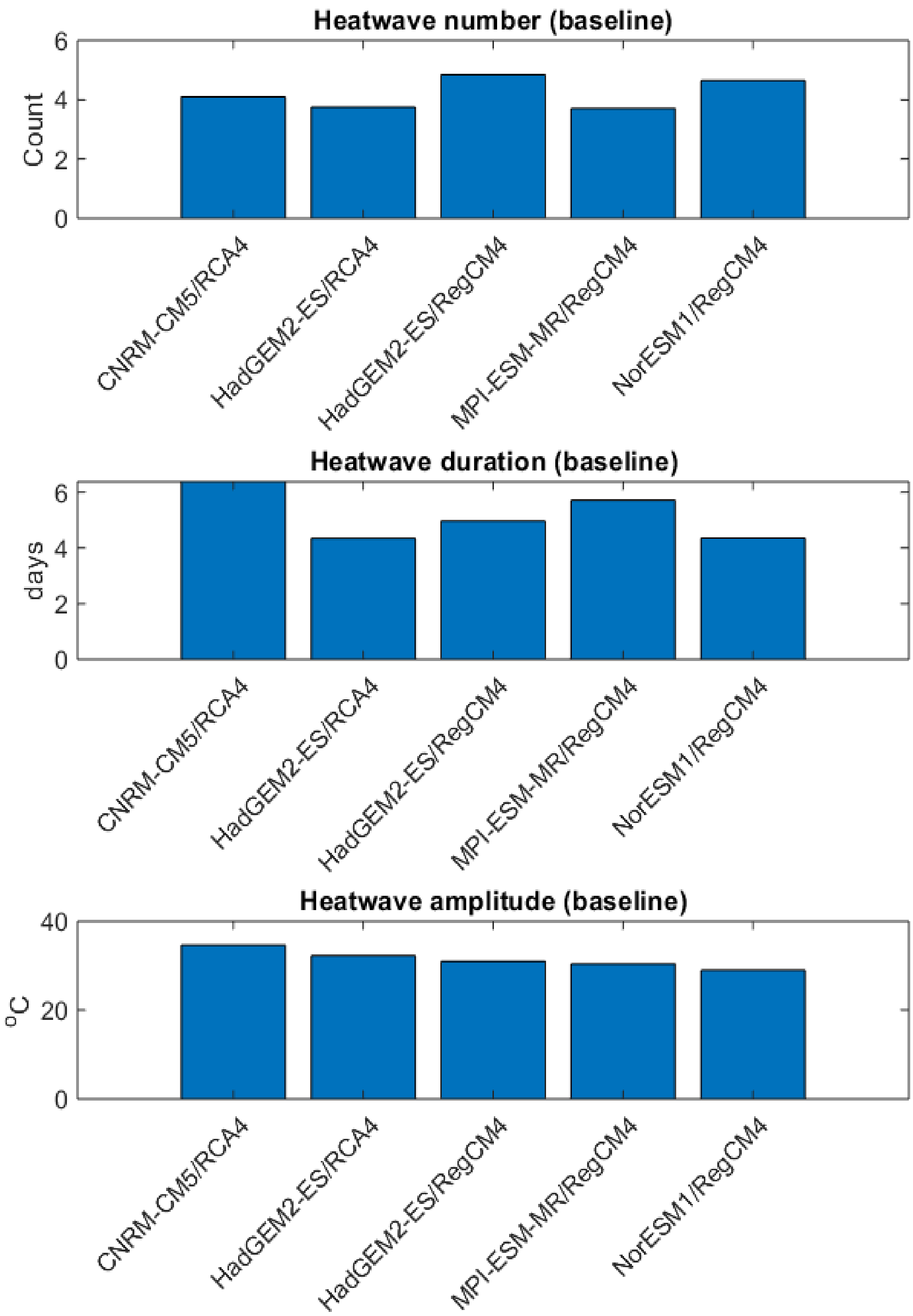


Figure 3.55 The climate models simulated HWN, HWD and HWA in the baseline period.

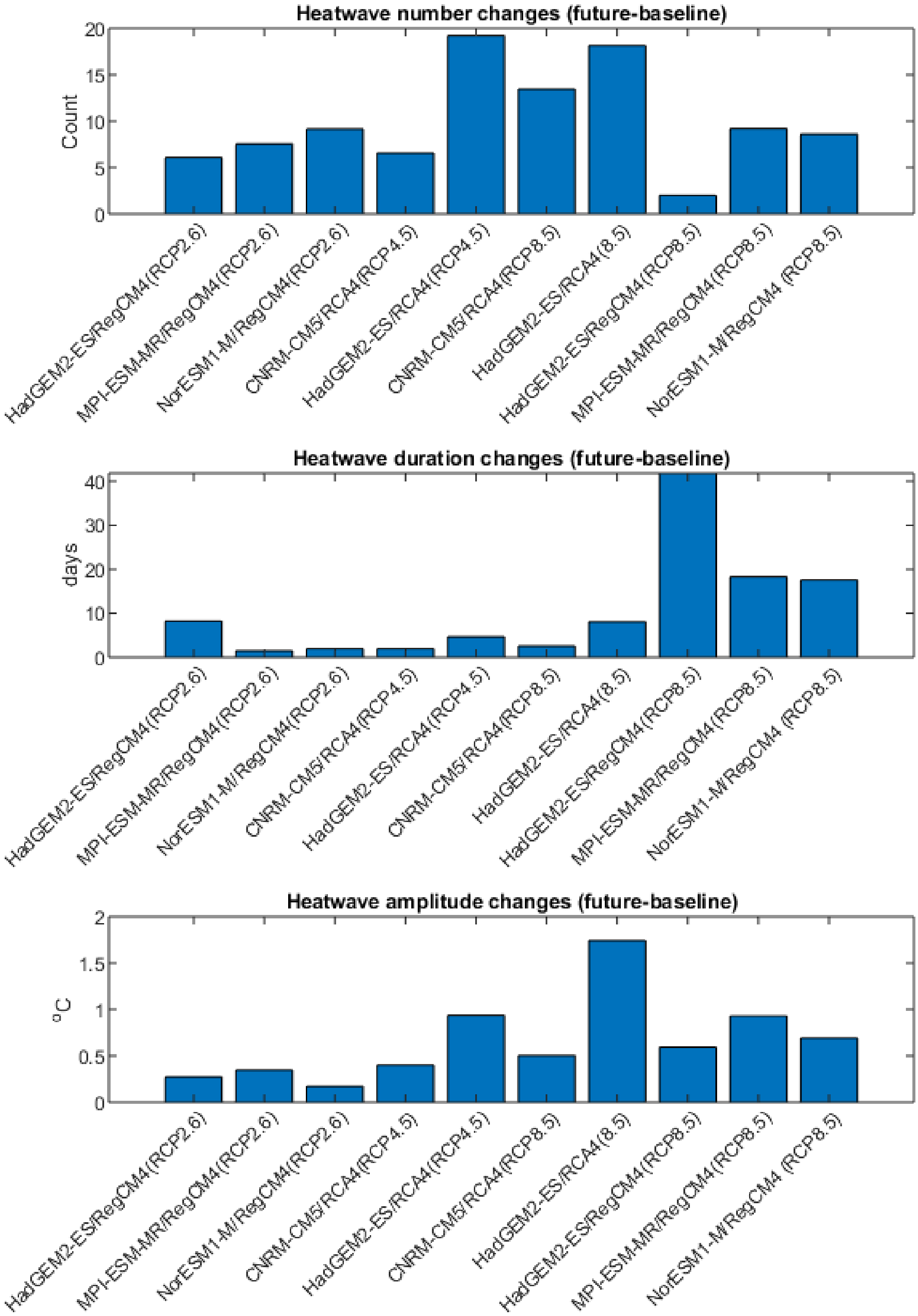


Figure 3.56 The projected changes of the heatwave numbers, heatwave duration and heatwave amplitude from the 10 different GCMs/RCMs pairs and RCPs scenarios

3.7.4 Summary of Changes in Temperature

The assessment of future trends in temperature has indicated that temperatures will increase for all scenarios considered. Changes in temperature indices between the baseline period and the future are summarised below:

- The heatwave number (HWN) which is the number of individual heatwaves identified in a given period are projected to increase by all climate models. The chance of heatwave event occurrence in the future is more than twice that of the baseline period.
- The length of heatwaves (HWD) identified by the HWN is also projected to increase in the future but it should be noted that larger increments showing increases in the duration of heat waves of more than ten days are projected by higher emission scenarios (RCP8.5) compared to the lower (RCP2.6) and middle (RCP4.5) scenarios which shows increases in the duration of heat waves of typically 5 days.
- The peak daily value in a heatwave event (HWA) identified by the HWN is also projected to increase more for the higher emission scenarios (RCP8.5) and less so for RCP2.6 and RCP4.5. The peak daily temperature is projected to increase by between ~0.5°C to >1.0°C whilst that projected by RCP 2.6 and RCP4.5 are generally <0.5°C.

The rising temperature may have strong implications to future heat and energy management of the underlying infrastructures and facilities. It should be pointed out that the climate model projections at this scale do not consider the effect of local urban development which may further elevate the heat stress via urban heat island effect. Therefore, future increase in temperature is expected to be much larger than the projected values compounded by local effect.

4 Stage 3- Initial Vulnerability Assessment

4.1 Basis for vulnerability and risk assessment

The vulnerability and risk assessment has been carried out following the general principles set out under Stage 3 of the PIANC Guideline on Climate Change Adaptation Planning /1/. The general process followed in this vulnerability and risk assessment is as follows:

1. Identification of Westports port infrastructure, assets and operations that might be impacted by the predicted future climate changes that have been identified in Section 2. This is intended to provide an overview of areas where climate change might have an impact, therefore this focuses on groups of assets and general operations carried out in the port.
2. Where available data on these assets or operations that will assist in identifying their vulnerability to climate change is collated.
3. The criticality of the identified assets and operations to the operation and commercial viability of the port is assessed. This will assist in assessing the overall risk to port operations for any areas that are identified to be vulnerable to climate change.
4. The vulnerability of each of the identified port infrastructure, assets and operations to the climate changes identified in Section 3 is tabulated. This assessment includes the magnitude of the predicted climate change and the vulnerability of the asset or operation to this change.
5. A preliminary risk assessment has been carried out to identify the assets and operations most likely to require adaption in the future to protect the port from the impact of climate change.

The vulnerability and risk assessment has been carried out using expert judgement based on a general understanding of the port infrastructure and operations. Detailed calculations or process-based modelling of the operations have not been carried out for this assessment. These should be considered at a later stage for the assets and operations identified as most likely to require adaptation to confirm any adaptions required and the likely timeframe in which these adaptions should be made.

4.2 Key Infrastructure, Assets and Operations

The Westports key infrastructure, assets and operations identified are set out in Table 4.1. This table also includes key geometrical data including dredged depth and elevation where relevant.

Table 4.1 Key infrastructure, assets and operations including geometrical data and key facts

Key Infrastructure, Assets and Operations				Key facts: Geometrical data: Location	Depth (m relative to CD)	Elevation (m relative to CD)	Responsible department or organisation: Management	Operation and maintenance
MARINE / OFFSHORE / IN RIVER	Operational use or modification of water area		Channel / fairway / waterway	Port Klang South Access Channel	Min. -18	N/A	Klang Port Authority	Klang Port Authority
			Anchorage		N/A	N/A		
	Assets	Structures	CT1 to CT9	Port Klang Channel	-15 to -17.5	7.2	WM Engineering	WM Engineers
			Dry Bulk terminal I (next to CT)		-15	7.2		
			Break Bulk terminal (next to CT)		-15	7.2		
			Liquid Bulk terminal (LBT1- LBT5)		-11.5 to -16.5	7.2		
			Dry Bulk terminal II (at the north)		-13.5 to -14.5	7.2		
			Aids to Navigation		N/A	N/A	Marine Dept.	Marine Dept.
	Operations		Pilotage	Westports Berths	N/A	N/A	Klang Port Authority	WM Pilots
			Marker buoys navigation aids		N/A	N/A	Marine Dept.	Marine Dept.
			Dredging / disposal		N/A	N/A	WM Berth Planning	Operations Managers
			Maintenance of infrastructure		N/A	N/A	WM Engineering	WM Engineers
			Cargo handling /Crane usage		N/A	N/A	WM Operations	Operations Manager
			Gangways		N/A	N/A	Vessel	Vessel
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Revetment for CT1-CT6	Port Klang Channel	N/A	7.2	WM Engineering	WM Engineers
			Revetment for CT7-CT9		N/A	8.4		
			Revetment for Dry Bulk terminal I		N/A	7.2		
			Revetment for Break Bulk terminal		N/A	7.2		
			Revetment for Liquid Bulk terminal		N/A	7.2		
			Revetment for Dry Bulk terminal II		N/A	7.2		
TERRESTRIAL; HINTERLAND	Operational use or modification of land		Cargo handling	Westports Land Side Terminals	N/A	Facilities built on land platform of 7.2 to 8.0m (before settlements) - varies	WM Operations	Operations Manager
			Parking					
			Container yard					
			Storage facilities (eg tank farm or other non container storage)				WM Engineering / Landed Clients	WM Engineers / Landed Clients
			Pump stations and associated equipment to support tank farm and liquid product handling					
			Offices				WM Various Depts. / Landed Clients	Dept. Managers / Landed Clients
			Transport infrastructure (road, rail, etc)				PKA / WM	WM Engineering
	Assets	Structures	Offices, buildings, storage				WM Engineering / Landed Clients	WM Engineers / Landed Clients
			Cargo handling equipment, cranes				WM M&R	M&R Engineers
			Electricity sub-station					
		Physical systems and utilities	Drainage system				WM Engineering / Landed Clients	WM Engineers / Landed Clients
			Sewerage system					
			Water supply system					
			Electric supply system				WM M&R	M&R Engineers

The criticality of these infrastructure, assets and operations have been assessed based on the criteria set out in Table 4.2. This assessment has focussed on the economic effects and possible impact on business continuity and has also considered potential safety issues. The assessed criticality of these infrastructure, assets and operations is set out in Table 4.3.

Table 4.2 Consideration for Determining Criticality. Source PIANC Climate Change Adaptation Guidelines /1/.

Implications for: / Scale of impact:	Safety	Economic effects; business continuity	Public effects and local community	Environment sustainability and compliance	Critical?
Catastrophic	Risk of large numbers of serious injuries or loss of life	Loss or degradation would risk long-term viability of business including supply chains	Essential services lost, daily life becomes intolerable, unacceptable physical suffering	Irrecoverable damage, proven breach, prospect of corporate penalty	Yes
Major	Risk of isolated instances of serious injuries or loss of life	Loss or degradation would have serious effects on business requiring significant remedial action	Severe disruption of essential services and hence daily life, high levels of physical suffering	Severe and continuing loss, significant management effort needed to deal with compliance failure	Probably
Moderate	Risk of small numbers of injuries	Intervention needed to protect business continuity	Frequent disruption of essential services; daily life difficult, moderate levels of physical suffering	Minor, reversible damage, action needed on issues of compliance	Unlikely
Minor or insignificant	Risk of near misses or minor injuries	Isolated difficulties (e.g. in supply chain, replacements or alternatives exist)	Intermittent disruption of essential services and daily life, low levels of physical suffering	Negligible damage, minor breaches, easily resolved	Not critical

Table 4.3 Criticality of key infrastructure, assets, and operations.

Key Infrastructure, Assets and Operations				Criticality: Not cirtical	Criticality: Unlikely	Criticality: Probably	Criticality: Yes
MARINE / OFFSHORE / IN RIVER	Operational use or modification of water area		Channel / fairway / waterway			●	
			Anchorage		●		
	Assets	Structures	CT1 to CT9				●
			Dry Bulk terminal I (next to CT)				●
			Break Bulk terminal (next to CT)				●
			Liquid Bulk terminal (LBT1- LBT5)				●
			Dry Bulk terminal II (at the north)				●
			Aids to Navigation		●		
	Operations		Pilotage		●		
			Marker buoys navigation aids			●	
			Dredging / disposal	●			
			Maintenance of infrastructure	●			
			Cargo handling /Crane usage			●	
			Gangways			●	
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Revetment for CT1-CT6		●		
			Revetment for CT7-CT9		●		
			Revetment for Dry Bulk terminal I		●		
			Revetment for Break Bulk terminal		●		
			Revetment for Liquid Bulk terminal		●		
			Revetment for Dry Bulk terminal II		●		
TERRESTRIAL; HINTERLAND	Operational use or modification of land		Cargo handling			●	
			Parking	●			
			Container yard			●	
			Storage facilities (eg tank farm or other non container storage)			●	
			Pump stations and associated equipment to support tank farm and liquid product handling			●	
			Offices	●			
			Transport infrastructure (road, rail, etc)				●
	Assets	Structures	Offices, buildings, storage	●			
			Cargo handling equipment, cranes			●	
			Electricity sub-station			●	
		Physical systems and utilities	Drainage system			●	
			Sewerage system		●		
			Water supply system		●		
			Electric supply system			●	

4.3 Vulnerability of key Infrastructure, Assets and Operations

The vulnerability of each of the Westports key infrastructure, assets and operations identified in Section 4.2 to future changes in climate have been assessed by expert judgement. The potential future changes in climate considered are:

- Changes to windspeeds. The low and medium scenarios estimate that windspeeds are predicted to remain unchanged, however, the high scenario predicts increase in wind speeds throughout the year.
- Increase in waves. These changes are principally offshore of the port in the Malacca Straits.
- Sea level rise is predicted to be significant
- Changes in current speeds are minor.
- Increased rainfall intensity during high rainfall events. This has an impact on flooding risk within the port area and may also lead to reduced visibility during these rainfall events that might impact port operations.
- Changes in temperature. Future trends indicate that temperatures will increase for all scenarios considered.

The potential vulnerabilities are set out in Table 4.4. The vulnerabilities in this table are colour coded based on the legend shown in Table 4.5. Table 4.4 also includes an indication of areas where climate change might impact maintenance costs or where there might be a negative impact on port operations.

Table 4.4 Vulnerability of key infrastructure, assets, and operations to climate change.

Key Infrastructure, Assets and Operations				Criticality				Vulnerability hazard impacts						Key facts		
														Performance		
				Not cirtical	Unlikely	Probably	Yes	Winds	Waves	Sea Water Levels	Currents	Rainfall/Flooding/Visibility	Temperature	Maintencance cost	Performance against target	Available adaptive capacity
MARINE / OFFSHORE / IN RIVER	Operational use or modification of water area		Channel / fairway / waterway			●		↑	↑	↑	↔	↑	↑			
			Anchorage		●			↑	↑	↑	↔	↑	↑			
	Assets	Structures	CT1 to CT9				●	↑	↑	↑↑	↔	↑	↑	↑	↑	
			Dry Bulk terminal I (next to CT)				●	↑		↑↑	↔	↑	↑	↑	↑	
			Break Bulk terminal (next to CT)				●	↑		↑↑	↔	↑	↑	↑	↑	
			Liquid Bulk terminal (LBT1- LBT5)				●	↑		↑↑	↔	↑	↑	↑	↑	
			Dry Bulk terminal II (at the north)				●	↑		↑↑	↔	↑	↑	↑	↑	
			Aids to Navigation		●			↑	↑	↑↑	↔	↑	↑			
	Operations		Pilotage		●			↑	↑	↑↑	↔	↑	↑		↑	
			Marker buoys navigation aids			●		↑	↑	↑↑	↔	↑	↑			
			Dredging / disposal	●				↑	↑	↑↑	↔	↑	↑			
			Maintenance of infrastructure	●				↑	↑	↑↑	↔	↑	↑	↑		
			Cargo handling /Crane usage			●		↑	↑	↑↑	↔	↑	↑		↑	
			Gangways			●		↑	↑	↑↑	↔	↑	↑			
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Revetment for CT1-CT6		●				↑	↑↑	↔				↑	
			Revetment for CT7-CT9		●				↑	↑↑	↔				↑	
			Revetment for Dry Bulk terminal I		●					↑↑	↔				↑	
			Revetment for Break Bulk terminal		●					↑↑	↔				↑	
			Revetment for Liquid Bulk terminal		●					↑↑	↔				↑	
			Revetment for Dry Bulk terminal II		●					↑↑	↔				↑	
TERRESTRIAL; HINTERLAND	Operational use or modification of land		Cargo handling			●		↑				↑	↑		↑	
			Parking	●								↑	↑			
			Container yard			●		↑				↑	↑		↑	
			Storage facilities (eg tank farm or other non container storage)			●						↑	↑			
			Pump stations and associated equipment to support tank farm and liquid product handling			●		↑				↑	↑			
			Offices	●								↑	↑			
			Transport infrastructure (road, rail, etc)				●	↑				↑	↑		↑	
	Assets	Structures	Offices, buildings, storage	●				↑				↑	↑			
			Cargo handling equipment, cranes			●		↑				↑	↑		↑	
			Electricity sub-station			●						↑	↑	↑	↑	
		Physical systems and utilities	Drainage system			●				↑↑		↑	↑	↑	↑	
			Sewerage system		●							↑	↑			
			Water supply system		●							↑	↑			
			Electric supply system			●		↑				↑	↑			

Table 4.5 Legend for Table 4.4

Change in Risk Profile	Magnitude of Change		
	High	Moderate	Low
Significantly Increasing Risk	↑↑	↑↑	↑↑
Increasing Risk	↑	↑	↑
Stable	↔	↔	↔
Reducing Risk	↓	↓	↓

4.4 Preliminary Assessment of Risk to Key Infrastructure, Assets and Operations

Based on the assessment reported in Sections 4.1 to 4.3 the facilities and operations that are most likely to be vulnerable to climate change have been identified, these are set out in Table 4.6, together with a summary of the key issues that have been identified that potentially make these vulnerable.

It is stressed that this assessment is subjective based on expert judgement on the available data and is therefore not definitive. It is recommended that a more detailed assessment is carried out to confirm this assessment (for example a calculation of the freeboard of the jetty structures should be carried out to more accurately assess the risk to these structures from increasing sea levels and wave action).

Table 4.6 Facilities and operations most likely to be vulnerable to climate change

	Facility / Operation	Key Issues
1	Container Berths CT1 to CT9	Increasing water levels and wave action may lead to: • Waves from either natural causes or ship wake overtopping the jetty deck leading to potential water damage to equipment or operational issues. • Waves from either natural causes or ship wake impacting the jetty deck soffit or beams causing structural overload and / or durability issues.
2	Dry Bulk, Liquid Bulk and Breakbulk Berths	Increasing water levels may lead to: • Waves from ship wake overtopping the jetty deck leading to potential water damage to equipment or operational issues. • Waves from ship wake impacting the jetty deck soffit or beams causing structural overload and / or durability issues.
3	Revetments along the land boundary	Increasing water levels may lead to increased waves overtopping which could potentially increase flooding risk in the operational areas immediately landward of these revetments. For the revetments in the southern area of the container terminal there is also a small possibility of increased damage to the revetment due to increased wave action in this area.
4	Storm water drainage network	The existing storm water drainage network may not have sufficient capacity to handle the predicted increase in rainfall intensity during high rainfall

		events together with increasing sea levels. This could result in localised flooding in the port operational areas for short periods of time.
5	Electrical substations and power infrastructure	The increased flooding risk described in Item 4 above may lead to a flooding risk at the electrical substations that may cause damage to this equipment.
6	Pump stations and associated infrastructure in liquid product terminals	The increased flooding risk described in Item 4 above may lead to a flooding risk at the product pump stations in the liquid product terminals that may cause damage to this equipment.
7	Pilotage and navigation to / from the berths	The increased rainfall intensity during high rainfall events will lead to reduced visibility that may negatively affect navigation during these storms. Increased wave action in the navigation channel may negatively impact pilots boarding and leaving ships.
8	Cargo handling	Predicted increased winds and rainfall intensity (causing reduced visibility) may have a negative impact on cargo handling equipment on the berths (including container cranes) and in the container yard.
9	Container yard and associated road / rail transport infrastructure	The increased flooding risk described in Item 4 above may lead to a flooding risk in the container yard and on roads that might negatively impact operations in these areas for short periods of time.

A preliminary risk assessment has been carried out to assess which of the nine facilities or operations set out in Table 4.6 are most likely to require climate adaptation measures to be adopted. This is carried out by using expert judgement to assess the likelihood of adaptation being required using the criteria set out in Table 4.7, and the consequence of not taking action using the criteria set out in Table 4.8. These two rankings are then multiplied together to obtain a risk score. Based on the data in Table 4.9 and Table 4.10 a colour coding can then be given setting out the risk level for each facility or operation.

Table 4.7 Determining and presenting risk likelihood. Source PIANC Climate Change Adaptation Guidelines /1/.

Qualitative description of likelihood	Likelihood rating	
It is **expected that** the climate hazard will occur, that the threshold will be exceeded or there will be another significant impact within the adaptation planning horizon under all climate change scenarios investigated.	Almost certain	5
It is **likely that** the climate hazard will occur, the threshold will be exceeded or there will be another significant impact within the adaptation planning horizon under some of the climate change scenarios investigated.	Likely	4
The climate hazard **may** occur or the threshold may be exceeded or there may be another significant impact within the adaptation planning horizon under some of the climate change scenarios investigated.	Possible	3
The climate hazard **could** occur, or the threshold could be exceeded or there could be another impact within the adaptation planning horizon under one or more of the climate change scenarios investigated.	Unlikely	2
The climate hazard (or the exceedance of the threshold or the manifestation of an impact) is **not expected** to occur other than in exceptional circumstances within the adaptation planning horizon under most of the climate change scenarios investigated.	Rare	1

Table 4.8 Determining risk consequence. Source PIANC Climate Change Adaptation Guidelines /1/.

If the occurrence of the hazard would cause impacts that…	… then an appropriate consequence rating is	
Irreplaceably or permanently affect critical assets, operations or systems and thus threaten the viability of the port or waterway with possible implications for the regional or national economy, potentially lead to loss of life, cause significant and irreversible contamination with hazardous substances, prevent the import or distribution of post-disaster aid, or have similar potentially catastrophic implications.	Catastrophic	5
Have a significant, negative long-term effect on critical assets, operations or systems and thus compromise the business continuity of the port or waterway, potentially lead to serious injury, result in significant or irreversible environmental impacts, compromise the import or distribution of post-disaster aid, or have similar potentially major implications.	Major	4
Have a negative, locally significant and/or short- to medium-term effect on critical assets, operations or systems with implications for business continuity in the affected parts of the port or waterway; potentially lead to minor injury, cause moderately significant environmental impacts, affect the ability of the facility to import or distribute post-disaster aid effectively, or have similar moderately significant implications.	Moderate	3
Temporarily affect the efficiency or effectiveness of critical assets, operations or systems or aspects thereof but with no significant implications for business continuity overall, cause environmental impacts of minor significance, interrupt aspects of post-disaster aid import or distribution, or have similar implications of minor significance.	Minor	2
Have negligible implications for critical assets, operations or systems and hence business continuity, insignificantly affect the environment or the import and distribution of post-disaster aid.	Insignificant	1

Table 4.9 Risk assessment outcomes. Source PIANC Climate Change Adaptation Guidelines /1/.

Likelihood → Impact ↓	Rare (1)	Unlikely (2)	Possible (3)	Likely (4)	Almost Certain (5)
Catastrophic (5)	5	10	15	20	25
Major (4)	4	8	12	16	20
Moderate (3)	3	6	9	12	15
Minor (2)	2	4	6	8	10
Insignificant (1)	1	2	3	4	5

Table 4.10 Required Adaption Action. Source PIANC Climate Change Adaptation Guidelines /1/.

Level of risk	Required adaptation action
Very high risk	Immediate adaptation action required
High risk	Adaptation action required as high priority
Moderate risk	Adaptation actions to be implemented via day-to-day management
Low risk	Risks to be managed and monitored via routine internal procedures

The risk levels calculated for each of the nine identified facilities and operations are set out in Table 4.11. This shows that:

- There is a High Risk that there may be issues with the container quays, and the dry bulk, liquid bulk and breakbulk berths due to rising sea levels. The reason that these are rated with a High Risk is that if sea level rise leads to either increased wave overtopping of the deck structure, or structural issues due to increased wave loading these are difficult to mitigate.
- There is a Moderate Risk of short duration flooding due either to increased overtopping of revetments of the ability of the drainage system to cope with increased rainfall intensity and sea level. The reason that these are rated with a Moderate Risk is that these issues can be readily addressed by minor modifications to the storm drains or revetment crests.
- There is a Moderate Risk of reduced visibility during high rainfall events impacting navigation. The reason that this is rated with a Moderate Risk is that these will be short duration disruptions and can be managed by port operation procedures and weather forecasting.

Table 4.11 Preliminary climate change adaptation risk assessment

	Facility / Operation	**Key Issue**	**Likelihood**	**Consequence**	**Risk Level**
1	Container Berths CT1 to CT9	Berths adversely impacted by increased water levels and wave action.	3	4	High Risk
2	Dry Bulk, Liquid Bulk and Breakbulk Berths	Berths adversely impacted by increased water levels.	3	4	High Risk
3	Revetments along the land boundary	Revetment overtopping increased due to increased sea level and wave action.	3	3	Moderate
4	Storm water drainage network	Drainage system not able to handle increased runoff during extreme rainfall events	3	3	Moderate
5	Electrical substations and power infrastructure	Potentially impacted by flooding during extreme rainfall events	2	3	Moderate
6	Pump stations and associated infrastructure in liquid product terminals	Potentially impacted by flooding during high rainfall events	2	3	Moderate
7	Pilotage and navigation to / from the berths	Potentially impacted by reduced visibility during extreme rainfall on a more frequent basis	4	2	Moderate
8	Cargo handling	Potentially impacted by increased windspeeds and / or increased rainfall intensity during high rainfall events	2	2	Low
9	Container yard and associated road / rail transport infrastructure	Potentially impacted by flooding during high rainfall events	2	2	Low

4.4.1 Anticipated Timing of Risk to Berths

The facility identified as being at highest risk due to climate change is the berth structures due to the predicted increase in sea level. There are many uncertainties in the timeframe over which this risk will materialise. In this section some guidance of possible timeframes are presented. The two key risks identified for the berths are:

- Overtopping of the deck of the berth.
- Increased wave impact on and submerging of elements of the jetty structure, in particular the soffit of the deck slab and the jetty deck beams.

This assessment focusses on container berths CT1 to CT9 and the Dry Bulk Berths, but similar conditions are also expected on the Liquid Bulk and Breakbulk Berths. Typical cross sections through the existing container berths (based on CT9) and dry bulk berths (based on DB1) are shown in Figure 4.1 to Figure 4.3.

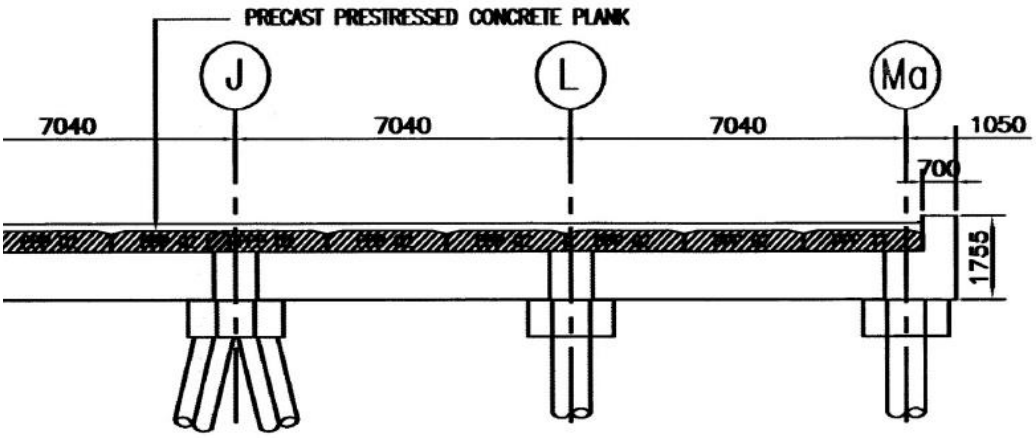


Figure 4.1 Typical cross section of the Container Berths (based on CT9).

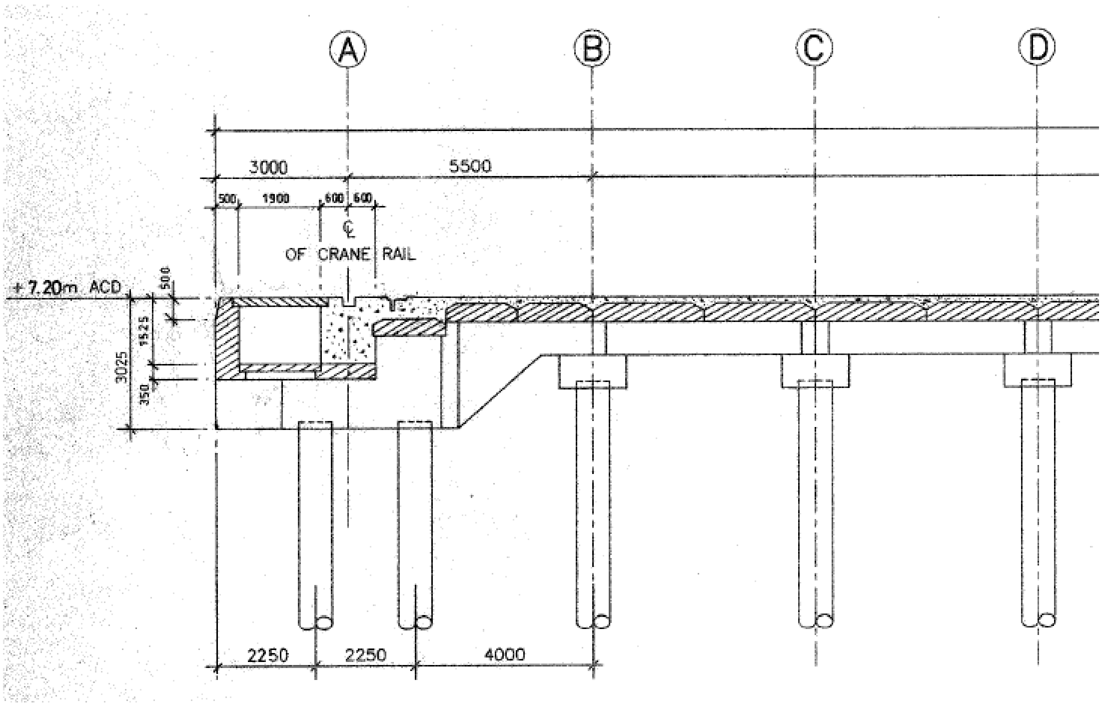


Figure 4.2 Typical cross section of seaward area of the Dry Bulk Berths (based on DB1).

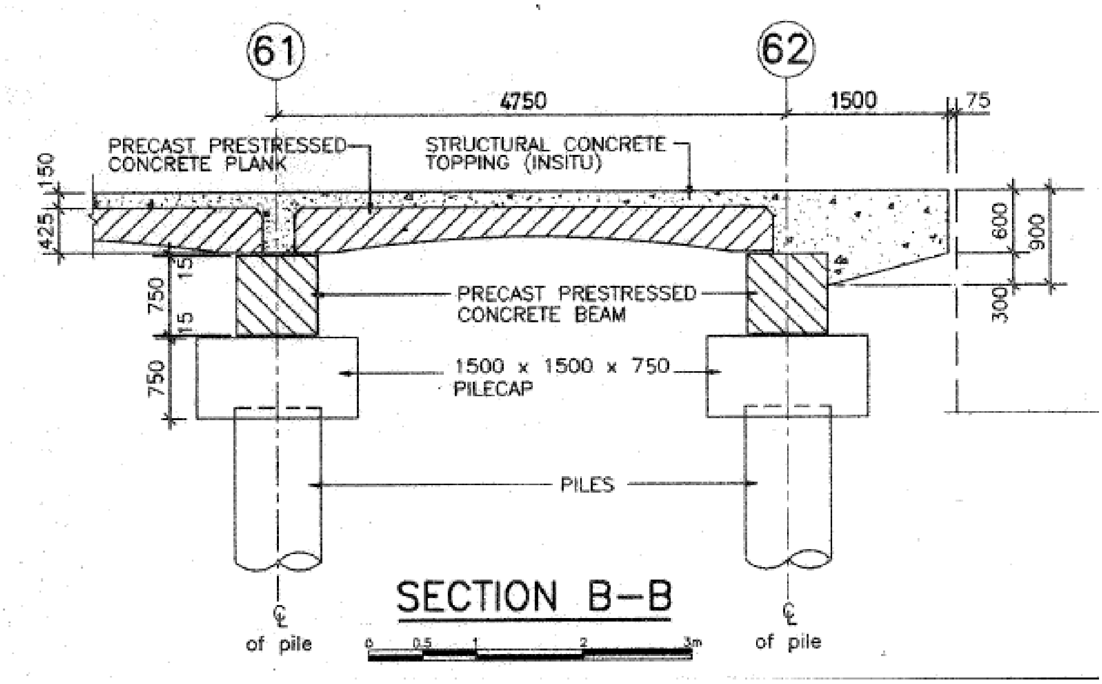


Figure 4.3 Typical details of Dry Bulk Berths (based on DB1) deck slab and beams.

The key existing water level and wave conditions in the vicinity of the container berths that have been calculated in /22/ and are being considered in this assessment are:

- Water levels:
  - MHWN +3.72 mCD
  - MHWS +5.09 mCD
  - HAT +5.82 mCD
  - 1 year return period +5.72 mCD
  - 10 year return period +5.89 mCD
  - 100 year return period +6.01 mCD
- Wave heights in the vicinity of CT9 (these progressively reduce towards CT1)
  - 1 year return period approx. 1.1m
  - 100 year return period approx. 1.8m.

No data is available on ship wakes, but these are expected to be up to approximately 1m.

Based on the above the following is noted for the present conditions:

- Freeboard to the berth deck is 2.1m above MHWS (1.2m above the 100 year return period water level). Based on this overtopping of the deck structure is expected to be minimal, although it is possible that waves with a return period above 1 year may cause some limited overtopping if they occur during a period of high tide.
- The downstand on the seaward face of the jetty extends to a level of +4.175 mCD. This is below water level on every tide during spring tides, and is subject to wave loadings.
- The soffit of the jetty beams for the Dry Bulk Berths are at +5.9 mCD. These beams are therefore above HAT and not regularly submerged at high tide, but will be subject to some wave loading.
- The soffit of the jetty beams for the CT1 to CT9 Container Berths are at +5.4 mCD. The soffit of these beams are therefore below HAT and the lower part of these beams are occasionally submerged at high tide. These beams are also subject to some wave loading.
- The soffit of the jetty deck slab is at approximately +6.6 mCD. This is above the extreme high water level, but will be below wave crest level if extreme waves occur combined with an extreme high tide.

As set out in Section 3.4.2 sea levels are expected to increase as set out in Table 4.12 for climate scenario RCP 8.5.

Table 4.12 Value of projected sea level rise of RCP 8.5 at Pelabuhan Klang from year 2020 to 2100 relative to a historical baseline of 1986-2005.

Year	RCP 8.5 Sea Level Rise [m]	
	Central Estimate	83% Confidence Limit
2020	0.07	0.09
2030	0.11	0.15
2040	0.16	0.22
2050	0.22	0.31
2060	0.29	0.41
2070	0.38	0.52
2080	0.47	0.65
2100	0.68	0.95

The predicted sea level rise has been applied to derive the percentage of time that the soffit level of the jetty beams for the Dry Bulk Berths(+5.9 mCD) and the Container Berths (+5.4mCD) and the soffit level of the deck slab (+6.6 mCD) are exceeded, the results are presented in Table 4.13 for the Dry Bulk Berths and Table 4.14 for the Container Berths.

Table 4.13 For Dry Bulk Berths (based on DB1): Exceedance of the soffit level of the jetty beams and jetty deck slab in percentage of time for projected sea level rise values of RCP 8.5 at Pelabuhan Klang from year 2020 to 2100 relative to a historical baseline of 1986-2005.

Year	Central Estimate (RCP 8.5 Sea Level Rise [m])	Percentage of Time Exceeded at Soffit Level of Jetty Beams, +5.9 mCD	Percentage of Time Exceeded at Soffit Level of Jetty Deck Slab, +6.6 mCD	83% Confidence Limit (RCP 8.5 Sea Level Rise [m])	Percentage of Time Exceeded at Soffit Level of Jetty Beams, +5.9 mCD	Percentage of Time Exceeded at Soffit Level of Jetty Deck Slab, +6.6 mCD
2020	0.07	0	0	0.09	0	0
2030	0.11	0	0	0.15	0	0
2040	0.16	0	0	0.22	0	0
2050	0.22	0	0	0.31	0	0
2060	0.29	0	0	0.41	0.1 (0.3 days per year)	0
2070	0.38	0.1 (0.3 days per year)	0	0.52	0.2 (0.7 days per year)	0
2080	0.47	0.2 (0.7 days per year)	0	0.65	0.5 (1.8 days per year)	0
2100	0.68	0.6 (2 days per year)	0	0.95	2.7 (10 days per year)	0

Table 4.14 For Container Berths (based on CT9): Exceedance of the soffit level of the jetty beams and jetty deck slab in percentage of time for projected sea level rise values of RCP 8.5 at Pelabuhan Klang from year 2020 to 2100 relative to a historical baseline of 1986-2005.

Year	Central Estimate (RCP 8.5 Sea Level Rise [m])	Percentage of Time Exceeded at Soffit Level of Jetty Beams, +5.4 mCD	Percentage of Time Exceeded at Soffit Level of Jetty Deck Slab, +6.6 mCD	83% Confidence Limit (RCP 8.5 Sea Level Rise [m])	Percentage of Time Exceeded at Soffit Level of Jetty Beams, +5.4 mCD	Percentage of Time Exceeded at Soffit Level of Jetty Deck Slab, +6.6 mCD
2020	0.07	0.3 (1 day per year)	0	0.09	0.4 (1.4 days per year)	0
2030	0.11	0.4 (1.4 days per year)	0	0.15	0.5 (1.8 days per year)	0
2040	0.16	0.6 (2 days per year)	0	0.22	0.8 (2.9 days per year)	0
2050	0.22	0.8 (2.9 days per year)	0	0.31	1.4 (5.1 days per year)	0
2060	0.29	1.2 (4.3 days per year)	0	0.41	2.2 (8 days per year)	0
2070	0.38	1.9 (6.9 days per year)	0	0.52	3.5 (12.7 days per year)	0
2080	0.47	2.9 (10.5 days per year)	0	0.65	5.5 (20 days per year)	0
2100	0.68	6.1 (22.2 days per year)	0	0.95	11.9 (43.4 days per year)	0

It is not possible to quantify absolute values of the increase in sea level that will be critical to the berth structure design and operability without a detailed analytical study, however the following is a preliminary estimate:

- An increase in water level of between 0.3m and 0.4m is likely to significantly increase the risk of wave overtopping of the berth structures. This is expected to occur between 2050 and 2070 based on RCP 8.5.
- An analysis of water levels based on RCP 8.5, presented in Table 4.13 and Table 4.14, shows that:
  - The soffit of the Dry Bulk Berth jetty beams would spend 0.1% of time (about 0.3 days per year) in the water beginning year 2070 due to sea level rise (central estimate). By year 2100, it is predicted that the soffit of the jetty beams would spend 0.6% of time (about 2 days per year) in the water. This value would go up to 2.7% of the time (about 10 days per year) if 83% confidence limit is referred.
  - The soffit of the Container Berth jetty beams presently spend 0.3% of time (about 1 day per year) and in year 2100, 6.1% of time (about 22 days per year) in the water. This value would go up to 11.9% of the time (about 43 days per year) if 83% confidence limit is referred.
  - The soffit of the jetty deck slab is observed to not be affected by the projected sea level rise values (central estimate and 83% confidence limit).

  It is not known if the increased submergence of the jetty deck beams will have a significant impact of the structure as these beams are regularly wetted by wave action or ship wake at high tide under existing conditions.
- At present the soffit of the berth deck slab has a freeboard of 0.8m above HAT. Thus, it is unlikely that any significant wave slam occurs on this deck slab even under extreme wave

conditions. The risk of some wave slam occurring does however increase as sea level rises although it is noted that this risk remains low as it requires extreme wave action to be coincident with extreme high spring tides.

- A sea level rise of between 0.2 and 0.3m will increase the risk of wave slam for waves with a return period of 1 year or above and a tidal level close to or above HAT. This is expected to occur between 2030 and 2050 based on RCP 8.5.
- A sea level rise of between 0.7 and 0.8m will increase the risk of wave slam for waves with a return period of 1 year or above and a tidal level close to or above MHWS. This is expected to occur between 2080 and 2100 based on RCP 8.5.

4.5 Recommendations for Risk Management or Mitigation

It is recommended that the following measures are implemented to continue to assess future risks and mitigate against the expected impact of climate change:

- This assessment of climate change risk should be updated every 5 years or as new predictions on climate change become available from IPCC or other recognised Authorities. This will allow the any actual changes to conditions at Westports to be assessed, and the predicted risks to be reviewed in the light of this actual data and updated predictions.
- A data collection programme should be implemented to develop a data base of met ocean conditions for use in future assessments of climate change risk. A limitation in the present assessment is the restricted availability of site-specific measured data. Measurements provide an in-depth understanding of the site conditions. Deployment of a weather station to measure wind and rainfall data and a wave recorder at the site would provide valuable information. Recent development of new hardware, software and digital solutions has made data acquisition easier and more affordable than was previously the case. Furthermore, real-time meteorological forecasts are now commercially available for weather-critical marine operations.
- Any new structures or facilities being developed for Westports should be designed taking account of predicted future climate change. This is particularly important for any new berth structures where the potential increase in sea level should be considered. For the planned extension of the container terminal south of CT9 this may well require the deck level for these berths to be higher than the +7.2 mCD of the existing berths, particularly as the design of these berths needs to take account of the increased exposure to wave action in this area as well as changes in sea level.
- If any upgrades or improvements are planned for the surface water drainage system within the port area these should be designed taking account of the predicted future increases in rainfall intensity due to climate change.

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APPENDICES

APPENDIX A

High Intensity Winds/Squalls

High Intensity Winds/Squalls

Due to the coarse spatial and temporal resolution of both the hindcast model (WRF) and the climate models considered, the simulations are not expected to capture local scale, high intensity events such as squalls. In addition, there is limited information and/or measurement on squalls in the Strait of Malacca, particularly at the site. This makes the assessment of future squall characteristics changes due to warmer climate extremely difficult. In current study, we provide an insight to possible changes of squalls frequency through diagnosing the changes of the synoptic conditions conducive for Sumatra squalls development.

The “Sumatra squall” is a high intensity and short-duration winds weather system in the Strait of Malacca. It typically forms in the Strait of Malacca and propagate from west to east as a narrow band of thunderstorm toward the western coast of Malay Peninsula (Yi and Lim, 2007). The squalls usually form in the morning hours and have life span longer than single cell thunderstorms (Lo and Orton, 2016). Their formation usually followed by onset of strong gusty surface winds exceeding up to 25 m/s and usually accompanied by heavy rain over Peninsular Malaysia, lasting 1 to 2 hours, affecting shipping and other activities. To date, the onset, structure and dynamic of the squalls are still not very well understood (Koh and Teo 2009), and the modelling of the squalls is extremely difficult (Chan et al. 2019). Ultra-high resolution numerical simulations coupled with advance initialization treatment are required to simulate the onset of squall events (Yi and Lim, 2007; Chan et al. 2019), and their evolutions are generally not well simulated.

A squall event is generally identified via the narrow rain band and its eastward propagation. The resolution (25km) of the CORDEX-SEA simulations as well as the 10 km WRF hindcast are not able to resolve the squalls rain band and associated dynamics. However, there are known synoptic environment conditions conducive for the development of squalls over the Strait of Malacca. Numerical experiments of Yi and Lim (2007) have identified these synoptic forcings for the development of squall events. Specifically, the squalls associated convections are triggered by the surface temperature differences between the Strait of Malacca and the land mass of Sumatra during the morning hours when the land surface temperature is at the coolest. Therefore, majority of squall events are recorded in the morning hours. Also, the squalls are mainly observed during the southwest monsoon when the prevailing winds over the Strait of Malacca are predominantly SE . Figure 0.1 shows the climatology of squalls frequency identified over the southern Strait of Malacca. In addition, Sumatra orography deflects the low-level winds and promoting low-level convergence to enhance the convection (Yi and Lim, 2007). We can diagnose these conditions as proxy to squall events, on the CORDEX-SEA simulation experiments and examine their chances in the future to provide some insight to possible changes to the chances of squalls development under warmer climate.

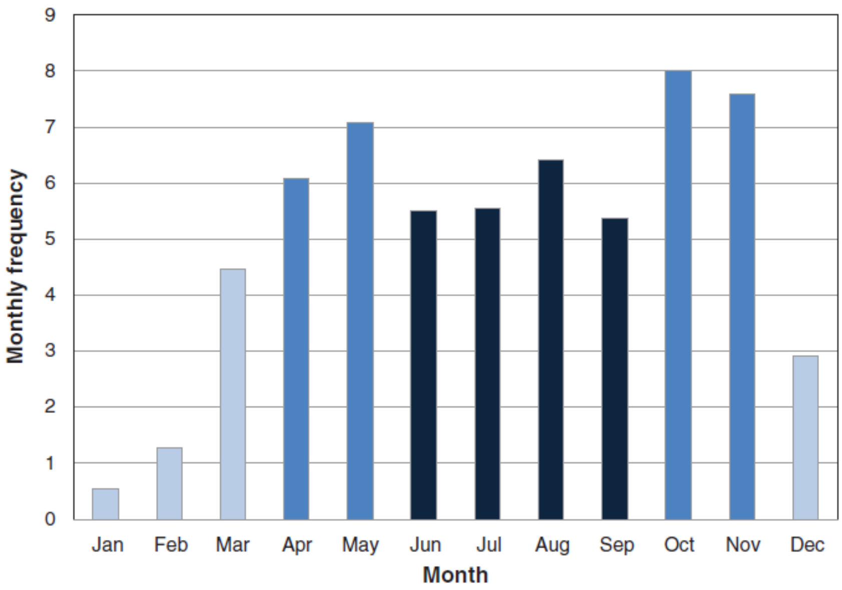

Figure 0.1 Averaged monthly frequency (1988-2009) of Sumatra squalls (source: Lo and Orton 2016)

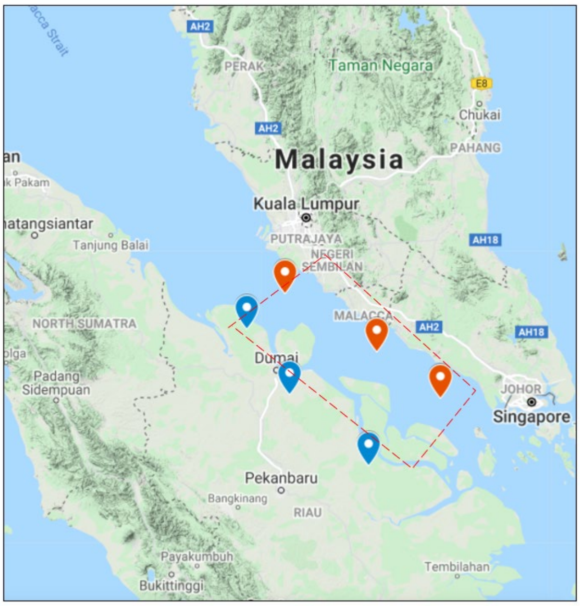

Figure 0.2 Figure 15. The three location pairs where the surface temperature differences were computed. The box with dotted line boundaries is where the spatial averaged of winds and convergence were carried out.

Figure 0.2). Here, we used the minimum daily temperature as it's the representation of the coolest temperature in dawn. The spatially averaged (within the box shown in (Figure 0.2) surface v-winds (v) and the winds convergence $(-\nabla\cdot\vec{v})$ were computed. For each climatological month, the mean frequency when averaged $\Delta T\_min>k°C$, $v > 0$ and $-\nabla\cdot\vec{v}>0$ were computed and taken as the proxy to squalls formation. There are five different GCMs/RCMs pairs considered and two different RCMs i.e RCA4 developed by Swedish Meteorological and Hydrological Institute (SMHI); and RegCM4 developed by International Center for Theoretical Physics (ICTP) were used. k=4 was used for the RCA simulations whilst k=2.5 was used from the RegCM3 simulations. The parameters were chosen manually, such that the annual cycles of the computed squall proxy is as close possible to the one reported in Lo and Orton (2016) (Figure 0.1).

Figure 0.3 shows the historical annual cycles of the squalls as simulated by the five GCMs/RCMs pairs considered. In general, the climate models have variable skills in producing the squall statistics. Although the simulations reproduced the high squall events during the southwest monsoon and lower squall events during the northeast monsoon, they failed to reproduce the bi-modality distribution with higher peaks in May and October-November. MOHC-HadGEM2-ES driven RegCM4 simulation tends to produce higher frequency in November but produces overall much lower frequency during the entire southwest monsoon. MOHC-HadGEM2-ES driven RCA4 produces the bimodality characteristics of the squalls, but the first peak appears two months delayed in July instead of May. Nevertheless, the overall higher squall frequencies during the southwest monsoon well captured by the simulations.

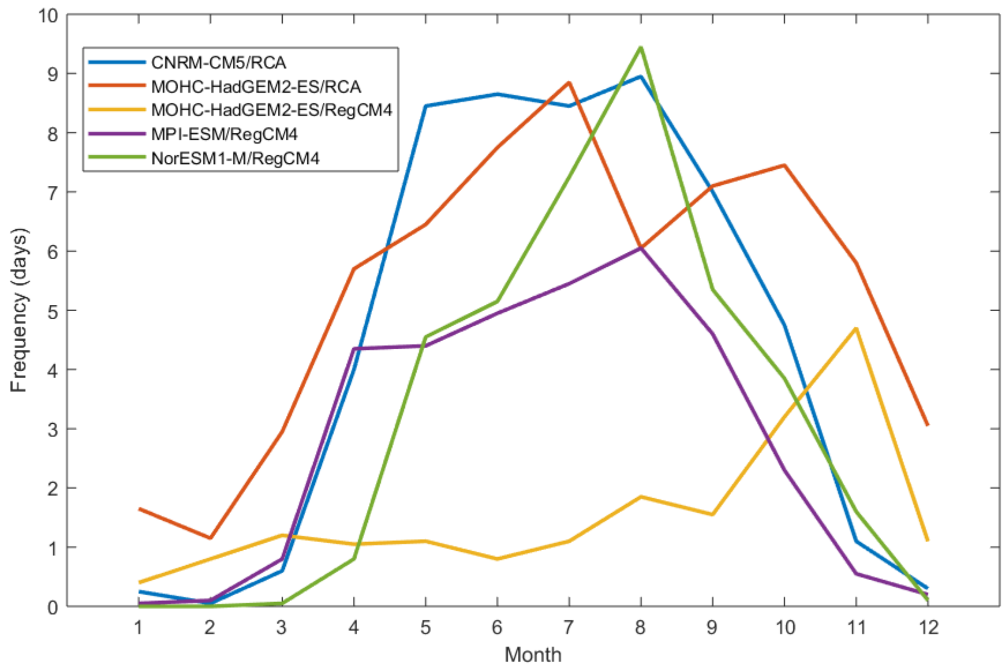

Figure 0.3 Figure 16. The simulated historical climatology of squall events based on the defined proxy.

The same scheme was used to compute the annuals cycle of squalls proxy frequency in the future period (2061-2080). Figure 0.4 shows the changes of the squall proxy annual cycle taken as the differences between the 2061-2080 and 1986-2005 period. First, it is noted that the projection is less sensitive to the RCPs considered. Robust reduction of squall events as indicated in the proxy is projected from October and across the entire northeast monsoon period to March. The projected reduction can be as large as 4 days compares to the historical period. Nevertheless, the projected changes during the southwest monsoon i.e the peak of squalls season shows considerable uncertainties. It is noted that these uncertainties are mainly from the regional climate models (i.e RCA4 and RegCM4) used in the downscaling. Specifically, the downscaled projections produced by RegCM4 as regional climate model estimated increment of squalls whilst that produced by RCA4 estimated a reduction. Although, the ensemble average estimated a slight increment of squalls during this period of the year, the changes are dominated largely by the projection from RegCM4 as there are a total of 6 projections by RegCM4 and merely a total of 4 projections by RCA4. Therefore, the future changes of squall events during the peak season are uncertain, hindered by the modelling technological shortage outlined earlier.

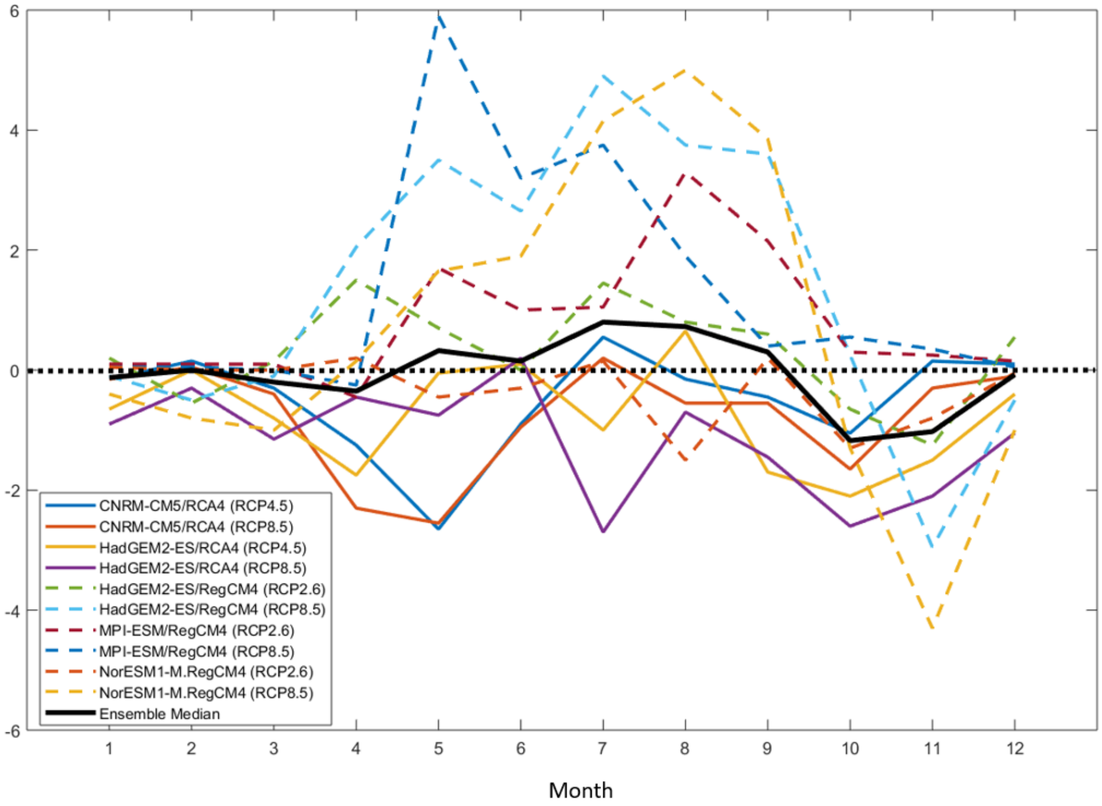

Figure 0.4 Figure 17. The projected changes of squall events as indicated by the defined proxies.

APPENDIX B

Bias Correction of Rainfall

Bias Correction of Rainfall

The bias correction is sometimes regarded as a variant of the statistical/empirical downscaling approach. In this context, we further downscaled 10 different future projected daily rainfalls to the station point (station ID: 2913122). In this implementation, the simulated daily values of the grids containing the station locations were first extracted from the CORDEX-SEA simulations. For each of the climatological months (January to December), the daily data within the reference period (1986-2005) are collected from both the observation and the climate models. The bias correction is applied on each of the 12 climatological months with separate calibration to account for the annual cycle of the rainfall. For each value in the modelled data sample, its quantile concerning the distribution is determined. The observed value corresponds to the similar quantile is determined from the observed distribution, and a change factor is calculated using these two values of similar quantile from the two distributions. A multiplicative factor is determined:

$F_r = P_{obs}(r) / P_{sim}(r)$

Where r indicates the r-th quantile under consideration. These change factors were applied to correct or shift the modelled data value of the similar quantile outside the reference period.

$P'_{sim}(r) = P_{sim}(r)\ F_r$

In this algorithm, the quantile values were calculated from the empirical distribution of both the observed and the modelled data directly instead of pre-fitting a parametric distribution to the sample data. The assumption of the any bias-correction approach is that additional local information which is not simulated by the coarser simulation grids are provided by the station data.

The majority of the bias correction methods are known to marginally modify the climate change signals of the un-corrected time series. To preserve the long-term trends, the algorithm used here first adjusted for the long-term differences between the simulated and the observed monthly mean data during the historical period. Then the monthly mean value for each month of the model output is calculated. The daily rainfall values were then normalized with respect to the mean values. The quantile mapping bias correction algorithm is then applied to the normalized rainfall time series. The adjusted time-series is then reattached with the monthly mean to create a complete daily time series.

APPENDIX C

Vulnerability and Risk Assessment Summary

Vulnerability and Risk Assessment Summary

Key Infrastructure, Assets and Operations				Key facts					Criticality				Vulnerability hazard impacts						Key facts								
				Geometrical data			Responsible department or organisation												Design data			Asset condition			Performance		
				Location	Depth (m relative to CD)	Elevation (m relative to CD)	Management	Operation and maintenance	Not critical	Unlikely	Probably	Yes	Winds	Waves	Sea Water Levels	Currents	Rainfall/Flooding/Visibility	Temperature	Design life (years)	Date of construction	Residual life	Good	Moderate	Poor	Maintencance cost	Performance against target	Available adaptive capacity
MARINE / OFFSHORE / IN RIVER	Operational use or modification of water area		Channel / fairway / waterway	Port Klang South Access Channel	Min. -18	N/A	Klang Port Authority	Klang Port Authority			•		↑	↑	↑	↔	↑	↑									
			Anchorage		N/A	N/A				•			↑	↑	↑	↔	↑	↑									
	Assets	Structures	CT1 to CT9	Port Klang Channel	-15 to -17.5	7.2	WM Engineering	WM Engineers				•	↑	↑	↑↑	↔	↑	↑							↑	↑	
			Dry Bulk terminal I (next to CT)		-15	7.2						•	↑		↑↑	↔	↑	↑							↑	↑	
			Break Bulk terminal (next to CT)		-15	7.2						•	↑		↑↑	↔	↑	↑							↑	↑	
			Liquid Bulk terminal (LBT1- LBT5)		-11.5 to -16.5	7.2						•	↑		↑↑	↔	↑	↑							↑	↑	
			Dry Bulk terminal II (at the north)		-13.5 to -14.5	7.2						•	↑		↑↑	↔	↑	↑							↑	↑	
			Aids to Navigation		N/A	N/A	Marine Dept.	Marine Dept.		•			↑	↑	↑↑	↔	↑	↑									
	Operations		Pilotage	Westports Berths	N/A	N/A	Klang Port Authority	WM Pilots		•			↑	↑	↑↑	↔	↑	↑								↑	
			Marker buoys navigation aids		N/A	N/A	Marine Dept.	Marine Dept.			•		↑	↑	↑↑	↔	↑	↑									
			Dredging / disposal		N/A	N/A	WM Berth Planning	Operations Managers	•				↑	↑	↑↑	↔	↑	↑									
			Maintenance of infrastructure		N/A	N/A	WM Engineering	WM Engineers	•				↑	↑	↑↑	↔	↑	↑							↑		
			Cargo handling /Crane usage		N/A	N/A	WM Operations	Operations Manager			•		↑	↑	↑↑	↔	↑	↑								↑	
			Gangways		N/A	N/A	Vessel	Vessel			•		↑	↑	↑↑	↔	↑	↑									
LAND-WATER INTERFACE; INTERTIDAL; RIPARIAN ZONE	Assets	Structures	Revetment for CT1-CT6	Port Klang Channel	N/A	7.2	WM Engineering	WM Engineers		•				↑	↑↑	↔						↓				↑	
			Revetment for CT7-CT9		N/A	8.4				•				↑	↑↑	↔										↑	
			Revetment for Dry Bulk terminal I		N/A	7.2				•					↑↑	↔										↑	
			Revetment for Break Bulk terminal		N/A	7.2				•					↑↑	↔										↑	
			Revetment for Liquid Bulk terminal		N/A	7.2				•					↑↑	↔										↑	
			Revetment for Dry Bulk terminal II		N/A	7.2				•					↑↑	↔										↑	
TERRESTRIAL; HINTERLAND	Operational use or modification of land		Cargo handling	Westports Land Side Terminals	N/A	Facilities built on land platform of 7.2 to 8.0m (before settlements) - varies	WM Operations	Operations Manager			•		↑				↑	↑								↑	
			Parking						•								↑	↑									
			Container yard								•		↑				↑	↑								↑	
			Storage facilities (eg tank farm or other non container storage)				WM Engineering / Landed Clients	WM Engineers / Landed Clients			•						↑	↑									
			Pump stations and associated equipment to support tank farm and liquid product handling								•		↑				↑	↑									
			Offices				WM Various Depts. / Landed Clients	Dept. Managers / Landed Clients	•								↑	↑									
			Transport infrastructure (road, rail, etc)				PKA / WM	WM Engineering				•	↑				↑	↑								↑	
	Assets	Structures	Offices, buildings, storage				WM Engineering / Landed Clients	WM Engineers / Landed Clients	•				↑				↑	↑									
			Cargo handling equipment, cranes				WM M&R	M&R Engineers			•		↑				↑	↑								↑	
			Electricity sub-station								•						↑	↑							↑	↑	
		Physical systems and utilities	Drainage system				WM Engineering / Landed Clients	WM Engineers / Landed Clients			•				↑↑		↑	↑							↑	↑	
			Sewerage system							•							↑	↑									
			Water supply system							•							↑	↑									
			Electric supply system				WM M&R	M&R Engineers			•		↑				↑	↑									