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*Influence of Climate Change on the
Wave Climate in the Persian Gulf
and Consequences for Port Planning*



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Influence of Climate Change on the Wave Climate in the Persian Gulf and Consequences for Port Planning

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from
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Influence of Climate Change on the Wave Climate in the Persian Gulf and Consequences for Port Planning

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Vorwort des Herausgebers

Küstenregionen werden von den Folgen des Klimawandels besonders stark betroffen sein. Dies gilt für die durch den Anstieg des Meeresspiegels zu erwartenden Veränderungen aber auch für die sich aus dem Klimawandel ergebenden Veränderungen der Wellenbedingungen. Die Veränderungen des mittleren Meeresspiegels haben unter anderem direkte Auswirkungen auf den Hochwasserschutz und die Entwässerung des Hinterlands, während die Veränderungen der Wellenbedingungen den Sedimenttransport, die Erosion und die Ablagerungsgebiete an den Küsten beeinflussen sowie – was für Bauwerke und deren Auslegung von größerer Bedeutung ist – die hydrodynamischen Belastungen auf Ingenieurbauwerke in und für Häfen.

Dies ist der Ausgangspunkt für die Arbeit von Frau Dr.-Ing. Eghtesadi, die sich zum Ziel gesetzt hat, mögliche klimawandelbedingte langfristige Veränderungen der lokalen Wellenbedingungen (das Wellenklima) im Persischen Golf zu ermitteln und die sich daraus ergebenden Konsequenzen für die Hafenplanung aus Sicht des Küsteningenieurwesens zu bestimmen sowie eine Methodik zur Ermittlung entsprechender Anpassungsstrategien für Häfen zu entwickeln.

Die besondere Herausforderung für Frau Dr. Eghtesadi war die begrenzte Datenlage. Es gab / gibt nur wenige Messdaten zum Seegang für den Persischen Golf. Winddaten und Klimamodelle sind ebenfalls nur sehr begrenzt verfügbar und/oder haben eine sehr grobe zeitliche und räumliche Auflösung. Im Ergebnis der Datenrecherche wurde eine Kombination aus REGCM-Modelldaten mit einer vergleichsweise groben zeitlichen Auflösung von $\Delta t = 3$ h und einer räumlichen Auflösung von $\Delta s = 0,22^\circ$ für den Zeitraum zwischen 1979 und 2100 in Kombination mit Daten aus dem ERA-5-Windmodell, die den Zeitraum von 1950 bis zur Gegenwart mit einer zeitlichen Auflösung von $\Delta t = 1$ h und einer räumlichen Auflösung von $\Delta s = 0,25^\circ$ abdecken, identifiziert und für die Arbeit ausgewählt. Diese Kombination von Datensätzen macht es erforderlich, die zeitliche Auflösung der REGCM-Daten herunterzuskalieren oder die hochauflösenden ERA-5-Daten zeitlich in die Zukunft zu erweitern. Das Klimawandelsignal wird aus dem REGCM-Modell ermittelt. Die Erhöhung der zeitlichen Auflösung (temporal downscaling) von $\Delta t = 3$ h auf $\Delta t = 1$ h erfolgt statistisch auf der Grundlage der Ergebnisse des ERA-5-Windmodells.

Der Downscaling-Ansatz basiert auf der Fourier-Transformation der Datensätze mit unterschiedlichen zeitlichen Auflösungen und einer Zerlegung der gröber aufgelösten Zeitreihe, der Übertragung und dem Zusammensetzen mit einer höheren zeitlichen Auflösung. Im Ergebnis wird ein Datensatz „ERA5-Prognose“ oder „zukünftiges ERA5“ abgeleitet, der eine szenariobasierte Extrapolation der Winddaten mit hoher zeitlicher Auflösung ($\Delta t = 1$ h) umfasst. Dieser Datensatz deckt einen Zeitraum zwischen 1950 und 2100 ab.

Mit dem vorgenannten Datensatz werden dann die Veränderungen abgeschätzt und die Auswirkungen auf Hafenbauwerke ermittelt. Hier ergeben sich für einzelne Standorte teilweise dramatische Erhöhungen.

Es ist mir eine Freude, dass Frau Dr. Eghtesadi ihre Dissertationsschrift im Band 31 der Hamburger Wasserbauschriften veröffentlicht.

Hamburg, 30. September 2026

Peter Fröhle

Leiter des Instituts für Wasserbau der Technischen Universität Hamburg

Foreword by the editor

Coastal regions will be particularly heavily affected by the consequences of climate change. This applies to the expected changes due to sea-level rise, but also to the changes in wave conditions resulting from climate change. Changes in mean sea level have direct impacts on flood protection and hinterland drainage, among other things, while changes in wave conditions influence sediment transport, erosion, and deposition areas on coasts, and – which is of greater importance for structures and their design – the hydrodynamic loads on engineering structures in and for ports.

This is the starting point for the work of Dr.-Ing. Eghtesadi, which aims to determine potential long-term climate change-induced variations in local wave conditions (the wave climate) in the Persian Gulf, to assess the resulting consequences for port planning from a coastal engineering perspective, and to develop a methodology for determining appropriate adaptation strategies for ports.

The specific challenge for Dr. Eghtesadi was the limited availability of data. There were/are only a few measured wave data available for the Persian Gulf. Wind data and climate models are also only available to a very limited extent and/or have a very coarse temporal and spatial resolution. As a result of the data research, a combination of REGCM model data with a comparatively coarse temporal resolution of $\Delta t = 3$ h and a spatial resolution of $\Delta s = 0.22^\circ$ for the period between 1979 and 2100, combined with data from the ERA-5 wind model covering the period from 1950 to the present with a temporal resolution of $\Delta t = 1$ h and a spatial resolution of $\Delta s = 0.25^\circ$, was identified and selected for the work. This combination of datasets makes it necessary to downscale the temporal resolution of the REGCM data or to extend the high-resolution ERA-5 data temporally into the future. The climate change signal is derived from the REGCM model. The increase in temporal resolution (temporal downscaling) from $\Delta t = 3$ h to $\Delta t = 1$ h is carried out statistically based on the results of the ERA-5 wind model.

The downscaling approach is based on the Fourier transform of the datasets with different temporal resolutions and a decomposition of the coarser-resolution time series, its transfer, and reassembly at a higher temporal resolution. As a result, an "ERA5 forecast" or "future ERA5" dataset is derived, which comprises a scenario-based extrapolation of wind data with high temporal resolution ($\Delta t = 1$ h). This dataset covers a period between 1950 and 2100.

Using the aforementioned dataset, the changes are then estimated, and the impacts on port structures are determined. In this context, some specific locations show dramatic increases.

It is a pleasure for me that Dr. Eghtesadi is publishing her dissertation in Volume 31 of the Hamburg Water Engineering Publications (Hamburger Wasserbauschriften).

Hamburg, September 30, 2026

Peter Fröhle

Head of the Institute of River and Coastal Engineering, Hamburg University of Technology

Acknowledgment

“If I have seen further, it is by standing on the shoulders of giants.”

— Isaac Newton

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On a personal note, I owe a profound debt of gratitude to my family and friends. To my dear brothers, Mehdi and Mohammad: thank you for being my biggest supporters since childhood. You have always held a special place in my heart, and your belief in me has given me strength throughout the years. This journey was made even brighter by the arrival of three little lights Elena, Adrian, and Emily whose presence has brought immense joy and hope into these demanding years.

To my love, Moein, words can hardly express how deeply grateful I am to have had you by my side throughout this journey. This PhD has been one of the most challenging and demanding chapters of my life, and I know that I could not have walked through it in the same way without you. Thank you for your endless patience, understanding, and unwavering support, for listening to me when I was overwhelmed, calming me when the pressure became too much, and reminding me to keep going when I doubted myself. Your love, kindness, and quiet strength have carried me through some of the most difficult moments of this journey.

Finally, I dedicate this work to the loving memory of my mother. Although she is no longer with me, her love, strength, and spirit continue to guide and inspire me every day. Everything I have achieved carries a part of her with it.

Abstract

Influence of climate change on the wave climate in the Persian Gulf and consequences for port planning.

The impact of climate change on wave parameters as well as wave loading on coastal structures in the Persian Gulf is presented in this PhD research by simulating the wave conditions for the past (1979-2020) and future (2021-2100) periods.

The study focuses on five major ports along the entire Iranian coast of the Persian Gulf covering a wide range of input parameters in terms of the geographical characteristics of the study points. The regional climate model RegCM4.7 provides hindcast and forecast wind data with a 3-hour temporal resolution. Additionally, the ERA5 wind model is utilized, providing hindcast data with a 1-hour resolution. A novel downscaling method based on data processing in the frequency domain is proposed to generate future wind data with 1-hour time steps. The trend of change from past to future is obtained from the RegCM model and is then applied to the ERA5 model hindcast data to generate a high-resolution future dataset. The advantage of the proposed downscaling method is that, unlike statistical methods, it does not lose information from the original data and ensures that extreme events are not ignored.

Wave conditions at the study sites are simulated using the SWAN model for both historical and future periods. The wave-structure interaction is investigated by calculating the wave load for different return periods. Since the wave-structure interaction depends on the type of coastal structure, we limited our study to the typical structures mainly used at the study points, including rubble mound breakwaters and different types of vertical walls, as well as the drag and inertia forces exerted by waves on cylindrical piles. Our calculations show that an increase in wave loading of up to 50% could be expected, particularly in regions with deep or intermediate water levels.

Zusammenfassung

Einfluss des Klimawandels auf das Wellenklima im Persischen Golf und Konsequenzen für die Hafenplanung

Die Auswirkungen des Klimawandels auf die Wellenparameter sowie die Wellenbelastung der Küstenstrukturen im Persischen Golf werden in dieser Doktorarbeit durch die Simulation der Wellenbedingungen in der Vergangenheit (1979-2020) und in der Zukunft (2021-2100) dargestellt.

Die Studie konzentriert sich auf fünf große Häfen entlang der gesamten iranischen Küste des Persischen Golfs, die eine breite Palette von Eingangsparametern hinsichtlich der geografischen Merkmale der Untersuchungspunkte abdecken. Das regionale Klimamodell RegCM4.7 liefert Hindcast- und Prognosedaten für den Wind mit einer zeitlichen Auflösung von 3 Stunden. Wir haben auch das Windmodell ERA5 verwendet, das nur Hindcast-Winddaten mit einem Zeitschritt von 1 Stunde liefert. Ein neuartiges Downscaling-Verfahren, das auf der Datenverarbeitung im Frequenzbereich basiert, wird vorgeschlagen, um zukünftige Winddaten mit 1-Stunden-Zeitschritten zu erzeugen. Der Trend der Veränderung von der Vergangenheit zur Zukunft wird aus dem RegCM-Modell gewonnen und dann auf die Hindcast-Daten des ERA5-Modells angewendet, um einen hochauflösenden Datensatz für die Zukunft zu erzeugen. Der Vorteil der vorgeschlagenen Downscaling-Methode besteht darin, dass im Gegensatz zu statistischen Methoden die Informationen der ursprünglichen Daten nicht verloren gehen und sichergestellt wird, dass Extremereignisse nicht ignoriert werden.

Die Wellenbedingungen an den Untersuchungspunkten werden mit dem SWAN-Modell simuliert, wobei sowohl ERA5- als auch RegCM-Winddaten für vergangene und zukünftige Zeiträume verwendet werden. Die Interaktion zwischen Welle und Struktur wird durch die Berechnung der Wellenbelastung für verschiedene Wiederkehrperioden untersucht. Da die Wechselwirkung zwischen Welle und Struktur von der Art der Küstenstruktur abhängt, beschränken wir uns bei unserer Studie auf die typischen Strukturen, die an den untersuchten Punkten hauptsächlich verwendet werden, einschließlich Schüttsteinwellenbrechern und verschiedenen Arten von vertikalen Wänden sowie der Widerstands- und Trägheitskräfte, die durch Wellen auf zylindrische Pfähle verursacht werden. Unsere Berechnungen zeigen, dass eine Zunahme der Wellenbelastung von bis zu 50 % zu erwarten ist, insbesondere in Regionen mit tiefen oder mittleren Wasserständen.

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Chapter 1

Introduction

1.1 Climate change

Climate has been defined by the Intergovernmental Panel on Climate Change (IPCC) in terms of the mean as the average weather and its variation over a given period and region. Climate change is also defined as a significant change in the variability or the mean condition that lasts for decades or longer [1]. The concentration of the greenhouse gases in the atmosphere has increased remarkably especially in recent decades due to the Industrial Revolution in the early nineteenth century as well as the rapid development of industrial activities [2, 3]. Solar ultraviolet radiation with short wavelengths is absorbed by six greenhouse gases in the atmosphere including SF_6 , PFC_5 , HCF_5 , NOX , CH_4 , and CO_2 and its energy is reflected with long wavelengths. These waves do not exit from the atmosphere due to their low energy and heat up the atmosphere, which is the most significant effect of these gases [4]. This phenomenon is called global warming by the scientists [5]. IPCC has concluded that the climate system is warming based on observations of increases in global average air and ocean temperatures, melting snow and ice, and changes in average sea level. Studies show an increase in global combined land and ocean temperature of about 0.89°C over the period 1901-2012 and about 0.72°C over the period 1951-2012, if described by a linear trend [6].

Since there is a close relationship between the hydrological cycle and the climate system, any changes in the climate will also affect the parameters of the hydrological cycle [7, 8]. The concentration of greenhouse gases in the atmosphere not only affects the temperature of the atmosphere, but other climate variations such as precipitation, evaporation, and humidity are also affected by this trend, which together are included in the phenomenon of climate change [9].

Runoff, streamflow, groundwater, evaporation and transpiration, floods and droughts are all influenced by precipitation and temperature, which are the main climate parameters [10, 11, 12]. It is interesting that so far almost all GCM models predict an increase in the earth's temperature and a change in the rainfall pattern for all parts of the earth and all of them confirm the effect of global warming on climate change by 2100 [9, 13]. Sea level has also risen during the 20th century. The average rate of sea level rise between 1901 and 2010 was $1.7\text{mm}\text{y}^{-1}$ with a range of 1.5 to $1.9\text{mm}\text{y}^{-1}$, while this value was $3.2\text{mm}\text{y}^{-1}$ with a range of 2.8 to $3.6\text{mm}\text{y}^{-1}$ for the years between 1993 and 2010 [6]. Some changes in the oceans such as more frequent ocean heat

waves, warming and lower oxygen levels are obviously due to human influence as well [14, 15]. Both ocean ecosystems and the people who depend on them have been and will continue to be affected by these changes through the end of this century [16]. Assessing the future changes in temperature and precipitation and their effects on environmental features such as water resources, sea and lake levels, etc. are some important issues in climate change [17, 18]. In this context, there are several models to simulate climate variables, which will be explained later.

The Global Mean Surface Temperature (GMST) has been increasing since the late 19th century [19, 20, 21]. Most people assume that the global climate is more or less constant. However, the fact is that the global climate is changing, and these changes can be seen in historical periods of a few thousand or a few hundred years [22]. Climate change is a natural phenomenon that occurs on time scales of thousands of years, but it has also been observed on the scale of centuries or decades [23]. On the scale of thousands of years, glacial periods can be observed [24]. Factors that exacerbate climate change include: changes in the Earth's orbit, continental drift, and changes in reflected solar radiation [25, 26, 27]. Evidence from Quaternary geology shows that species have typically migrated in response to environmental changes. They also confirm that the climate change predicted for the future is enormous and will be an unprecedented process in geological history.

In this study, we investigate the effects of climate change on wave conditions in the Persian Gulf and the potential measures that need to be considered in the design or maintenance of coastal structures in ports.

1.2 Persian Gulf - geography and importance

The Persian Gulf (sometimes called the Arabian Gulf) is a semi-closed lunate gulf located in the southern part of Iran in the vicinity of Oman, the UAE, the KSA, Qatar, Bahrain, Kuwait and Iraq. Its area is about 237473 km^2 which makes it the third largest Gulf in the world. The Persian Gulf is connected to the Oman Sea and the Indian Ocean via the Strait of Hormuz and the Arabian Sea. The Shatt al-Arab river delta forms the northwest shoreline. The length of the Persian Gulf is 990 km and its width is 340 km at the widest part while at the strait of Hormuz is less than 55 km [28]. The average depth of the Persian Gulf is 35 m and there are some parts with depths of more than 100 m . The Persian Gulf is one of the largest habitats for marine organisms like corals and mammals as well as various fishes; therefore, protecting the environment and its ecosystem is a concern of the neighboring countries as well [29, 30, 31].

Waters are generally very shallow as illustrated in Fig 1.1. Water depth decreases slightly from the Strait of Hormuz in the northwest direction. In terms of physiography, most of the Iranian coastline is mountainous with frequent cliffs which affect the climate behavior in those areas (Fig. 1.2).

This Gulf and its coastal areas are the world's largest crude oil reservoir, and related industries dominate the region [32]. The Persian Gulf contains the largest offshore oilfield in the world. About 30% of the world's crude oil is supplied from the Persian Gulf, while the countries around the Persian Gulf have about two-thirds of the world crude oil and 35% of its natural gas reserves [33]. Therefore, investigation of the climate change in the Persian Gulf can be very useful in order to prevent the energy production of the whole world from being adversely affected.

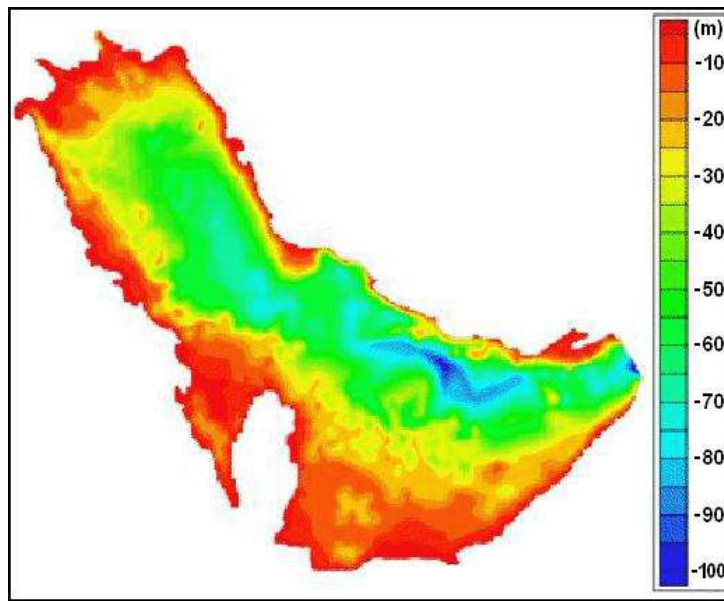


Figure 1.1: Depth of the Persian Gulf

It has to be noted however that there are coral reefs along the Persian Gulf coastline and atolls offshore which regardless of the severe climate conditions, can grow and reproduce. One can see the distribution of the coral reefs in the Persian Gulf In Fig. 1.3. They cause sheltered areas and decrease the wave height as well as the wave energy in those areas [30].

Due to the vastness of the Persian Gulf, wind and wave dynamics vary along its length. As a result, climate change could have different effects at different locations in the Gulf. Therefore, in this study, we limit our investigations to certain points of the Persian Gulf, which are the most important ports on the Iranian coastline, as listed below.

1.2.1 The most important ports on the Iranian coastline of the Persian Gulf

There are several ports in the Persian Gulf. Since our goal is to assess coastal climate change, we selected the major ports in the Iranian part of the Gulf. Lengeh, Rajaee, Bahonar, Asaluyeh and Bushehr are the case studies we worked on. Their coordinates as well as their depth are shown in Table 1.1 while their location in the Persian Gulf is shown in Fig 1.4. As it can be seen, the study ports are located at different positions in the Persian Gulf with a wide range of water depths (from 2.4m to $\approx 50m$), which gives us the opportunity to study the wave conditions for different sea states.

Lengeh port

This port is located in the west of Hormuzgan province, and it is a historical port that was the most important port in the Achaemenid Empire. Some factors like having a good connection



Figure 1.2: A satellite view of the Persian Gulf in the southern part of Iran

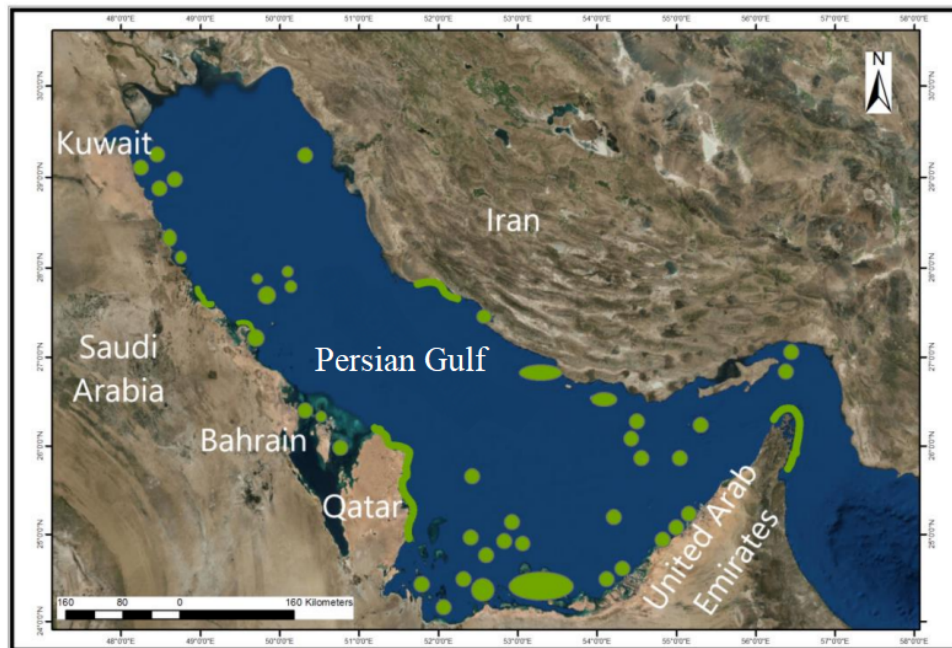


Figure 1.3: Abundance of coral reefs in the Persian Gulf [30]



Figure 1.4: Location of the ports to be studied in the Persian Gulf

Table 1.1: Coordinates and water depth of the ports to be studied

Name	Latitude	Longitude	Depth (m)
Lengeh	26.537	54.896	13.8
Rajae	27.079	56.075	9.9
Bahonar	27.110	56.205	12.0
Asaluye	27.460	52.590	49.3
Busher	29.009	50.814	2.4

with Iran's road network, proper geographical location and closeness to the Strait of Hormuz as well as the international waters, also short distance to the neighboring countries, and the large amount of export of oil and non-oil products and high loading and unloading of goods have contributed to this port being strategic and one of the most important Iranian ports in the south of Iran. The maximum length of ships that have called at this port is 185 meters. The maximum draught is 5.1 m while the maximum carrying capacity is 7680 t [34].

Rajae port

This port (also called Shahid Rajae) is an economic area which is located 23 km west of Bandar Abbas in the north of Qeshm Island and the Strait of Hormuz. Rajae covers roughly 50% of the marine trade affairs of Iran and transfers the goods to 80 famous international ports. It is an important connecting area which has an access to the Indian Ocean and the Persian Gulf via Iran to the Caspian Sea and then through Russian to Europe. So its location is in the north-south transit corridor, which is the most important corridor in the world. The maximum length of the vessels recorded to have entered this port is 366 meters. The maximum draught is 14.1 meters and the maximum Deadweight is 148558 t [34, 35].

Bahonar port

Bahonar (also called Shahid Bahonar) port plays a key role in the export of non-oil products. It is the third main port of Iran in terms of export and national and international transportation of passengers. Having a good connection to the open seas and short distance to free zones as well as islands and commercial ports has led it to become a unique location. This harbor has a special feature with a 10.2 m pond depth. The maximum length of the vessels recorded to have entered this terminal is 224.97 meters. The maximum draught is 25.5 meters while the maximum Deadweight is 23176 t [34].

Asaluye port

Asaluye port can be listed as a medium-size port located on the northwest coast of the Persian Gulf. It is about 100 km away from the South Pars gas field. Asaluye plays an important key role in the extraction of natural gas with the fourth aromatics plant, which is the largest aromatics

project in the world. This port provides facilities for handling LPG and liquid cargo. Around 11.4 million tons of cargo are handled there annually. The maximum length of vessels that have called at this port is 295m. The maximum draught is 10.4m and the maximum carrying capacity is 99094 t [34].

Bushehr port

This port is also one of the most important commercial ports and has a medium size in Iran, due to large loading and unloading of goods and oil and non-oil products. The maximum length of vessels calling at this port is 274 metres and the maximum capacity is about 50000 t. This port is located in the Soltani Estuary in the Bushehr Peninsula on the coast of the Persian Gulf. Much of the peninsula is considered shallow water and mudflats with varying depths of less than 5m. The tidal channel of the Soltani Estuary is the only deep navigable zone in the northeast of the Bushehr Peninsula [34].

1.3 General objectives and open questions

The objective of the current research is to develop a methodology to determine the adaptation strategies for ports to the consequences of climate change. We have analyzed the consequences of climate change on ports in the Persian Gulf, with a particular emphasis on changes in wave conditions and their impact on port planning, necessitating an investigation into extreme events.

To accomplish this aim, we have addressed the following questions:

i) How to assess the climate change?: In chapter 2 we present an overview of the methods used to describe the effects of climate change. Various climate change scenarios are discussed, and the one utilized in this study is presented, chosen based on two primary factors:

a) Which scenario covers the specific past and future time periods required for this study?

b) What spatial and temporal resolution is necessary to accurately forecast extreme events within the chosen scenario?

As we will discuss in this chapter, to achieve the required resolution within the study period, downscaling would be necessary to conduct the simulations to assess the wave conditions. Go-harnejad et al. (2020) [36], for instance, utilized a simple dynamical downscaling method to generate one-hour data from a monthly temporal resolution in their study, which examines the effect of climate change on wave energy in the Persian Gulf.

Similar downscaling methods based on statistical parameters have been employed in other studies, such as that by Kamranzad et al., who dedicated several papers to studying wave characteristics in the Persian Gulf:

The spatial and temporal wind and wave characteristics in the Persian Gulf were investigated based on local ECMWF wind data and numerically modeled wave characteristics for a 31-year period (2018) [37]. The wave energy has been investigated in the north part of the Persian Gulf by considering the wave energy spatial and temporal distribution for a long time period (2017) [38]. they have also used GCM3.1 to investigate the effects of climate change on the wind regime

in the Persian Gulf (2015) [39]. However, all of these studies focused on average wind and wave characteristics, as statistical downscaling methods do not provide all the necessary information to encompass extreme events which play a significant role in port design considerations. Therefore, in order to generate data with finer resolution, we have developed a novel downscaling method based on frequency domain analysis, which will be explained in detail in chapter 3. The proposed model ensures that all information is retained during the downscaling process and is even capable of reproducing extreme events that may be concealed in the original low-resolution data. Based on this method, we generated wind data with one-hour temporal resolution, which is sufficiently fine to study extreme events. The results of the downscaling method are analyzed and discussed in chapter 4.

2) How to model the wave?: After evaluating the effects of climate change on wind conditions, we established a model using SWAN (Simulating Wave Nearshore) to simulate waves in the key ports of the Persian Gulf. A two-level nesting approach is employed for the simulations to attain a fine enough mesh size at the target points (550 meters). The simulation strategy is described in chapter 5.

3) How to assess the changes in wave conditions and their consequences for port planning? Several studies have been published that examine the adaptation of port planning to climate change around the world. Becker et al. (2012) list the general challenges of such adaptation from the scientific, economic, political and social points of view [40]. General adaptation strategies and planning of ports and transport infrastructures are presented by [41]. Yang et al. (2018) assessed the risk and cost of port adaptation for 14 major container ports in China [42]. Chow et al. (2017) have also investigated the implications of climate change on port planning from an economic perspective [43]. Gallivan et al. (2009) conducted a comprehensive review of the impacts of climate change on various U.S. ports [44]. These studies show that while climate change appears to be having some impact on wave conditions around the world, the impact would be more severe on some coasts where the significant costs of adaptation would be worthwhile. However, separate climate change studies should be conducted for each region and port, taking into account all environmental and economic factors. Due to the importance of the Persian Gulf for global energy production and transportation, it seems necessary to assess the effects of climate change in this region. So far, the wind and wave dynamics as well as effects of climate change on the Persian Gulf have been studied from several perspectives:

The region of high wave energy in the Persian Gulf has been assessed with regard to wave energy for 40 years by Salimi et al. [45]. The results indicated that the northwestern part of the central Persian Gulf has the highest power level and average energy. It is also concluded that the energy in winter is at its highest level and double the level in autumn.

Mahmoodi et al. (2019) [46] have also used the ERA5 dataset to present the spatio-temporal distribution of annual, seasonal and monthly mean wave energy based on the significant height of combined wind waves and swell, mean wave direction and energy wave period for the years 2000 to 2017. The results of the analysis show that the level of wave energy potential is higher in the central parts of the region, especially in winter when it is influenced by the dominant winter Shamal wind. The rise in sea level and temperature due to climate change has been assessed by Hereher et al.(2020) [47]. For this purpose, the remotely sensed data on a decadal scale

were applied with consideration of coral reefs. The results show that more than 3100km^2 of the coastal region in this gulf is 1m above sea level and there is a positive trend of monthly SST in the western part of the Persian Gulf.

Mafi Gholami et al. (2019) [48] studied the social vulnerability of 20 districts in the northern part of the Persian Gulf to climate change under the RCP8.5 scenario. The result indicated that due to the predicted drought as well as sea level rise in this area, the social vulnerability in these areas is expected to increase. The results show a slow positive trend for the Persian Gulf during the last four decades, although the future trend shows the greatest warming in summer and the least warming in the autumn and winter in the region by 2100. They expect the mean annual SST to rise by about $2.2\text{ }^{\circ}\text{C}$ by the end of the century.

Noori et al. (2019) [49] investigated the sea surface temperature changes over the Persian Gulf and Gulf of Oman. Since the sea level temperature (SST) would change due to the impact of climate change, the driving forces have an effect at the regional scale. For this aim the SST during the last 40 years as well as until the end of the 21st century by applying a Proper Orthogonal Decomposition (POD) mode has been assessed.

The wind energy sustainability has been investigated due to the climate change impact in the Persian Gulf by Wang et al (2020) [50]. Three RCMs from CORDEX with daily resolution for a period of 20 years have been used for the present as well as the future. The present wind data has been compared with the ERA interim wind field in order to find the accuracy of the RCMs. In addition the wind power at turbine height has been calculated for the future and results indicated a considerable change in the mean annual wind power and the same future wind direction as the present direction. In 2013 [51] they used the wave numerical model SWAN and also the ECMWF wind field to generate the wave characteristics time series (1984-2008) in the Persian Gulf. The results showed the wave energy trends have both decadal and seasonal variability and there was a reduction in the wave power during the years between 1990 and 2000. They compared the wind speed as well as wave power variations and found that a small wind speed change can cause a large wave power variation. The wave power variation changes from the lowest value in summer to the highest value in winter due to seasonal fluctuation.

Goharnejad et al. (2013) [52] investigated the impact of climate change on the sea level rise of the southern coastal area of Iran. They have used data from two scenarios of the CGCM3 one of the General circulation Models. They have evaluated a significant sea level rise due to climate change effects.

All of the studies mentioned above focused on investigating the average conditions of wave characteristics. However, to propose a comprehensive study that incorporates considerations of climate change in the design of coastal structures, one must consider the following points:

a) How would extreme events change due to climate change?

b) What consequences do the extreme changes have on the ports?.

Taebi et al. (2008) [53] simulated and validated the wave climate in the Persian Gulf and the Gulf of Oman. They used ECMWF data for the wind field and simulated the wave for 1992-2002 with the Mike 21 spectral model. They also used Extreme Value Analysis to calculate the wave characteristic for different return periods and the significance of storms in each direction. The results showed a good agreement between Iranian seas wave modeling (ISWN) results and validation data. They have assessed only 11 years with low accuracy in spatial (1.125° by 1.125°) and temporal resolution of 6 hours.

In this work, besides using higher temporal and spatial resolution which answers the first question, to address the second question, we study the wave-structure interactions and focus on certain ports that are more important from the economic and energy point of view.

Wave-structure interaction could also be studied in two different aspects:

The hydraulic response of the wave such as wave run-up, overtopping, etc. and the load imposed by the wave on the coastal structure.

Since there is no such study in the Persian Gulf, we dedicate the last part of this work to finding the wave loading on typical coastal structures which are used in the study points.

For this purpose, various types of wave loading are calculated for a broad range of return periods, ranging from 1 to 200 years, based on both forecast and hindcast wave data. Based on the typical coastal structures along the northern coast of the Persian Gulf, our focus was on analyzing wave loads on various breakwaters and vertical walls as well as drag and inertia forces acting on cylindrical piles. The results of such investigation are discussed in the chapter 6 and can be used as a guideline for the design and maintenance of the coastal structures.

Chapter 2

Climate change models

2.1 Climate change scenarios

Projections of greenhouse gas emissions vary widely, depending on both socio-economic development and climate policy [54]. Based on the latest report of the IPCC, the Earth's climate is obviously changing in every region and throughout the climate system and most changes are unprecedented in thousands, if not hundreds of thousands of years and some changes such as the ongoing sea level rise are irreversible for hundreds to thousands of years. Since projecting regional climate as affected by climate change is difficult, the best alternative method is to define possible future potentials under climate scenarios [55].

The emission of greenhouse gases is determined using various driving forces. The impact of different driving forces on the emissions results are described by different methods with different uncertainties. Each method and its corresponding uncertainty is represented as a climate change scenario. The purpose of using scenarios is to analyze the situations with uncertain outcomes. It is not intended to predict the future by means of these scenarios. Instead, the scenarios are employed to evaluate the stability of decisions or options under a wide range of possible futures by considering uncertainties and alternative futures. In climate change research, different aspects of the future are created to study the possible results of anthropogenic climate change. The climate scenarios describe the trajectories of such aspects which are acceptable and likely to be true. They characterize a lot of driving forces such as processes, impacts and possible responses that are of high importance in climate change analyses [56]

2.1.1 SRES scenarios

The emission scenarios were published by the IPCC in 1992 to analyze possible climate change and serve as a basis for General Circulation Models to develop climate change scenarios [5]. The so-called IS92 scenarios were the first global scenarios to estimate all greenhouse gas emissions. Since then, the understanding of potential future greenhouse gas emissions and climate change has changed considerably, and the IPCC has introduced different scenarios based on new knowledge and assumptions. In the year 2000, a new set called SRES (Special Report on Emissions Scenarios) was developed, which covers a major set of driving forces of future

emissions. Forty scenarios in four main categories (A1, A2, B1, B2) for the future of the world's climate have been proposed [8, 9, 57] Technical terms used in the SRES scenarios are as follows:

Storyline: Indeed, a storyline is an explanation of a scenario or (family of scenarios) used to highlight the dynamics and the main scenario characteristics and their relationships.

Scenario: Probable future events have been projected based on a quantified storyline and obvious logic.

Scenario family: One or more scenarios that have the same demographic, economic, politico-societal, and technological storyline.

The four storylines are based on the amount of greenhouse gas and aerosol emissions in the Earth's atmosphere until the end of this century; each includes different issues caused by human activities, such as economic, social, political, technological, demographic, and environmental developments [4]). Every scenario storyline projects the emission of these gases differently. Fig 2.1 shows the four IPCC SRES scenario storylines. A brief description of the four scenarios is given in the following:

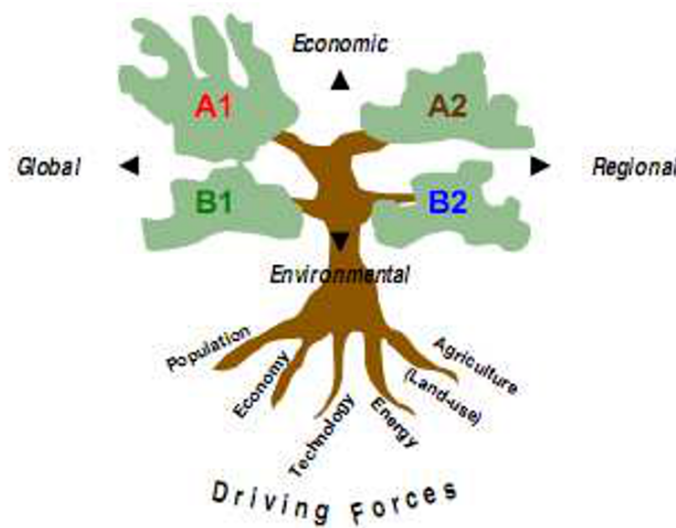


Figure 2.1: A diagram which shows the four IPCC SRES storylines [57]

A1 storyline and scenario family: In this scenario family a rapid growth in the economy is assumed. Population growth will continue until mid-century and then decline, along with the rapid growth of technology by the end of the century. In this category, it is also expected that the world will move towards globalization, capacity development, and the promotion of culture and economy, as well as a reduction in the substantial difference in per capita income worldwide. This family includes three scenario groups. The A1FI group scenarios assume the continued use of fossil fuels. In the A1T group scenarios, the non-use of fossil fuels is assumed. The A1B

group assumes a balance between the use of fossil fuels and new energy sources [4].

A2 storyline and scenario family : In this family, a heterogeneous world that relies on maintaining regional values is projected, while development patterns will move with slow progress, and the growth of economic patterns will be region-based [4].

B1 storyline and scenario family: The basis of this family of scenarios is globalization and global convergence. The population growth will be maximized until the middle of the century, like the A1 group, and then there will be a decline along with rapid technology development. A growing economic trend with increasing environmental protection technologies is projected by the end of the century, and the critical response to economic, social, and environmental sustainability with the development of social equality has been emphasized [4].

B2 storyline and scenario family: This family emphasizes a world based on regional and local values and finding appropriate solutions for economic, social, and environmental problems. In this family, the world's population will grow at a lower rate than the A2 scenario group projections. The average economic growth and technological changes are less than the projections in the B1 scenario groups. It is significant that environmental sustainability with the development of social equality has been considered [4].

IPCC has emphasized the A2 and B2 scenarios more than other scenarios; the reason for this can be explained by considering that in the A2 and B2 scenarios, the changes in climate variables are clearer on regional scales in comparison with other scenarios.

2.1.2 RCP scenarios

The Representative Concentration Pathway (RCP) is a pathway of greenhouse gas concentrations (not emissions) developed by the IPCC to replace the previous SRES scenarios. Four pathways were used for climate modeling and research for the IPCC's Fifth Assessment Report (AR5) in 2014 [56]. Unlike the SRES scenarios, these scenarios were developed independently by individual research groups rather than by the IPCC. The RCPs represent different development pathways of concentrations of greenhouse gases, aerosols and associated emissions. They were produced using coupled energy-economy-climate-land-use models (called Integrated Assessment Models) and form consistent scenarios of future greenhouse gas emissions. Based on the RCPs, new projections of potential climate change in the 21st century and beyond were calculated using global climate models. The RCPs represent a broad range of climate outcomes, based on a literature review, and are neither forecasts nor policy recommendations. The RCPs consist of a strict mitigation scenario (RCP2.6), two medium scenarios (RCP4.5 and RCP6.0) and a very high GHG emissions scenario (RCP8.5) [58]. Scenarios with no additional mitigation actions ("baseline scenarios") result in pathways between RCP6.0 and RCP8.5. Fig. 2.2 shows a comparison of the old scenarios (IS92a, SRES) with the RCP scenarios [59]. This figure shows the change in total anthropogenic radiative forcing ('radiative forcing' RF in W/m^2) compared to the pre-industrial value around 1765.

RCP2.6 is representative of a set of scenarios that have the goal of keeping global warming

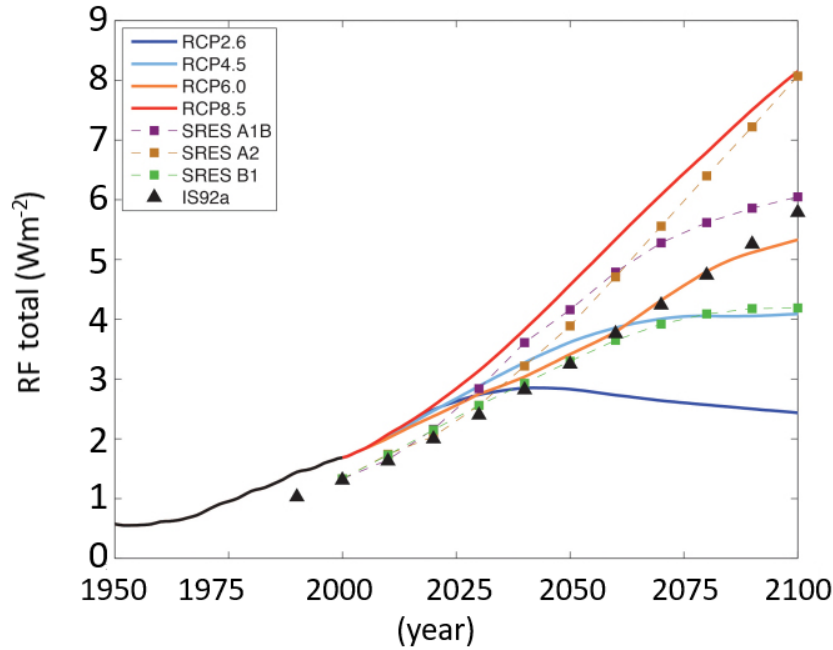


Figure 2.2: Comparison of the old scenarios (IS92a, SRES) with the RCP scenarios: Historical (for the 20th century) and projected (for the 21st century) [59].

likely below $2^{\circ}C$ above pre-industrial temperatures. There are several pieces of evidence for RCPs that suggest a strong consistent, near linear relation between the projected global change of temperature and cumulative CO_2 emissions by 2100. (Synthesis Report 2021) Table 2.1 shows a brief description of the four RCP scenario sets [60]. The socio-economic scenarios calculated

Table 2.1: Comparison between the four RCP scenario sets

Scenario	Description
RCP2.6	Peak in radiative forcing at $\approx 3W/m^2$ before 2100 and then decline to $2.6W/m^2$ by 2100
RCP4.5	Stabilization without overshoot pathway to $4.5W/m^2$ at stabilization after 2100
RCP6	Stabilization without overshoot pathway to $6W/m^2$ at stabilization after 2100
RCP8.5	Rising radiative forcing pathway leading to $8.5W/m^2$ by 2100

according to each radiative forcing take into account population growth, gross national product, energy consumption, and other factors. For example, an increase in world population to 12 billion by 2100 makes the RCP8.5 scenario likely, and primary energy consumption would have to be three times higher than today. Nine billion people by the end of the century would potentially lead to the RCP2.6 scenario. There are also differences in the energy mix, with a

very low share of oil in RCP2.6 and a very high share of coal of almost 50% in RCP8.5. Carbon dioxide emissions increase from nearly 10GtC/year today to nearly 30GtC/year by the end of the century under RCP8.5, but fall to zero around 2080 under RCP2.6 [61]. In our study we use RCP8.5 scenarios in order to investigate the most extreme future conditions.

2.2 General Circulation Models (GCM)

In order to investigate the response of a climate system to the different phenomena with the aim of climate prediction on seasonal to decadal time scales, or to project the future climate over the coming century or beyond, the primary available tools are the climate models. General Circulation Models (GCM) are three-dimensional numerical models which have been developed based on various climate scenarios in order to simulate the effects of greenhouse gases on the Earth's present climate, and they can project future climate changes [7]. The GCM models simulate the interaction between the soil, atmosphere, and oceans by solving the continuity equations of fluid dynamics on discrete spatial and temporal scales [62]. They are complicated numerical models based on physical rules which simulate mathematical relations among the changes and movement of the atmosphere and the hydrosphere in a three-dimensional network on the Earth's surface, as well as heat exchange and interaction between ice, oceans, and land [63, 56]. The equations used in GCMs are divided into two main categories: energy and momentum exchange equations, and the conservation of mass and water vapor. The atmosphere has been divided into a network of volume elements, and then in each of the volume elements, the following equations are solved [64, 65]:

1) The equation of conservation of energy: according to this equation, the force equals the increase of internal potential energy plus the work done.

2) The conservation of momentum equation: In this equation, the energy is mass times the acceleration.

3) The mass conservation equation: This equation states that the total density multiplied by the wind speed (equal-mass) is zero in all three dimensions.

4) The equation of the perfect gas law: According to this law, the product of pressure and volume equals the gas constant times the absolute temperature.

In general, the global climate models include two categories: AGCM models that consider the interaction of the atmosphere, and OGCM models in which the interaction of the oceans is considered [66, 67]. The General Circulation Models usually are combinations of the two above groups and contain AOGCM models [68].

Based on IPCC reports, the General Circulation Models use three-dimensional networking on a large scale on the Earth in order to study climate. Over 40 organizations in the world have produced and developed GCM models up to now. These models are different in the size of the network in the ocean and the Earth, the number of layers, CO_2 concentration and various applications that are entirely explained on the IPCC website [69]. The results of model outputs

have been collected by the Data Distribution Center (DDC) monthly which are freely available [70].

The spatial scales of these models are 250-600 km on the Earth's surface and 10-20 vertical layers in the atmosphere. Fig. 2.3 shows this meshing schematically. The large scale network simulation on the Earth's surface has decreased the accuracy of climate change studies for the future periods, however the GCM models have a good precision at oceanic and continental scales and simulate large-scale complex global climate system properties well. This point is one of the most significant causes of uncertainty in climate change studies based on GCMs. Another reason for the rise of uncertainty in these studies is the various feedback mechanisms in different methods. Hence, one GCM model with the same input data could lead to different results because of uncertainties in the processes and the feedbacks of the default model [7]. Hence, downscaling methods could be used in order to increase the spatial resolution of these models and convert their outputs to surface variables at the scale of the case study basin. Employing these methods leads to the development of Regional Climate Models (RCM).

There are two different categories in downscaling:

1. Dynamical downscaling: This downscaling approach uses numerical methods with higher resolution in different ways. In fact, this method comprises perching the fine spatial resolution of the model onto the form of the GCM coarse spatial resolution. Therefore, they perform the same simulations as GCMs but in higher resolution. The weak point of this method is that the computational effort of such models is equal to the GCM model analysis. They need the limited area models (LAMs) or the regional climate models (RCMs). The higher resolution outputs come from the use of large scale and lateral boundary conditions from GCMs with $\approx 0.5^\circ$ latitude and longitude scale [71].

2. Statistical method: In this technique, the observed changes in the case study surface variables at a regional scale have been calculated as a function of the statistical characteristics of the large-scale climate variables. After defining the appropriate function, the large-scale climate variables are the input data and the surface variable will be the result [72]. The Weakness in the extrapolation is the flaw of this method and also considering the point that the model parameters will be constant in the future conditions, the flexibility of the models will be decreased a lot. Compared to dynamic downscaling, the statistical approach is simpler and more flexible [73].

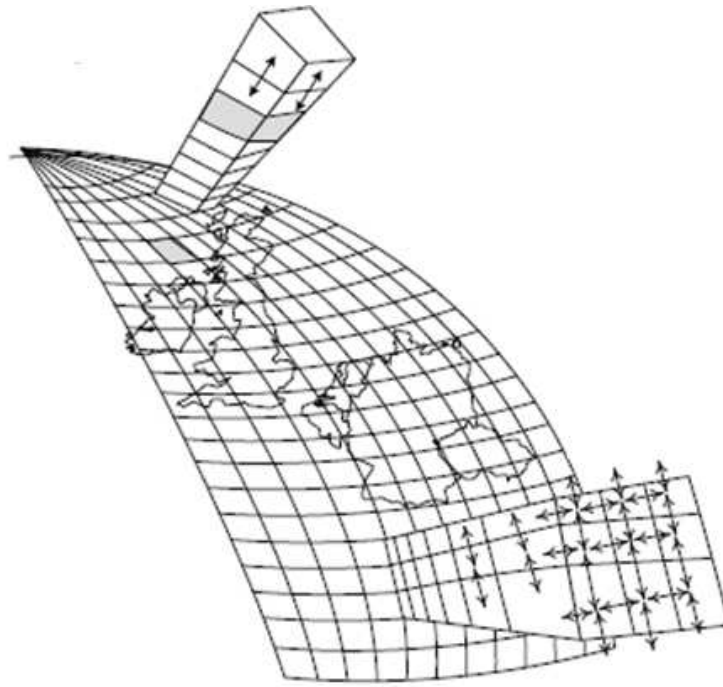


Figure 2.3: Meshing of GCM models

2.3 Regional Climate models (RCM)

As mentioned above, RCMs are based on an integration with a GCM to produce output on some case studies. In fact, RCMs are downscaled versions of GCMs with the purpose of having better resolution and finer sub-grids. RCMs were initiated in the late 1980s and have experienced a tremendous boom in the last three decades [74]. The concept behind this downscaling technique is that the GCM can represent the response of the global circulation to large-scale forcings such as greenhouse gases or variations in solar irradiance, while the RCM can downscale these large-scale data in space and time by accounting for the effects of forcings that occur at scales below the GCM grid scale due to complex landscape topography, land cover, inland waters and coastlines, and mesoscale dynamical processes [75]. Today, there is a wide range of RCMs around the world, used by large and diverse communities for a wide range of users for different aspects of research, such as climate change simulation.

2.3.1 CORDEX CORE Simulations

The World Climate Research Program (WCRP) considers regional downscaling as both an important research topic and an opportunity to involve a wider community of climate scientists in its activities [76]. The Coordinated Regional Climate Downscaling Experiment (CORDEX) has provided a facilitator to accomplish this aim [77]. The key concepts of the CORDEX framework are outlined: provide a high resolution of RCM data, provide a basis for investigation into extreme event predictions for all major populated areas of the world, and use a set of models for future studies, such as the effect of climate change at different levels of global warming

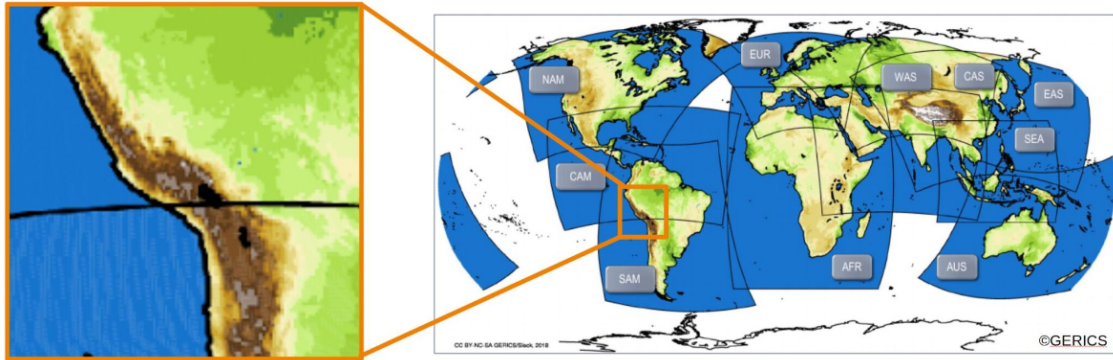


Figure 2.4: CORDEX CORE model domains used in the simulations [80].

+1.5°C or +2°C. It will be progressively expanded with the application of more models and experiments.

The RCMs which currently provide input to the CORDEX CORE framework simulate nine areas with a horizontal resolution of 0.22° (about 25 km) which is shown in the following Fig. 2.4 [78, 79]. We used the data from the downscaling of South Asia (WAS), whose CORDEX domain is shown in Fig. 2.5.

For our study we should choose an RCM that covers our area with high resolution. Since CORDEX CORE includes simulations for South Asia, the data is at 0.22° spatial resolution, and some parameters are available on a 3-hourly time step, we chose the RegCM 4.7 model and were able to download the required data from the Earth System Grid Federation (ESGF), which supports a worldwide system of data centers providing access to the world's largest archive of climate model data [81]. The data used are from UAS and VAS which are the x and y components of the wind provided at 10m height from 1979-2100. On the other hand, our purpose is to investigate the impact of climate change in terms of a high temperature increase; therefore, we have selected the RCP8.5 scenarios and, with this trend, the high ECS, backup: MIROC-MIROC5 driving model. The Equilibrium Climate Sensitivity (ECS) is the expected increase in temperature over the long term that could be the equilibrium global mean near-surface air temperature [82, 83]. Equilibrium climate sensitivity is probably in the range of 1.5°C to 4.5°C (high confidence), extremely unlikely at less than 1°C (high confidence) and very unlikely at more than 6°C (medium confidence) [6].

2.3.2 REGCM4.7

The RegCM is a regional climate model that has been developed over many years and has a large community of model users. RegCM, initially produced at the National Center for Atmospheric Research (NCAR), is supervised by the Earth System Physics (ESP) Division of the ICTP. It has improved from the first version that was created in 1989 to versions which were released later in 1993 (REGCM2), 1999 (REGCM2.5), 2006 (REGCM3), 2010 (REGCM4.0), 2011 (REGCM4.1), 2014 (REGCM4.5) and finally in 2017 (REGCM4.7) [84, 85, 86]. This model is the first regional model to simulate long-term regional climate projections [87]. RegCM4 contains

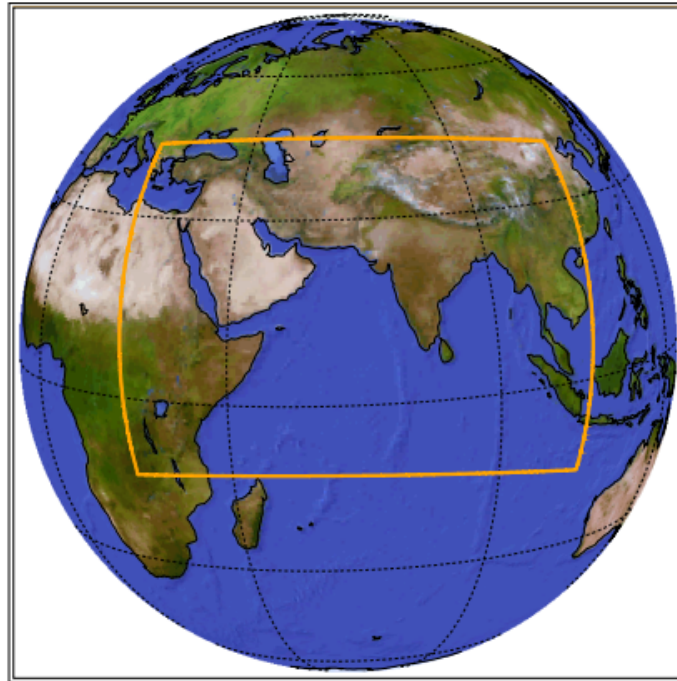


Figure 2.5: South Asia domain of the CORDEX CORE simulations called WAS [80].

important structural and open-source code pre- and post-processing program upgrades, along with the addition of some new physical parameters, which make the model more flexible and easy to use; it could be used for different studies like climate forecasting in various parts of the world [88]. The Regional Climate Research NETwork (RegCNET) supports RegCM through the Earth System Physics Department of the Abdus Salam International Centre for Theoretical Physics (ICTP) [89]. The extension of advanced research in developing countries is one of the important goals of the ICTP. As of RegCM4.5, it could be applied to a non-hydrostatic dynamic core and has a horizontal resolution of about a few kilometers.

Several groups have used RegCM for their climate change studies in the South Asia region. These studies mainly include the investigation of the effects of climate change on precipitation, air temperature, wind and storm dynamics, and wave flooding projections [90] - [91].

2.4 ERA5 wind model

As mentioned in the previous section, RegCM4.7 provides wind data with a 3-hour temporal resolution. Although it offers a better resolution than its previous versions, it is still not enough to make a proper study of the influence of climate change on the wave conditions considering the wind dynamics in the Persian Gulf. Therefore we are interested in using a wind model which has the following properties:

- It should have a higher temporal resolution.
- A good agreement with the actual measurements is also required.

Considering these two factors we chose the ERA5 wind model.

ERA5 produced by the Copernicus Climate Change Service (C3S) at ECMWF is a fifth generation atmospheric reanalysis of the global climate which covers the period from January 1950 to the present [92, 93]. This model provides wind data with one-hour resolution and has a 30-km grid size and by discretizing the atmosphere into 137 levels from the surface up to a height of 80 km, it provides hourly estimates of a vast number of atmospheric, land and oceanic climate variables. ERA5 improves the characterization and understanding of the main global coastal low-level jet (CLLJ) systems because of its finer resolution (horizontal and vertical) and hourly output. ERA5 depicts an improvement in showing the wind speed and temperature vertical profiles within the boundary layer in CLLJ regions. ERA5 displays larger CLLJ frequencies of events and larger wind speed severity in comparison to previous reanalyses. The Max-Planck Institute for Meteorology releases a useful open-source software, which includes many operators to process climate and future data, called CDO (Climate Data Operator) [94]. They cover basic data selection tools, spatial interpolation, and statistical and arithmetic functions. The u_{10} and v_{10} for the Persian Gulf from 1979–2021 have been downloaded with a spatial and temporal resolution of 0.25 by 0.25 and 1 hour, respectively.

Chapter 3

Downscaling method

As mentioned in Chapter 1, we utilize the following models in order to investigate wave conditions:

i) The REGCM model, which is a climate-change-based model. It provides both hindcast and forecast wind data with a 3-hour temporal resolution.

ii) The ERA5 model, which provides only hindcast data with a 1-hour temporal resolution. It should be noted that the ERA5 data are constructed using actual measurements and are therefore closer to reality than the REGCM model outputs. However, to evaluate the effect of climate change in the future, we need to use a climate change model such as REGCM. On the other hand, the 3-hour temporal resolution of the REGCM model seems to be insufficient for our purpose. As evidence, the consideration of wind data at several study points in the Persian Gulf showed that the wind direction as well as its speed vary significantly (several times a day). Therefore, it is expected that a lot of information might have been lost in a data set with a 3-hour time step. To ensure we don't miss any information in our simulations, our goal is to have a 1-hour time resolution as the input to the simulations.

Considering all of the above, the following strategy is used to generate future wind data:

The absolute values of wind speed and wind direction as well as their temporal resolution are obtained from the ERA5 model, but the overall change from past to future is extracted from the REGCM model.

Since the origin of the generated data is the ERA5 wind, in this thesis we call the generated data "ERA5 data for future", keeping in mind that the ERA5 model itself doesn't provide future data. As mentioned in Chapter 2, we avoided using averages to downscale the wind data. Although it would be simpler and faster, considering the different temporal resolutions, a lot of data could be lost using this method. In other words, by averaging the wind speed and comparing future and past values to find the scaling factor, the dynamics of the wind change are lost. It could also lead to missing potential storms hidden between the time steps, especially in the case of a 3-hour time resolution. To overcome this limitation, we used an alternative method, which is to analyze the wind data in the frequency domain by taking the Fourier transform of the original data. The advantage of looking at the wind data in the frequency domain is that the Fourier transform of the data is much smoother than the original data in the time domain. Although there are fast

variations in time, since the overall pattern of the wind repeats with certain periods, its frequency domain representation would be simpler and easier to deal with. It is worth noting that the more data points there are in time, the smoother and more accurate the Fourier transform of the data becomes. Therefore, we always look at the entire data set when using frequency domain analysis. In the following section, we explain the basic idea behind the proposed method.

3.1 Concept of system and frequency response

Let's assume we have a system $S(x)$ with $x(t)$ as input and $y(t)$ as output which are time varying functions:

$$y(t) = S(x(t)) \quad (3.1)$$

We define $h(t)$ as the output of the system when the Dirac delta function is the input:

$$h(t) = S(\delta(t)) \quad (3.2)$$

where the Dirac delta function is defined as follows:

$$\begin{aligned} \delta(t) &= 0, & \text{for } t &\neq 0 \\ \int_{-\infty}^{\infty} \delta(t) dt &= 1 \end{aligned} \quad (3.3)$$

We show the Fourier transform of $h(t)$ as $H(f)$ where f stands for frequency, and call it the frequency response of the system.

The Fourier transform of a function $x(t)$ is shown by $X(f)$ and defined as follows [95]:

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi ft} dt, \quad (3.4)$$

which is a complex function and describes the function $x(t)$ in the frequency domain. In other words, it shows the contribution of different frequency components in constructing the original function.

We will show below that if the system S is linear and time invariant (LTI), its frequency response can be used to find the output of the system for any given input [96]. Linearity of the system means that superposition can be used to find the output of the system, which means:

$$S(x_1(t) + x_2(t)) = S(x_1(t)) + S(x_2(t)). \quad (3.5)$$

It can be easily concluded that for a linear system S and a constant parameter a :

$$S(ax(t)) = aS(x(t)). \quad (3.6)$$

It is well known from calculus that the Dirac delta function is an identity element for the convolution operation [97]. In other words, the convolution of any function $x(t)$ with $\delta(t)$ results in

the same $x(t)$ function:

$$x(t) = x(t) * \delta(t). \quad (3.7)$$

where the convolution of two functions is defined as follows:

$$(f * g)(t) := \int_{-\infty}^{\infty} f(\tau)g(t - \tau)d\tau. \quad (3.8)$$

Therefore, for a linear and time-invariant system S , its response to the input $x(t)$ can be found as follows:

$$\begin{aligned} y(t) &= S(x(t)) = S(x(t) * \delta(t)) = S\left(\int_{-\infty}^{\infty} x(\tau)\delta(t - \tau)d\tau\right) \xrightarrow{\text{linearity}} \\ y(t) &= \int_{-\infty}^{\infty} S(x(\tau)\delta(t - \tau))d\tau = \int_{-\infty}^{\infty} x(\tau)S(\delta(t - \tau))d\tau = x(t) * S(\delta(t)). \end{aligned} \quad (3.9)$$

This means that the response of the system to any input can be found by convolving of the input with the response of the system to the Dirac delta function $h(t)$ defined above.

$$S(x(t)) = x(t) * S(\delta(t)) = x(t) * h(t). \quad (3.10)$$

On the other hand, from the definition of the Fourier transform, it is also known that the convolution operation in the time domain turns into algebraic multiplication in the frequency domain [96]. That means the Fourier transform of a convolution is the product of the Fourier transforms of the functions involved:

$$\mathcal{F}(f(t) * g(t)) = \mathcal{F}(f(t)) \times \mathcal{F}(g(t)). \quad (3.11)$$

Where $\mathcal{F}(f(t))$ is the Fourier transform of $f(t)$. for the sake of simplicity, we show the Fourier transform of a function by its capital letter: $X(f)$ is the Fourier transform of $x(t)$.

So, the response of a system to any given input in the frequency domain can be found by multiplying the input signal by the frequency response of the system $H(f)$:

$$Y(f) = X(f) \times H(f). \quad (3.12)$$

The above equation tells us that knowing the frequency response of a system is sufficient to find the output of the system for any given input data. On the other hand, the frequency response of any system can be found if we only know the output for a given input. To explain better, let's assume that the response of a system to $x(t)$ is $y(t)$, then we have:

$$Y(f) = X(f) \times H(f). \quad (3.13)$$

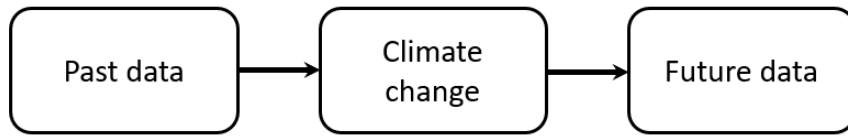
Therefore, the frequency response of the system can be calculated as follows:

$$H(f) = \frac{Y(f)}{X(f)}. \quad (3.14)$$

In conclusion, for a linear and time-invariant system, just one pair of input and output signals gives us all the information about the system and can be used to find the response of the system to any given input signal.

3.2 Using a systematic approach for climate change

The main idea is that we consider the climate change as a linear and time-invariant system:



We must note that the use of the term linearity here is different from its common use in climate change studies, where climate change is known as a nonlinear phenomenon (not system of course). From this point of view, climate change is a system whose input could be meteorological data from the past or present, and its output is the same data for the future after applying the effects of climate change. For example, it gets the present wind data at a certain point and gives a prediction of wind at the same point for the future. Linearity here means that if, for example, the present wind increases by 10%, climate change will produce the same pattern for future wind, just with a 10% increase. Although it cannot be claimed that this is a 100% accurate assumption, considering the dynamics of the wind in the Persian Gulf, where wind speed is usually low and extreme events are rare, the effects of climate change are very close to linear.

In order to find the frequency response of the climate change as a system, we need to know the output for a certain input as explained in the previous section. Since the REGCM model provides the hindcast and forecast wind data as a climate change-based model, we use it to find the frequency response of the climate change. We then use this frequency response to find the forecast data for ERA5 wind:

$$H_{\text{climate change}}(f) = \frac{Future_{REGCM}(f)}{Past_{REGCM}(f)}$$

$$Future_{ERA}(f) = Past_{ERA}(f) \times H_{\text{climate change}}(f) \quad (3.15)$$

We have to take into account that the effect of climate change and consequently the frequency response may vary from one point to another, especially for a large area such as the Persian Gulf; therefore, it has to be calculated for each point separately. Therefore, it has to be calculated for each point separately. However, the grid points of the REGCM and ERA5 models are not at the same locations. Fig 3.1 shows these points on the map of the Persian Gulf. As can be seen, not only do the points not match, but because the two models provide data in two different coordinate systems, one set of grid points lies on straight lines, while the other model's grid

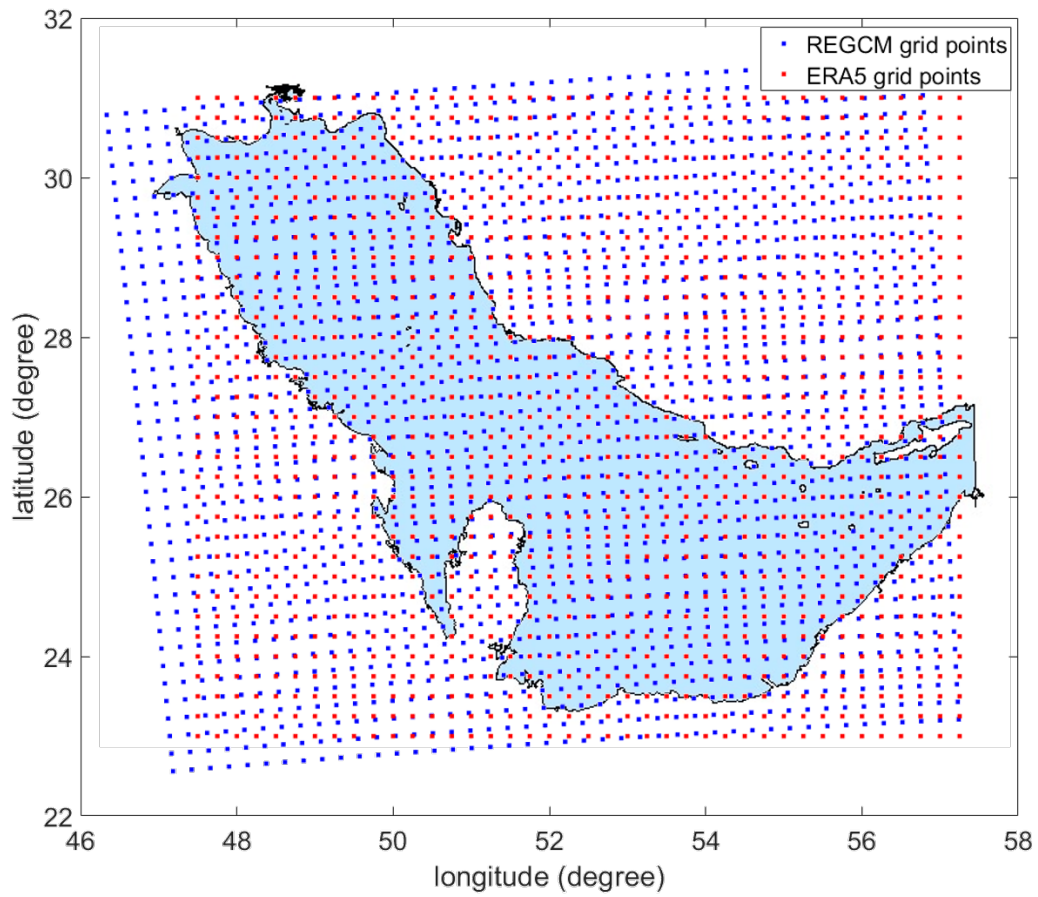


Figure 3.1: The grid points of ERA5 (spherical) and REGCM (cartesian) models in the Persian Gulf.

points form a curved line. This, of course, results from mapping the curved surface of the Earth as a sphere onto a flat 2D plane. Therefore, in order to generate the future wind of the ERA5 model, we have to follow the steps listed below:

a) Taking the Fourier transform of the REGCM wind data for past and future and for all the grid points (1677 points correspond to a 43×39 grid).

b) Determining the frequency response of all points. This can be done by dividing the Fourier transform of the future wind by the Fourier transform of the past data. Note that since the past and future wind data sets have different numbers of time samples (42 years vs. 80 years), their Fourier transforms also have different frequency samples. To overcome this limitation, we divided the future period (2021 - 2100) into two 42-year sub-periods of the same length as the past period (1979 - 2020). These two periods would be (2021-2062) and (2059-2100); we then found the frequency response of each sub-period separately. This approach not only solves the problem of unequal frequency samples, but also makes the entire calculation more accurate because it considers the long-term and short-term effects of climate change separately. In other words, we have two frequency responses to assess the climate change effect for the first and second half of the century, which are not necessarily the same. Of course, as can be seen, we have four years of overlap between the two subperiods (2059-2062). For these years, we have used the average of the two frequency responses.

c) Now that we have the frequency response for the REGCM grid points, we need to calculate it for the ERA5 grid points (1254 points correspond to a 38×33 grid). For this, we used a simple first-order interpolation as follows:

Let's assume that the frequency response for a certain point P is H and unknown. This point is surrounded by four points whose frequency responses are known from (b). H can be found by taking a weighted average of the known frequency responses, where the contribution of each surrounding point is inversely proportional to its distance from the target point P :

$$H = \left(\frac{H_1}{d_1} + \frac{H_2}{d_2} + \frac{H_3}{d_3} + \frac{H_4}{d_4} \right) \times \left(\frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3} + \frac{1}{d_4} \right)^{-1} \quad (3.16)$$

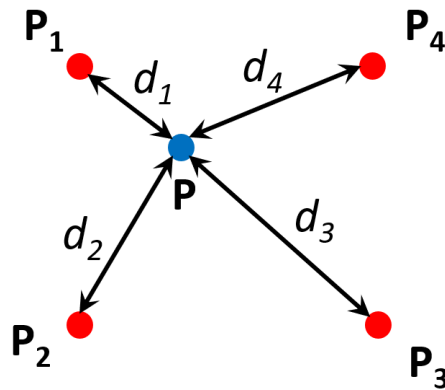


Figure 3.2: The interpolation method which is used to find the frequency response of point P using the responses of its surrounding points.

Please note that this interpolation has to be done for all the grid points and all the frequencies, which means a total number of $1254 \times 122'640$ interpolations for each sub-period. 122'640 is the number of frequency samples coming from the time samples of a 42-year period.

d) Taking the Fourier transform of the past wind of the ERA5 model for all the points and multiplying them by the frequency responses calculated in (c).

e) Calculation of the inverse Fourier transform of the results of (d) gives us the so called future ERA5 wind data.

There are still two issues to be discussed here. The first issue is that both wind speed and wind direction need to be generated for the future. Since these two parameters are coupled, they must be studied together; otherwise, their correlation would be lost. Therefore, we decided to study the wind as a vector with two orthogonal components and to study each component separately. This means that all steps (a) to (e) must be performed for both the x- and y-components of the wind.

Another issue is that the temporal resolution of ERA5 data is 1 hour, while it is 3 hours for REGCM. This means that frequency responses computed from REGCM data have no information about frequencies above $\frac{1}{3}\text{hour}^{-1}$. The Fourier transform of the ERA5 data, on the other hand, covers a wider range of frequencies up to 1hour^{-1} . In our calculations, we assume that the frequency response for the frequency range between $\frac{1}{3}\text{hour}^{-1}$ and 1hour^{-1} is unity, which means that the wind spectrum in this frequency range doesn't change from past to future. This would be a logical assumption since, regardless of the model, the wind spectrum doesn't have a strong component in this frequency range, meaning that there is no particular pattern in the wind data that repeats every hour or two. Of course, this doesn't mean that we might lose possible events that occur between the sampling times. In fact, the frequency domain analysis method helps us to avoid losing such information. Here we explain it in more detail:

Let's assume that a hypothetical time series of wind speed has the following values:

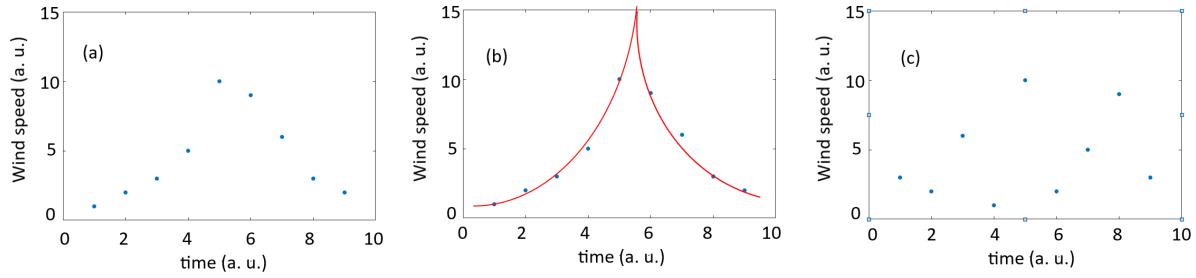


Figure 3.3: (a) The time domain illustration of the S1 data set, (b) a possible fit to this data set which predicts a peak between the fifth and sixth sample point, (c) the time domain illustration of the S2 data set.

$$S1 = [1, 2, 3, 5, 10, 9, 6, 3, 2]$$

This data set is shown in Fig 3.3(a). Although the sampling time is discrete and we don't know what the real data is at all times, we can guess what happens between the sampling time steps. For example, Fig. 3.3(b) shows a possible fit to the hypothetical data set. It doesn't necessarily show the real wind speed values, but it shows that there might be a higher wind speed between the fifth and sixth sample, which is missing due to the limited sampling resolution. Now imagine that we keep the values of our hypothetical time series, but change the order of the numbers:

$$S2 = [3, 2, 6, 1, 10, 2, 5, 9, 3]$$

This data set is also shown in Fig 3.3(c). One can easily see that the probability of a much higher wind speed being lost between sampling times is lower than in the previous case. This means that not only are the values in a time series important, but also the order of the numbers. In the statistical approaches to studying a time series data, there is no difference between the data shown in Fig 3.3(a) and Fig 3.3(c), which is a big disadvantage of these methods. On the other hand, frequency domain analysis takes all orderings into account and is better able to reconstruct the possible missed events. Fig 3.4 shows the Fourier transform of the two data sets, which are completely different except for the zero frequency, which is basically the average of the numbers.

A MATLAB code has been developed to perform all the above steps. The most time-consuming part of the code is step (c), where it has to find the four nearest REGCM grid points for each ERA5 grid point and perform the interpolation for the whole frequency range.

In the first step, all REGCM wind data are converted into 3D matrices. Therefore, we have six $43 \times 39 \times 122640$ matrices, including two sets of three matrices: one for the past data and two for the first and second half of the future wind data; both for the x and y components. Calculations for each direction can be handled separately.

Then a Fast Fourier Transform is performed on the 3rd dimension of these matrices and the results are again stored in three $43 \times 39 \times 122640$ matrices (122640 represents the number of time samples corresponding to 42 years every 3 hours). Fig3.5 shows as an example the time-domain and frequency-domain x-component of the wind data at grid point (21,21), which corresponds to point (52E,28N). To make the curves clearer, we have limited the time domain to

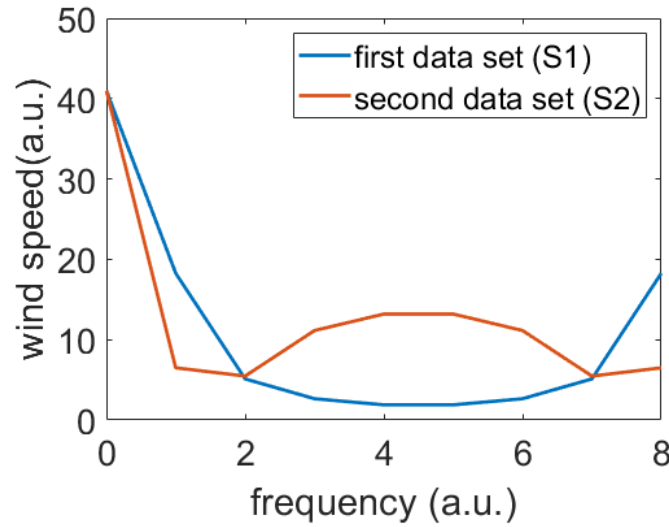


Figure 3.4: The Fourier transform of the two data sets shown in Fig 3.3.

one year (1980) and the frequency domain to $1.5 \times 10^{-3} \text{hour}^{-1}$. It can also be seen in this figure that the wind data have some major frequency components corresponding to daily, monthly and yearly variations, although their behavior in the time domain is not easy to distinguish. In the next step, in order to find the frequency response, we divided the 3rd dimension of the future matrices by the 3rd dimension of the past matrix. The frequency response of the grid (21,21) for the two halves of the future period is shown in Fig 3.6 as an example. Taking the Fourier transform of the past wind data from the ERA5 model would be the next step, which would generate a $38 \times 33 \times 367920$ matrix (367920 represents the number of time samples corresponding to 42 years every 1 hour). Fig 3.7 shows the wind data of grid point (18,18) in both frequency and time domain, again with limited time and frequency range. Now we have to calculate the frequency response at the ERA5 data grid points by the interpolation described above. Such a frequency response for grid point (18,18) is shown in Fig 3.8 it generates two $38 \times 33 \times 122640$ matrices (for the two half periods).

Finally, we can find the Fourier transform of the future ERA5 wind by multiplying the frequency response matrices by the Fourier transform of the past ERA5 wind in the third dimension. As mentioned before, we don't have a frequency response in the frequency range between $\frac{1}{3} \text{hour}^{-1}$ and 1hour^{-1} . For this range we assume that the frequency response is equal to unity. However, from Fig 3.5 and Fig 3.7 we can see that the wind data do not have a significant component in this frequency range.

The inverse Fourier transform of the computed matrices leads to the regenerated ERA5 wind data for the future. We repeat these steps also for the y-component of the wind. The last thing to note here is that the future ERA wind in the frequency domain is constructed by various calculations and therefore taking the inverse Fourier transform of it leads to some complex numbers. The generated future ERA wind at grid point (18,18) in the year 2030 is shown in Fig 3.9 as an example. It can be seen that the imaginary part of this wind data is two orders of magnitude smaller than the real part. Therefore, we can neglect this part and take the real part as the future wind data. It is worth mentioning that for all other grid points, the imaginary part of

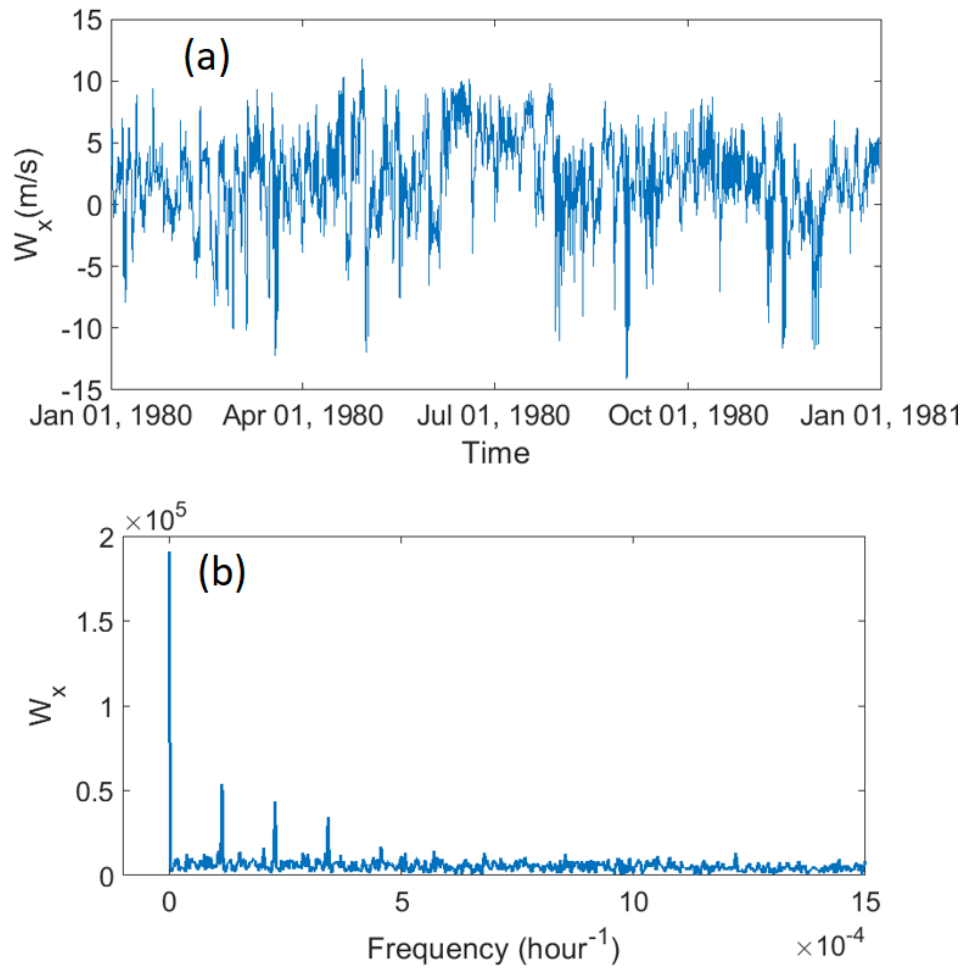


Figure 3.5: (a) The time domain data of REGCM wind at point (52E,28N) in the year 1980, (b) the frequency domain illustration of the wind data shown in (a).

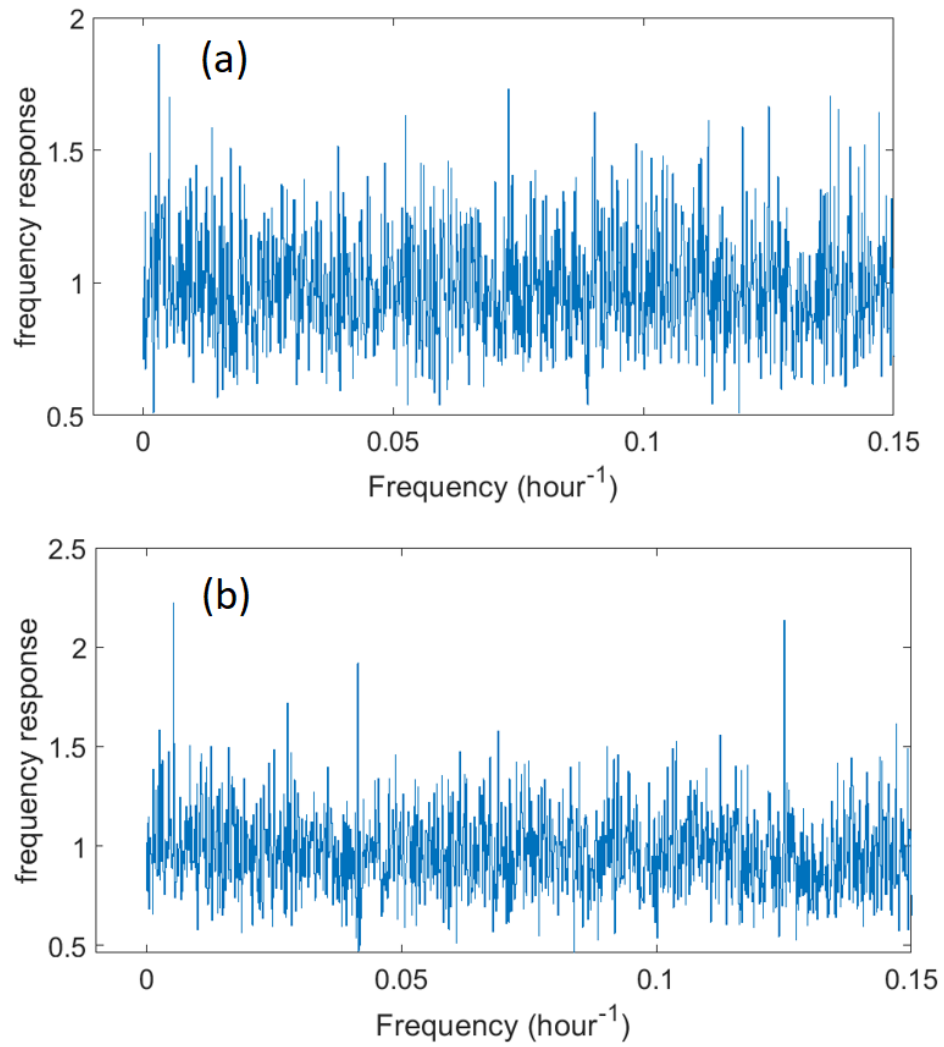


Figure 3.6: (a),(b) Frequency responses of the point at (52E,28N) for the first and second halves of the future period respectively.

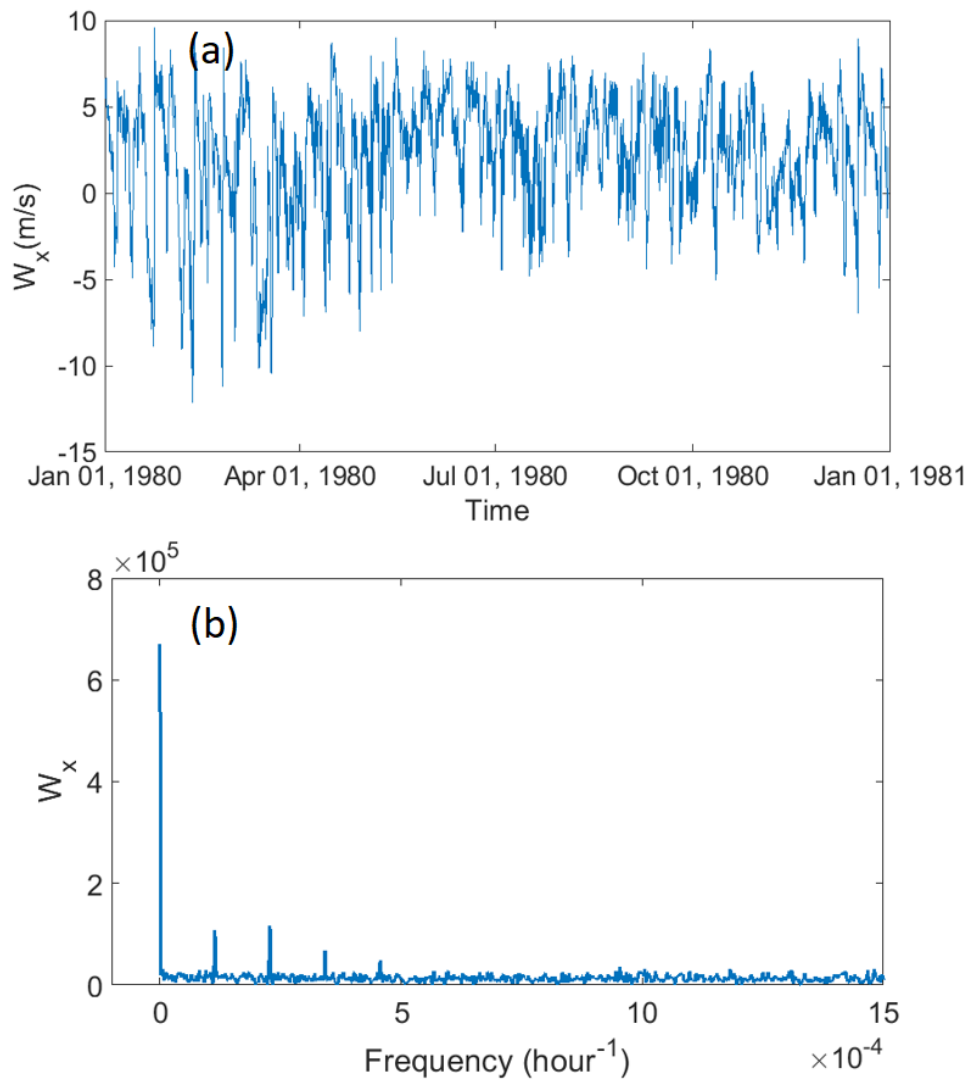


Figure 3.7: (a) The time domain data of ERA wind at grid point (18,18) in the year 1980, (b) the frequency domain illustration of the wind data shown in (a).

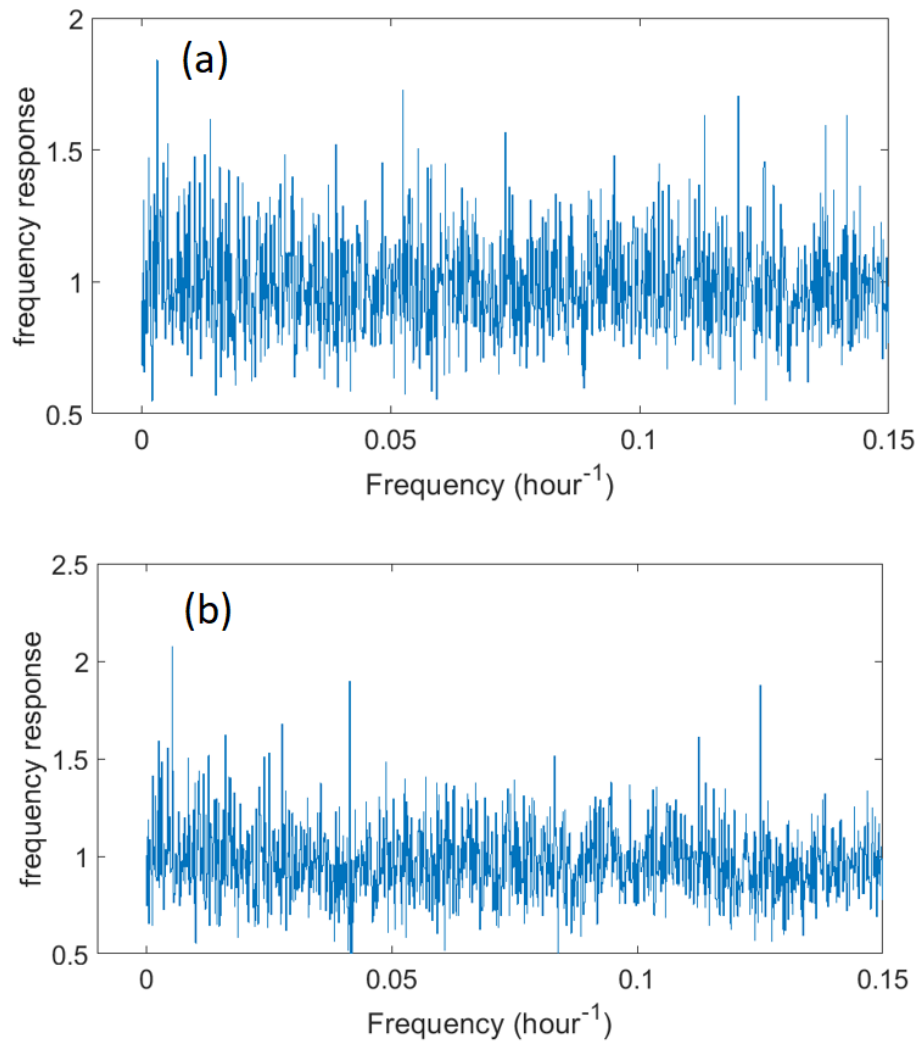


Figure 3.8: (a),(b) Frequency responses of the point (18,18) for the first and second halves of the future period respectively.

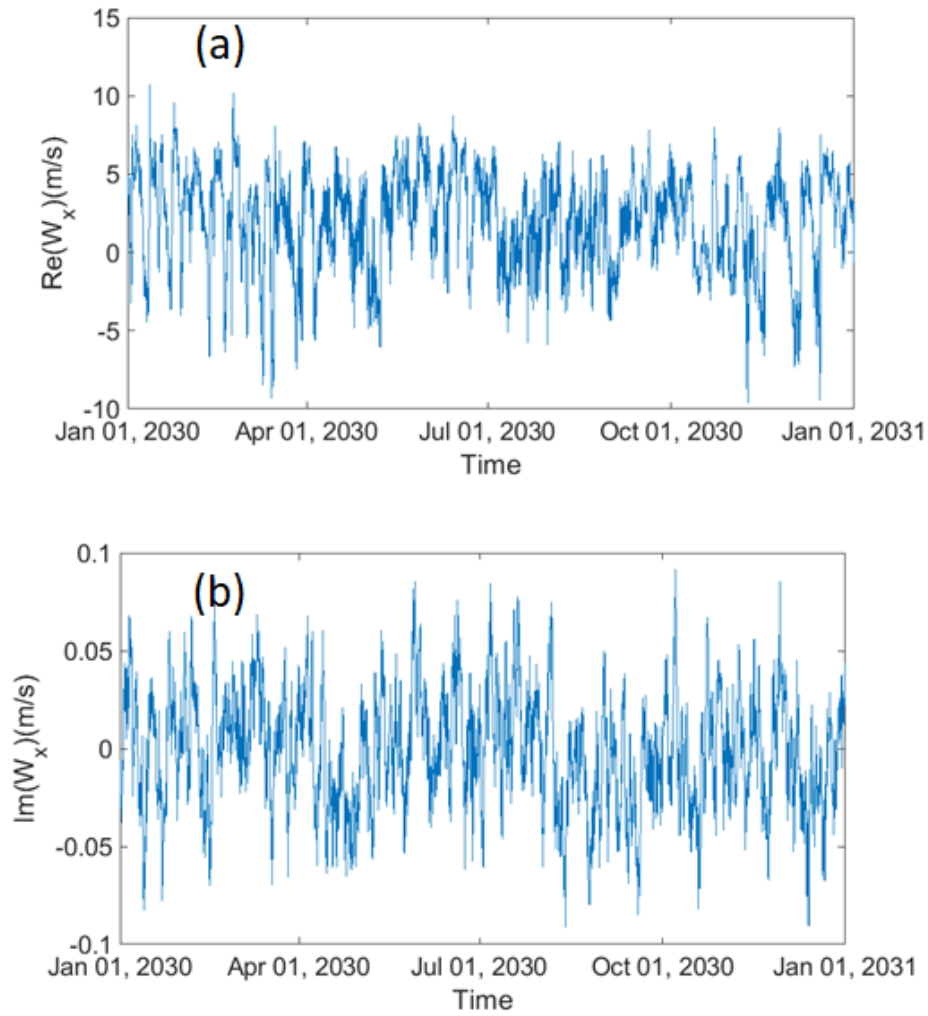


Figure 3.9: (a) The real part of the generated future ERA wind for the grid point (18,18), (b) the imaginary part of the generated wind data.

the wind is negligible.

Chapter 4

Analysis of the ERA5 and REGCM wind data

In the previous chapter, we explained our method for generating future wind data with a 1-hour temporal resolution based on ERA5 data for the past as well as REGCM wind data for the past and the future. We called it "ERA5 future wind" because its temporal resolution and wind speed values are obtained from the original ERA5 hindcast data. In this chapter, we analyze the generated wind data and compare them with the hindcast data. We also perform the same analysis for the REGCM data. Due to the vastness of the Persian Gulf, the wind dynamics are not the same over the whole area. Therefore, we limit our study to five major ports on the northern coast of the Persian Gulf, which are described in section 1.2:

Point1: Lengeh port (54.896 E, 26.573N),

Point2: Rajaei port (56.205 E, 27.110 N),

Point3: Bahonar port (56.075 E, 27.079 N),

Point4: Asaluyeh port (52.590 E, 27.460 N),

Point5: Bushehr port (50.814 E, 29.009 N).

4.1 Wind data analysis at Lengeh port

Fig 4.1 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of wind velocity at Lengeh port from the ERA5 model, while the time series for the REGCM model are shown in Fig 4.2.

Fig 4.3 shows the wind roses of these four data sets. It has to be noted here that in these curves, the direction from which the wind is blowing is shown. As can be seen from the wind roses, at this point, wind blows mainly in two different directions. Therefore, we classify the wind data of

each model into two classes based on the direction of the wind. Fig 4.4 and 4.5 show histogram diagrams of the wind data, which illustrate the contribution of each direction to the overall data. The information regarding the hindcast and forecast wind data for both the ERA5 and REGCM models is summarized in Table 4.1.

Table 4.1: Summary of wind data at Lengeh port

	REGCM hindcast		REGCM forecast			ERA5 hindcast		ERA5 forecast	
Group 1	Mean direction	271	Mean direction	269	Group 1	Mean direction	258	Mean direction	259
Group 2	Mean direction	85	Mean direction	86	Group 2	Mean direction	83	Mean direction	83
	Max of wind velocity (m/s)	17.5	Max of wind velocity (m/s)	27.3		Max of wind velocity (m/s)	12.1	Max of wind velocity (m/s)	12.3
	Mean of wind velocity (m/s)	4.8	Mean of wind velocity (m/s)	4.8		Mean of wind velocity (m/s)	3.08	Mean of wind velocity (m/s)	3.07

As can be seen, there is no significant change in the wind speed and direction from past to future based on either model.

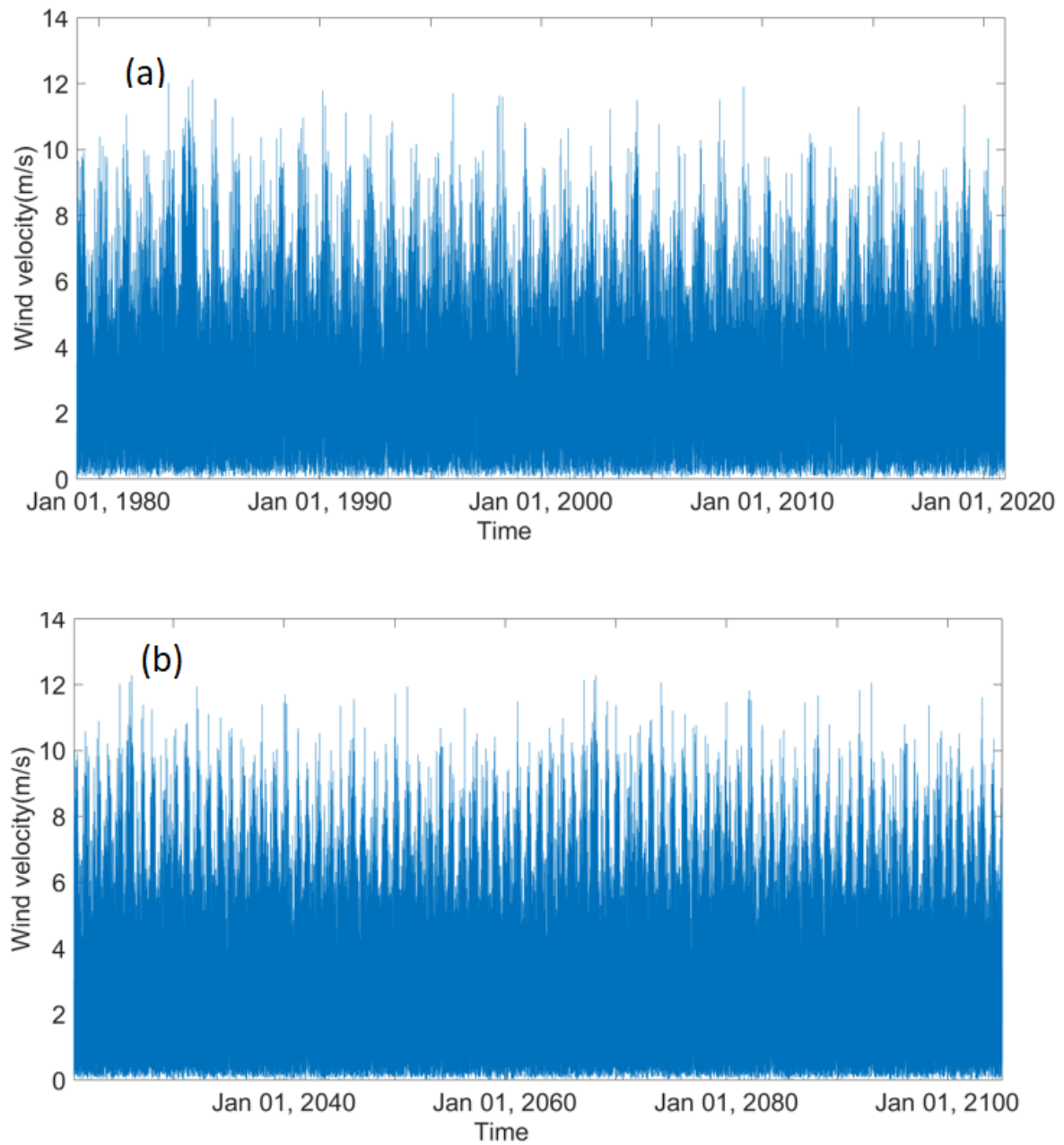


Figure 4.1: Time series of the ERA5 wind data at Lengeh port for the (a) past and (b) future period.

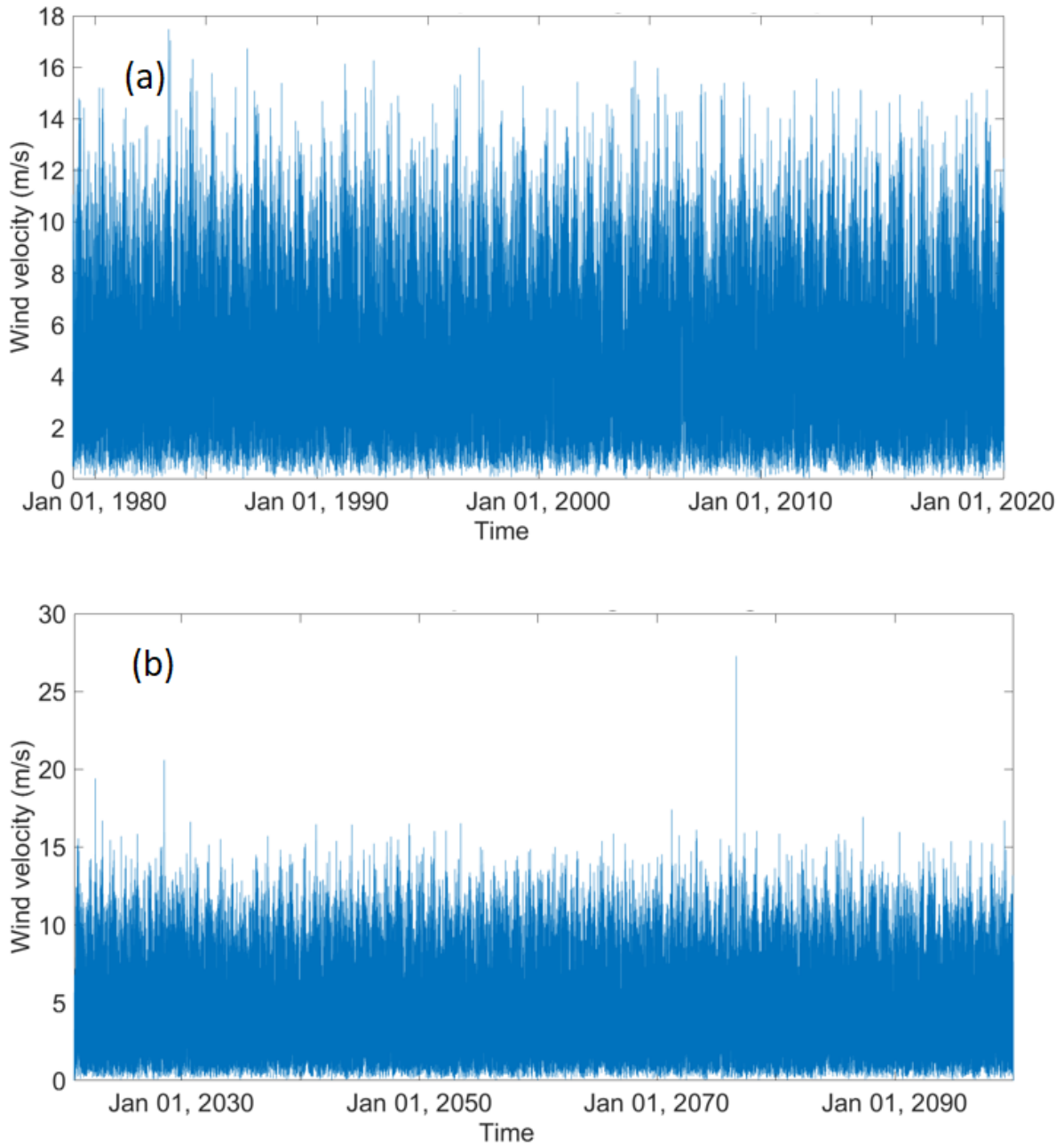


Figure 4.2: Time series of the REGCM wind data at Lengeh port for the (a) past and (b) future period.

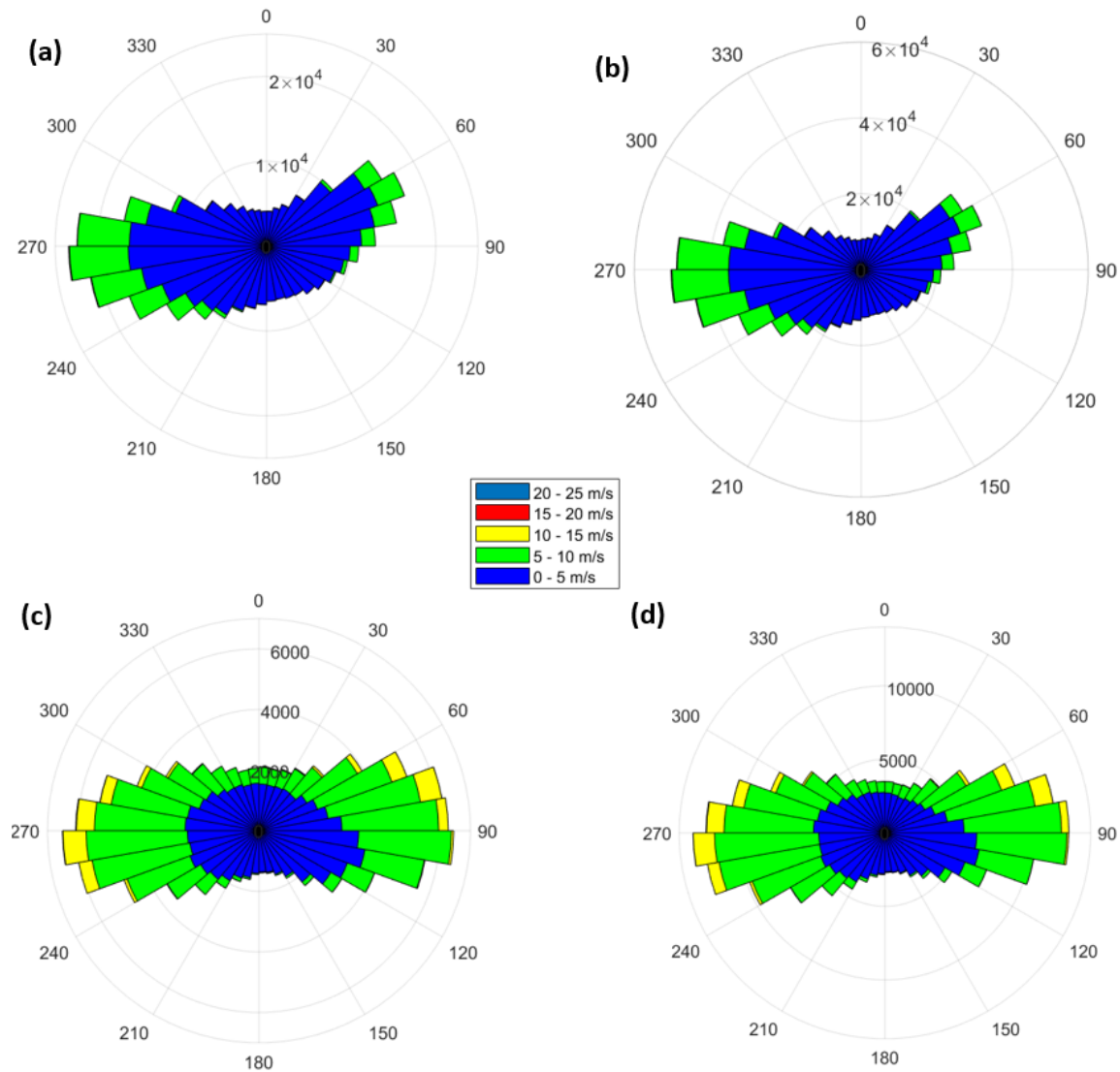


Figure 4.3: Wind rose diagrams of the ERA5 and REGCM wind data at Lengheh port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

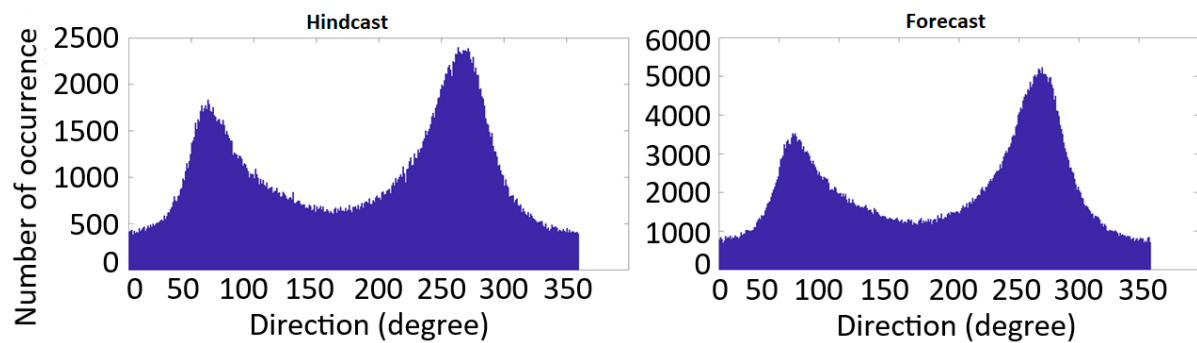


Figure 4.4: Histogram diagram of the ERA5 wind data at Lengheh port

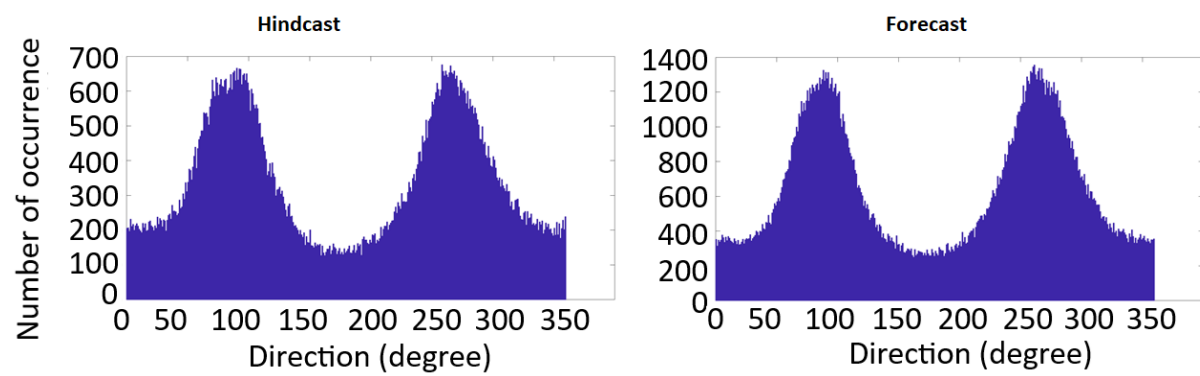


Figure 4.5: Histogram diagram of the REGCM wind data at Lengeh port

4.2 Wind data analysis at Rajaei port

The second port that we studied is the Rajaei port, located at coordinates (56.205 E, 27.110 N). Fig 4.6 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of wind velocity at Rajaei port from the ERA5 model, while the corresponding time series for the REGCM model are shown in Fig 4.7.

Fig 4.8 shows the wind roses of these four data sets. Again, it can be seen from the wind roses, that the wind blows mainly in two different directions. Fig 4.9 and 4.10 show histogram curves of the wind data, showing the contribution of each direction to the overall data. The information regarding the hindcast and forecast wind data for both the ERA5 and REGCM models is summarized in Table 4.2. Similar to Lengeh port, there is no significant change in the wind speed and direction from past to future for either model.

Table 4.2: Summary of wind data at Rajaei port

	REGCM hindcast		REGCM forecast			ERA5 hindcast		ERA5 forecast	
Group 1	Mean direction	228	Mean direction	226	Group 1	Mean direction	219	Mean direction	217
Group 2	Mean direction	82	Mean direction	83	Group 2	Mean direction	64	Mean direction	69
	Max of wind velocity (m/s)	17	Max of wind velocity (m/s)	21.8		Max of wind velocity (m/s)	14.8	Max of wind velocity (m/s)	14.8
	Mean of wind velocity (m/s)	4.17	Mean of wind velocity (m/s)	4.17		Mean of wind velocity (m/s)	2.37	Mean of wind velocity (m/s)	2.40

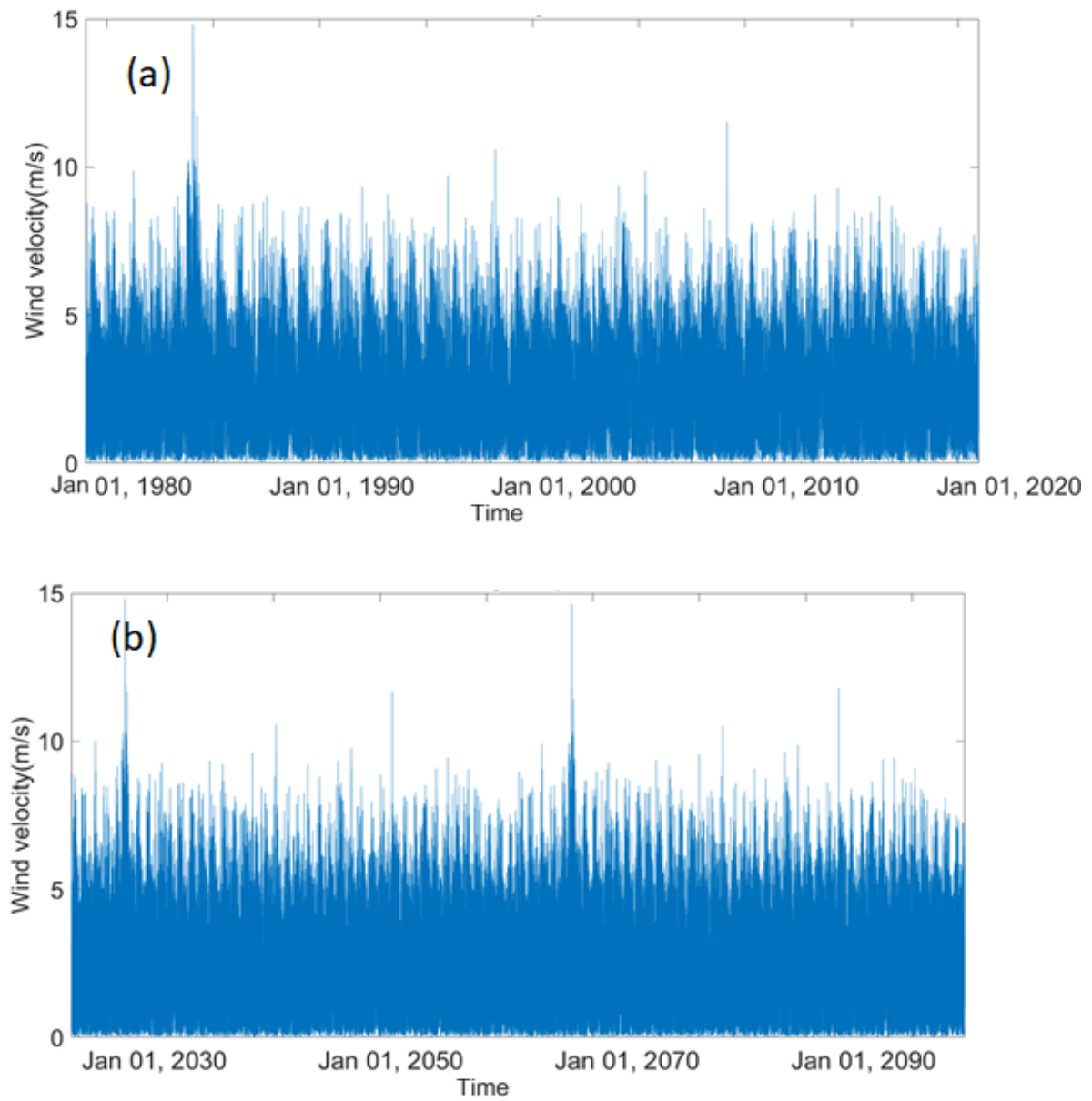


Figure 4.6: Time series of the ERA5 wind data at Rajace port for the (a) past and (b) future period.

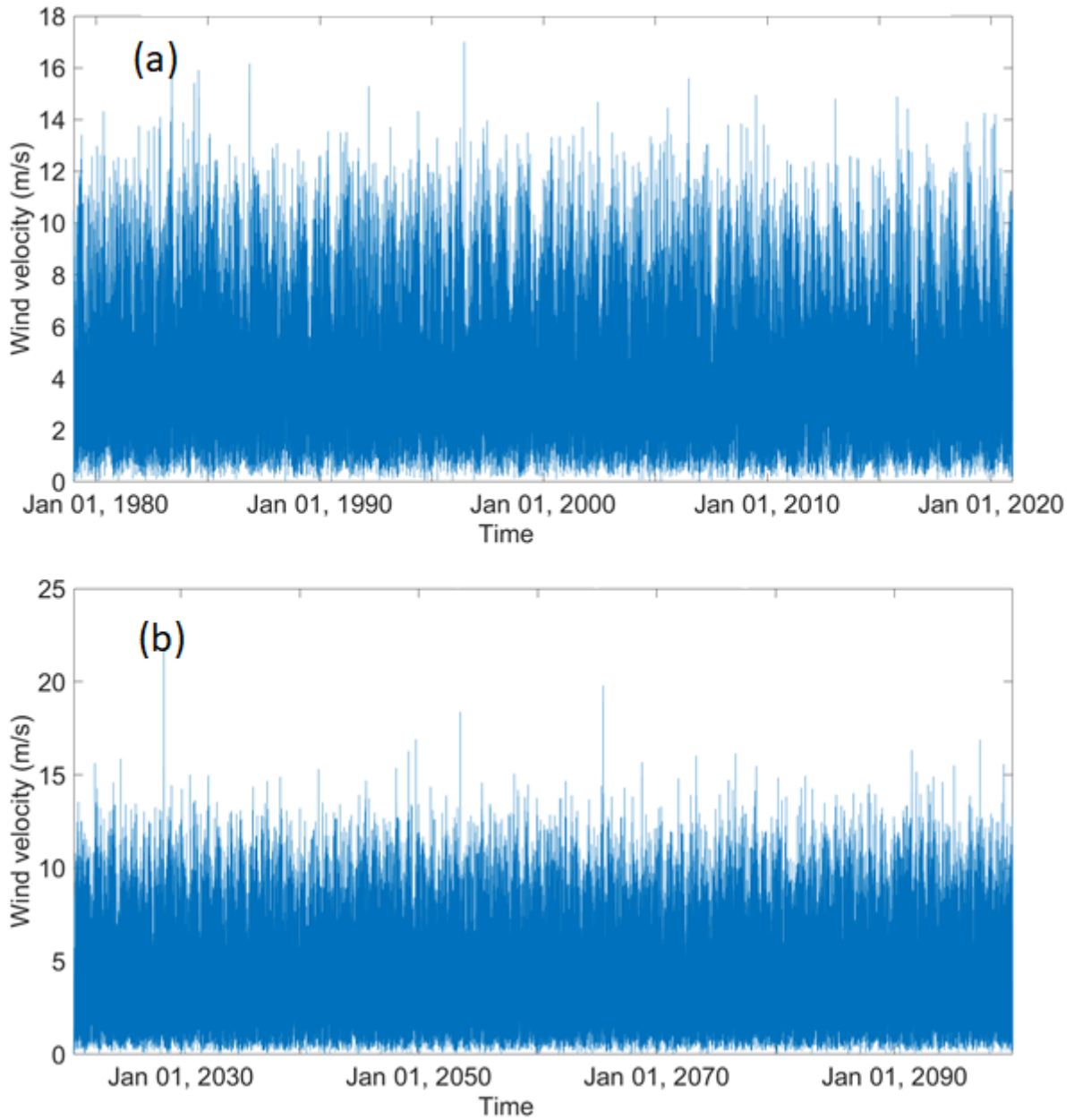


Figure 4.7: Time series of the REGCM wind data at Rajaei port for the (a) past and (b) future period.

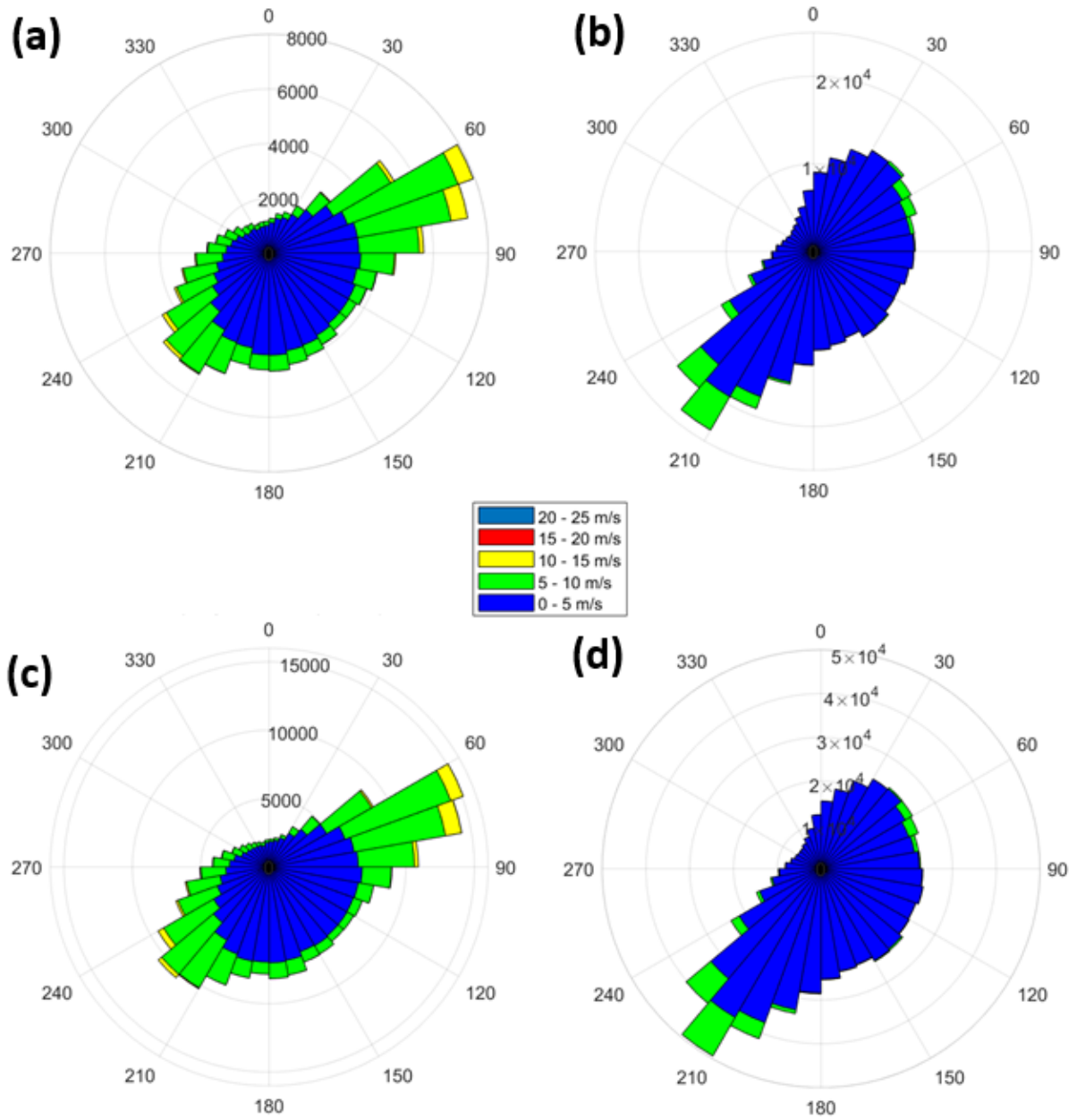


Figure 4.8: Wind rose diagrams of the ERA5 and REGCM wind data at Rajae port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

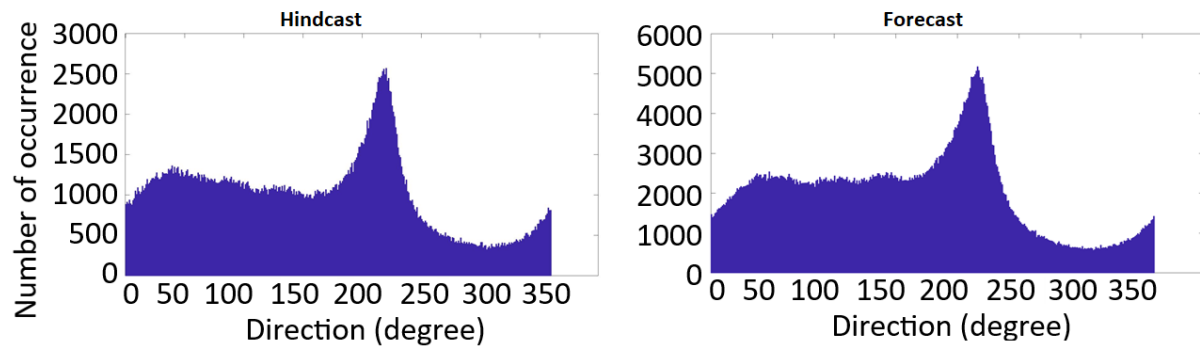


Figure 4.9: Histogram diagram of the ERA5 wind data at Rajaei port

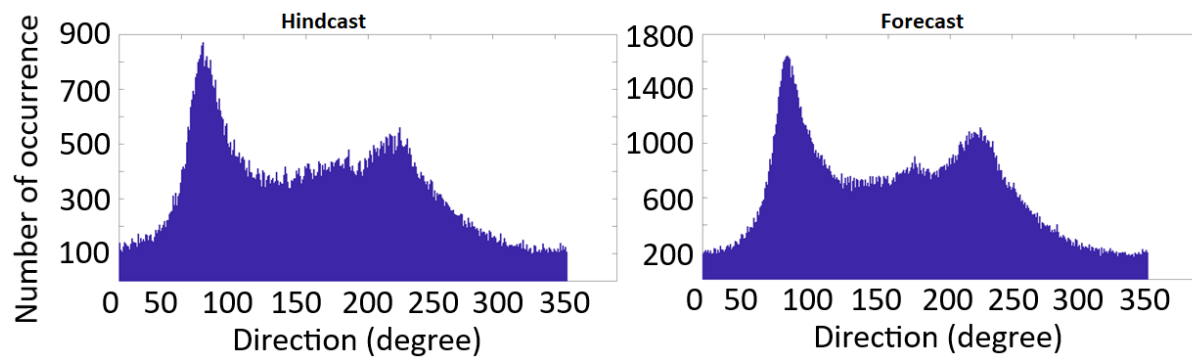


Figure 4.10: Histogram diagram of the REGCM wind data at Rajaei port

4.3 Wind data analysis at Bahonar port

Here we show the information on the ERA5 and REGCM wind data for Bahonar port, located at (56.075 E, 27.079 N).

Fig 4.11 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of wind velocity at Bahonar port from the ERA5 model, while such time series for the REGCM model are shown in Fig 4.12.

Fig 4.13 show the wind roses of these four data sets. Again, it can be seen from the wind roses, that the wind blows mainly in two different directions. Fig 4.14 and 4.15 show histogram curves of the wind data which shows the contribution of each direction in the overall data. The information regarding the hindcast and forecast wind data for both the ERA5 and the REGCM models are summarized in Table 4.3. Similar to Lengeh and Rajaei ports, there is no significant change in the wind speed and direction from past to future for either model. The statistics of the wind are very similar for these three points, as expected since they are located very close to each other.

Table 4.3: Summary of wind data at Bahonar port

	REGCM hindcast		REGCM forecast			ERA5 hindcast		ERA5 forecast	
Group 1	Mean direction	226	Mean direction	225	Group 1	Mean direction	216	Mean direction	212
Group 2	Mean direction	82	Mean direction	84	Group 2	Mean direction	65	Mean direction	68
	Max of wind velocity (m/s)	19.3	Max of wind velocity (m/s)	22.1		Max of wind velocity (m/s)	14.96	Max of wind velocity (m/s)	14.93
	Mean of wind velocity (m/s)	4.45	Mean of wind velocity (m/s)	4.39		Mean of wind velocity (m/s)	2.46	Mean of wind velocity (m/s)	2.50

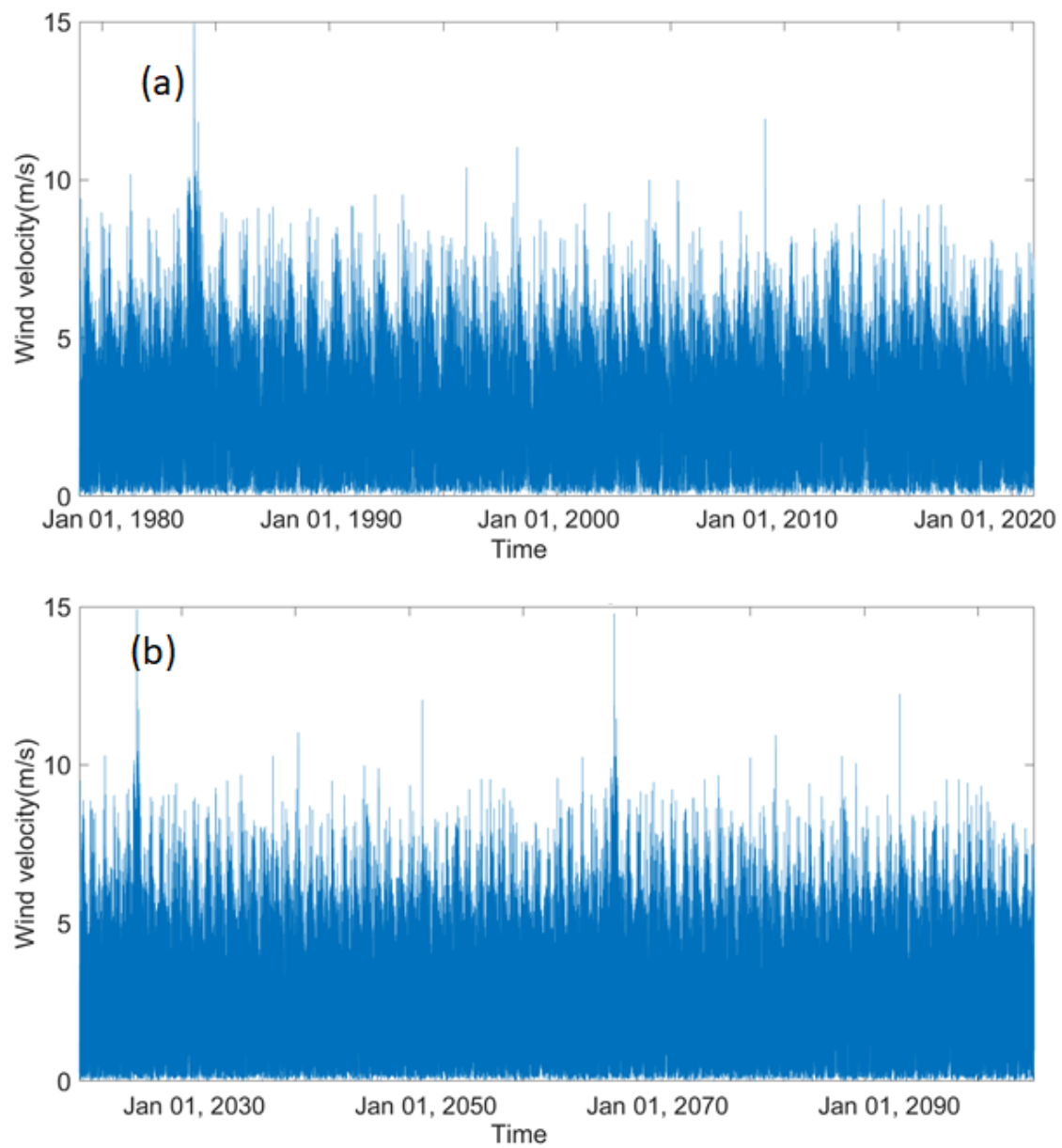


Figure 4.11: Time series of the ERA5 wind data at Bahonar port for the (a) past and (b) future period.

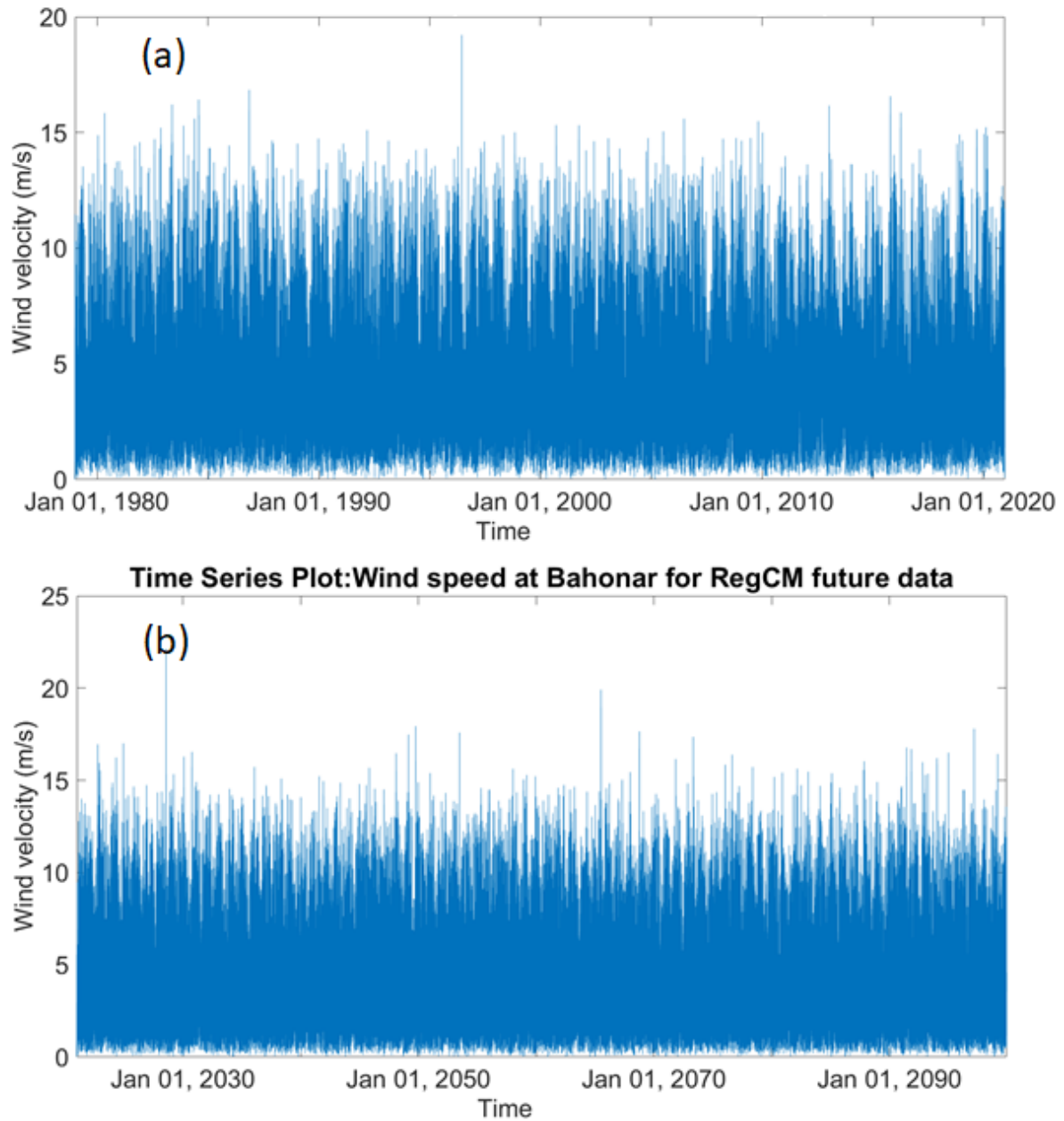


Figure 4.12: Time series of the REGCM wind data at Bahonar port for the (a) past and (b) future period.

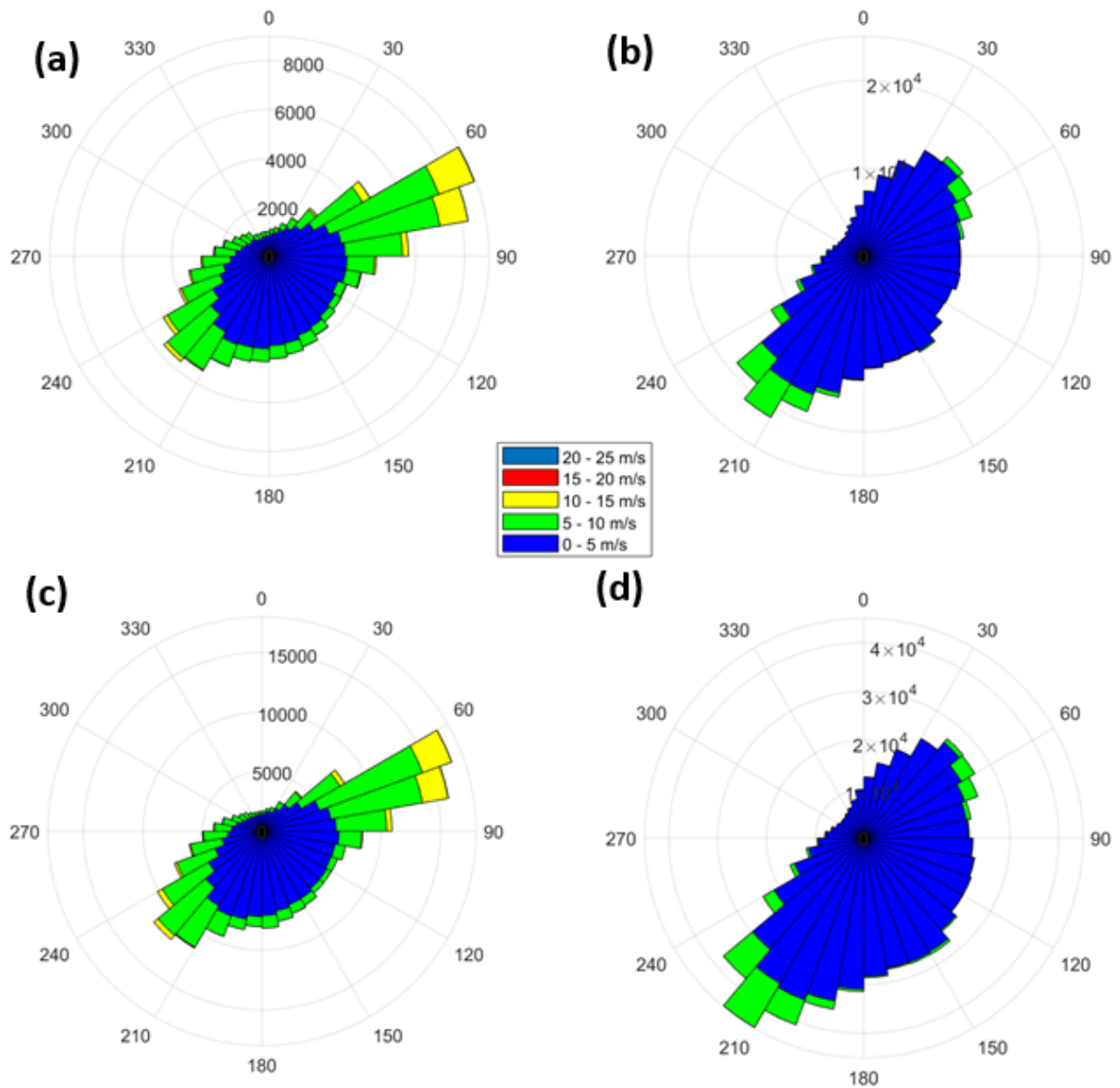


Figure 4.13: Wind rose diagrams of the ERA5 and REGCM wind data at Bahonar port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

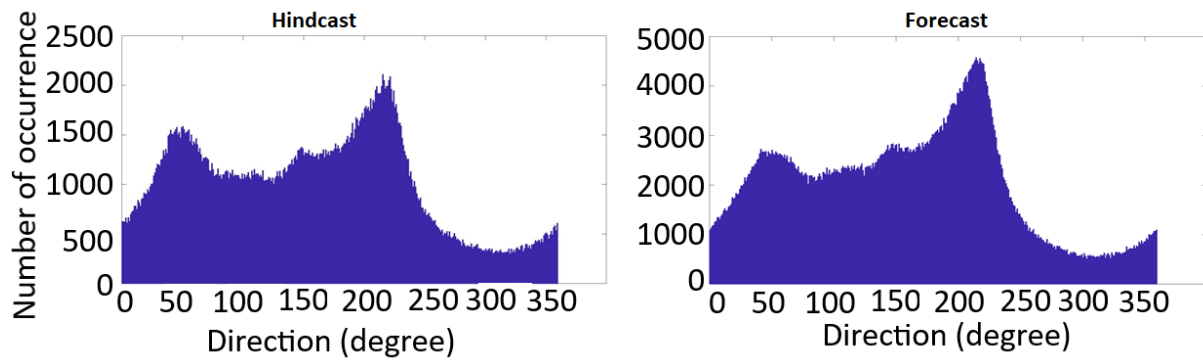


Figure 4.14: Histogram diagram of the ERA5 wind data at Bahonar port

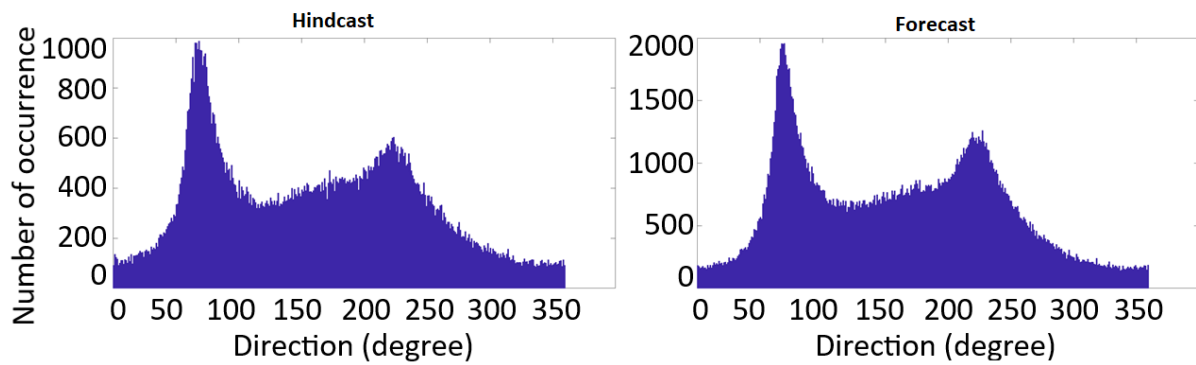


Figure 4.15: Histogram diagram of the REGCM wind data at Bahonar port

4.4 Wind data analysis at Asaluye port

Here we show the information on the ERA5 and REGCM wind data for Asaluye port, located at (52.590 E, 27.460 N).

Fig 4.16 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of wind velocity at Asaluye port from the ERA5 model, while the time series for the REGCM model are shown in Fig 4.17.

Fig 4.18 shows the wind roses of these four data sets. Unlike the previous three points, in Aslauye, the wind blows mainly in one direction in the ERA5 model. Figures 4.19 and 4.20 show histogram curves of the wind data which describe the contribution of each direction to the overall data. The information regarding the hindcast and forecast wind data for both the ERA5 and REGCM models is summarized in Table 4.4. Similar to the other ports, there is no significant change in the wind speed and direction from past to future for either model.

Table 4.4: Summary of wind data at Asaluye port

	REGCM hindcast		REGCM forecast			ERA5 hindcast		ERA5 forecast	
Group 1	Mean direction	290	Mean direction	292	Group 1	Mean direction	218	Mean direction	225
Group 2	Mean direction	87	Mean direction	93	Group 2	Mean direction	-	Mean direction	-
	Max of wind velocity (m/s)	16.7	Max of velocity (m/s)	22.7		Max of wind velocity (m/s)	11.6	Max of wind velocity (m/s)	11.3
	Mean of wind velocity (m/s)	5.0	Mean of wind velocity (m/s)	4.9		Mean of wind velocity (m/s)	2.7	Mean of wind velocity (m/s)	2.7

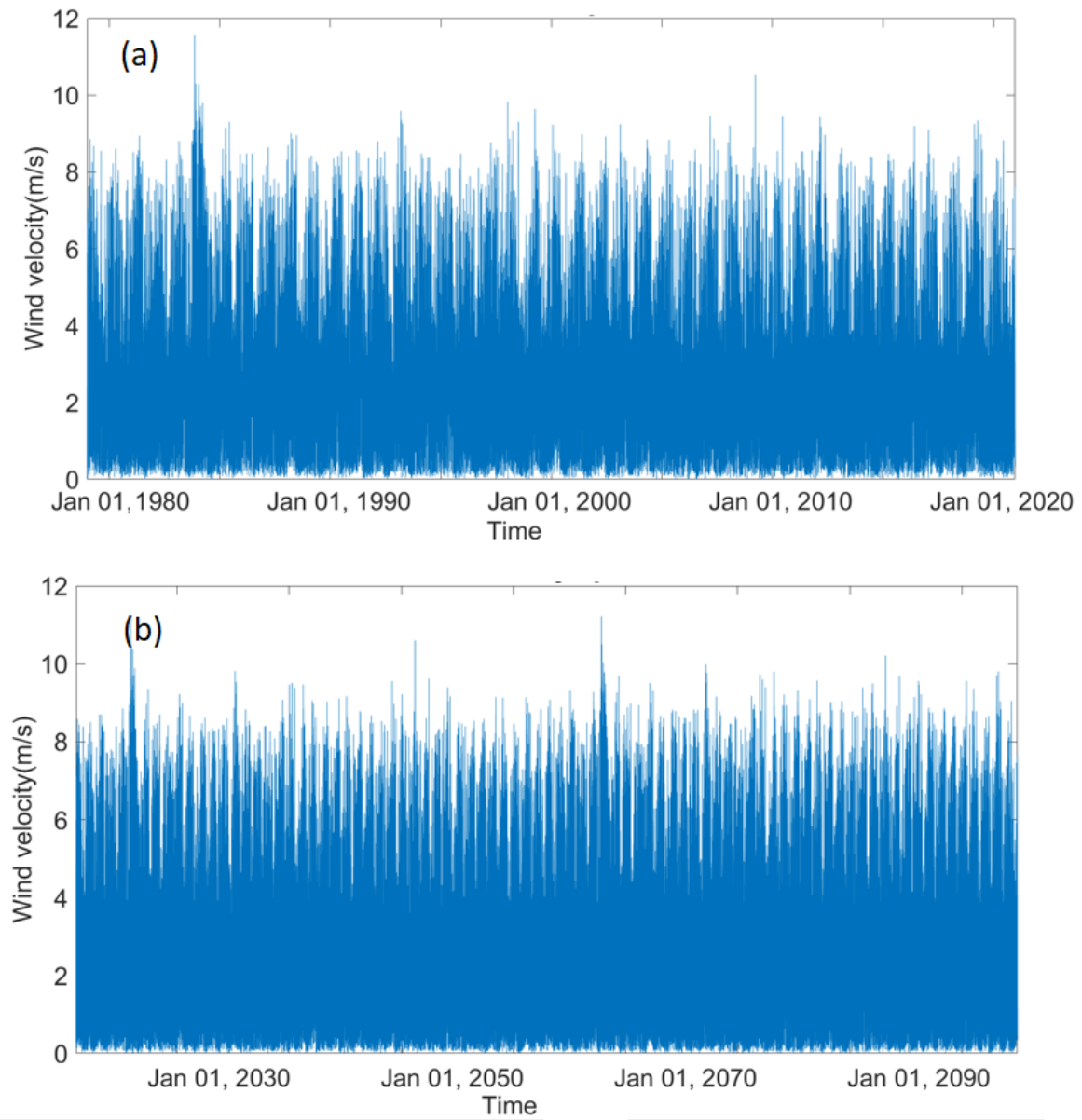


Figure 4.16: Time series of the ERA5 wind data at Asaluye port for the (a) past and (b) future period.

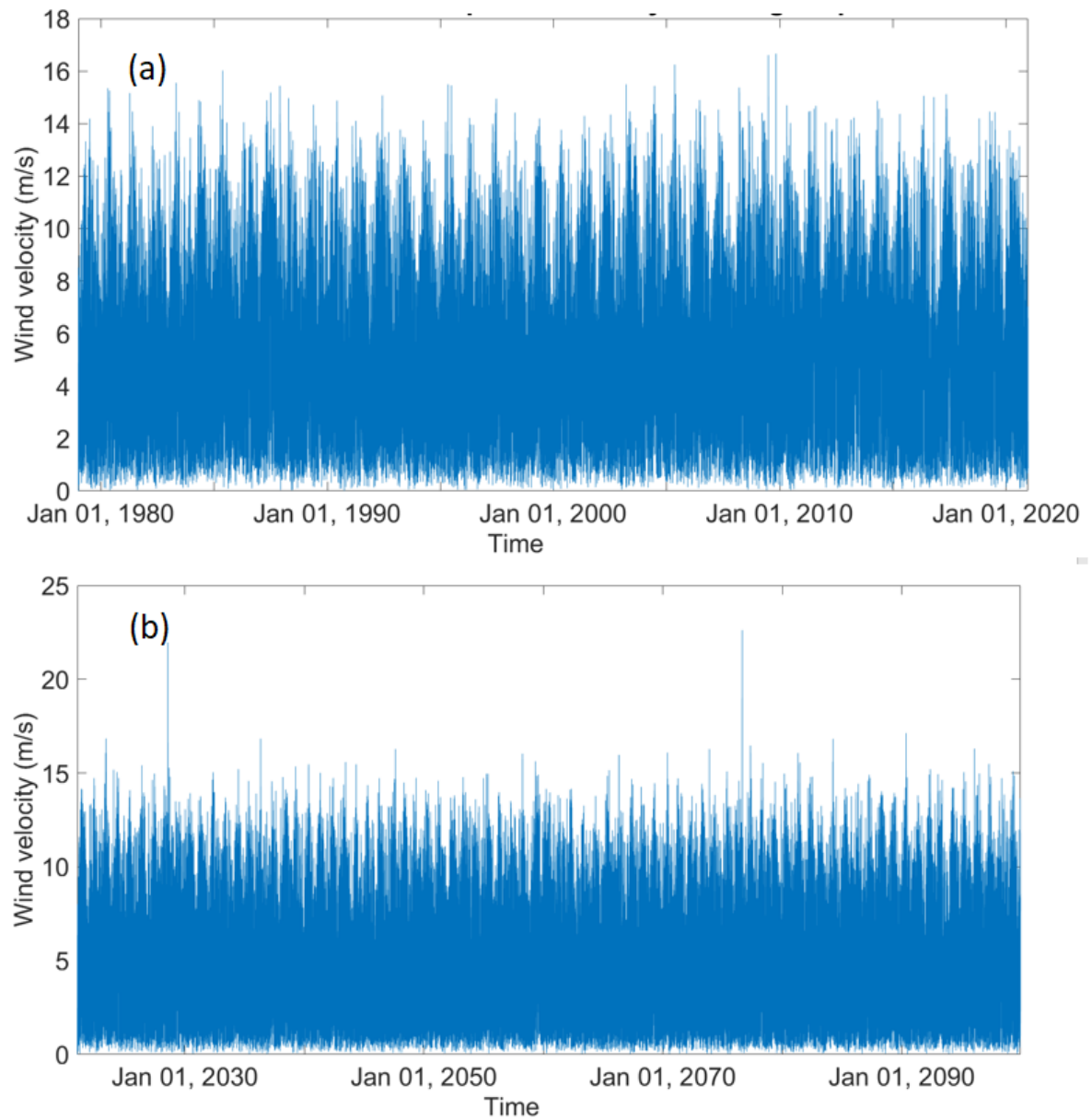


Figure 4.17: Time series of the REGCM wind data at Asaluye port for the (a) past and (b) future period.

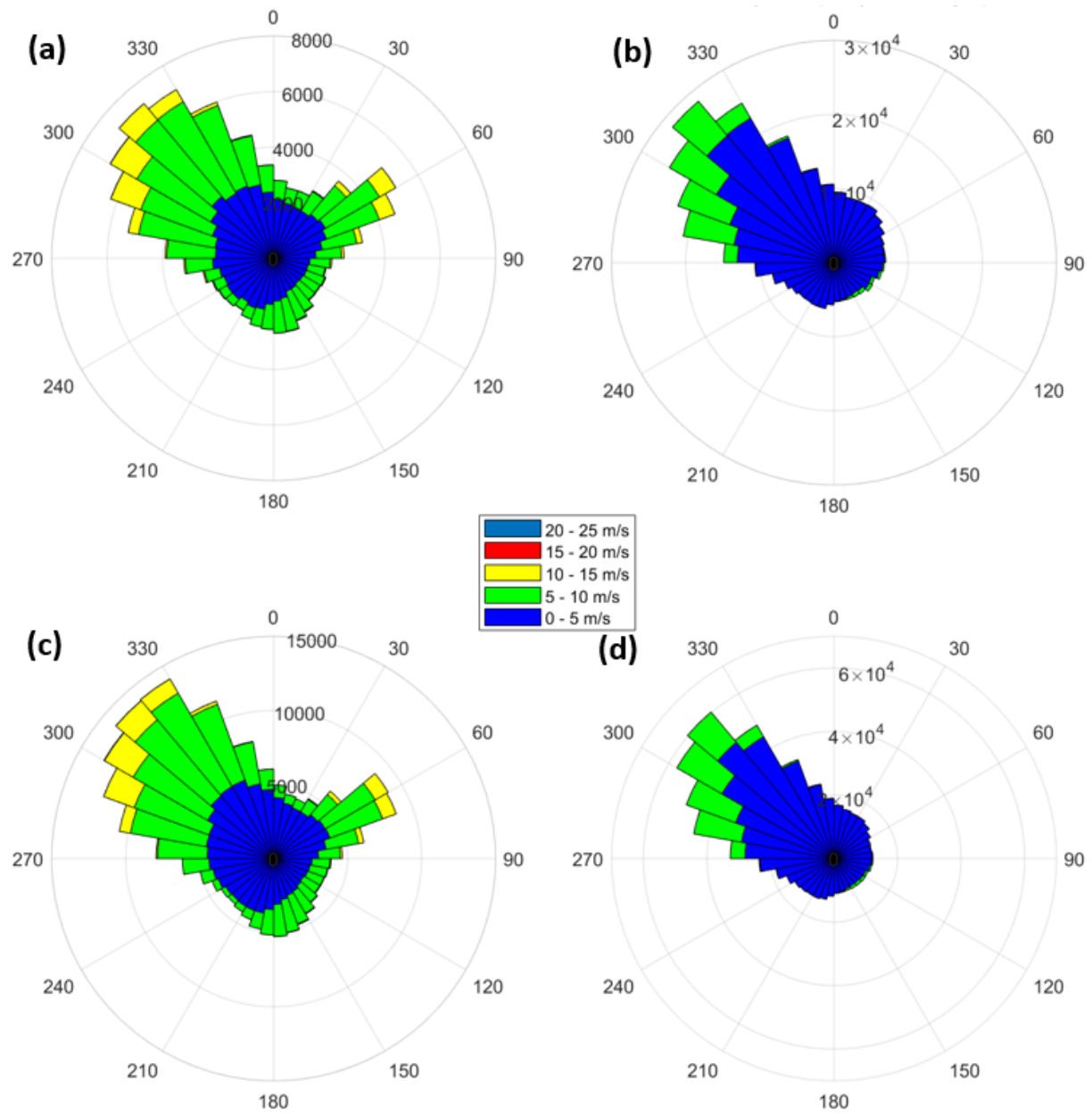


Figure 4.18: Wind rose diagrams of the ERA5 and REGCM wind data at Asaluye port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

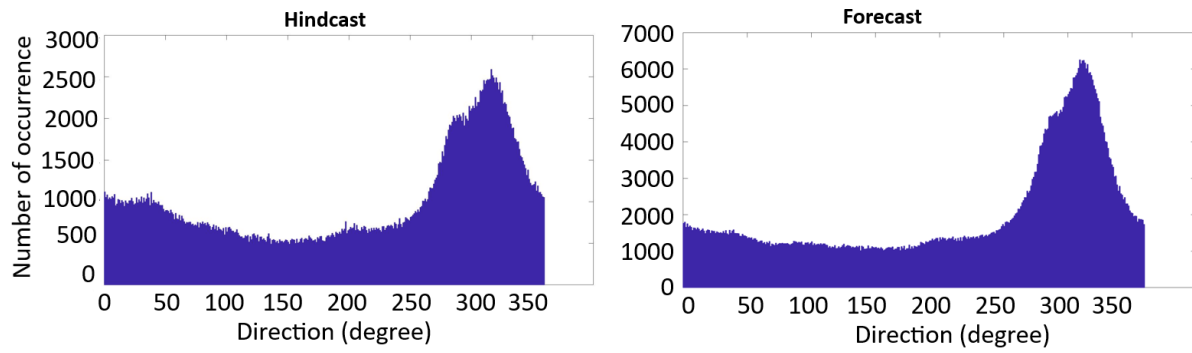


Figure 4.19: Histogram diagram of the ERA5 wind data at Asaluye port

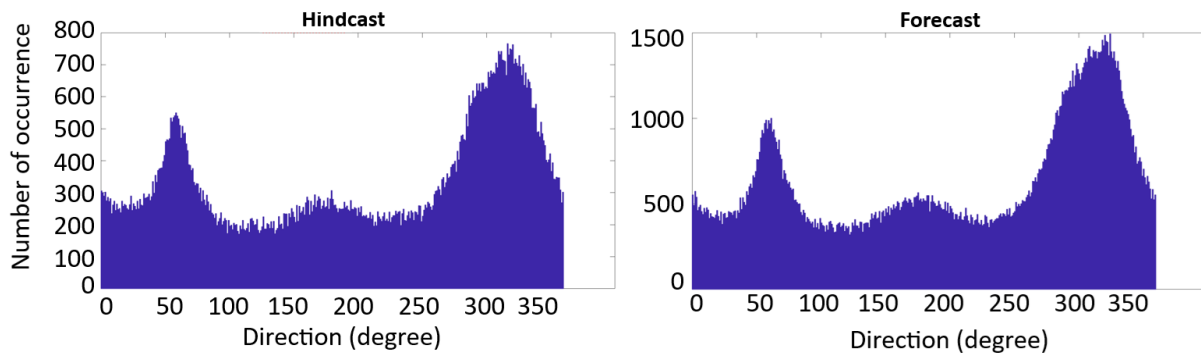


Figure 4.20: Histogram diagram of the REGCM wind data at Asaluye port

4.5 Wind data analysis at Bushehr port

Here we show the information on the ERA5 and REGCM wind data for Bushehr port, located at (50.814 E, 29.009 N).

Figure 4.21 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of wind velocity at Bushehr port from the ERA5 model, while the corresponding time series for the REGCM model are shown in Fig 4.22.

Figures 4.23 shows the wind rose of these four data sets. Figure 4.24 and 4.25 show histogram curves of the wind data, which represent the contribution of each direction to the overall data. Similar to Asaluye, the ERA5 model predicts the wind for Bushehr to blow mainly in one direction. The information regarding the hindcast and forecast wind data for both the ERA5 and REGCM models is summarized in Table 4.5. Similar to other ports, there is no significant change in the wind speed and direction from past to future for either model.

Table 4.5: Summary of wind data at Bushehr port

	REGCM hindcast		REGCM forecast			ERA5 hindcast		ERA5 forecast	
Group 1	Mean direction	311	Mean direction	314	Group 1	Mean direction	225	Mean direction	231
Group 2	Mean direction	101	Mean direction	106	Group 2	Mean direction	-	Mean direction	-
	Max of wind velocity (m/s)	17.6	Max of wind velocity (m/s)	19.1		Max of wind velocity (m/s)	13.8	Max of wind velocity (m/s)	14.1
	Mean of wind velocity (m/s)	4.95	Mean of wind velocity (m/s)	4.77		Mean of wind velocity (m/s)	3.49	Mean of wind velocity (m/s)	3.54

Looking at the wind data at all five study sites, it can be concluded that the REGCM model generally predicts stronger winds. The ratio of the average wind speed in the REGCM model is between 1.5 and 2 times greater than the wind speed in the ERA5 model. In terms of wind direction, there is no significant difference between the two models for the first three ports located in the eastern part of the Persian Gulf. However, for Asaluye and Bushehr, which are located on the northwestern coast, the ERA5 model predicts the wind blowing mainly in one direction, while in the REGCM model two classes of wind direction are detectable. However, one direction has a much larger contribution.

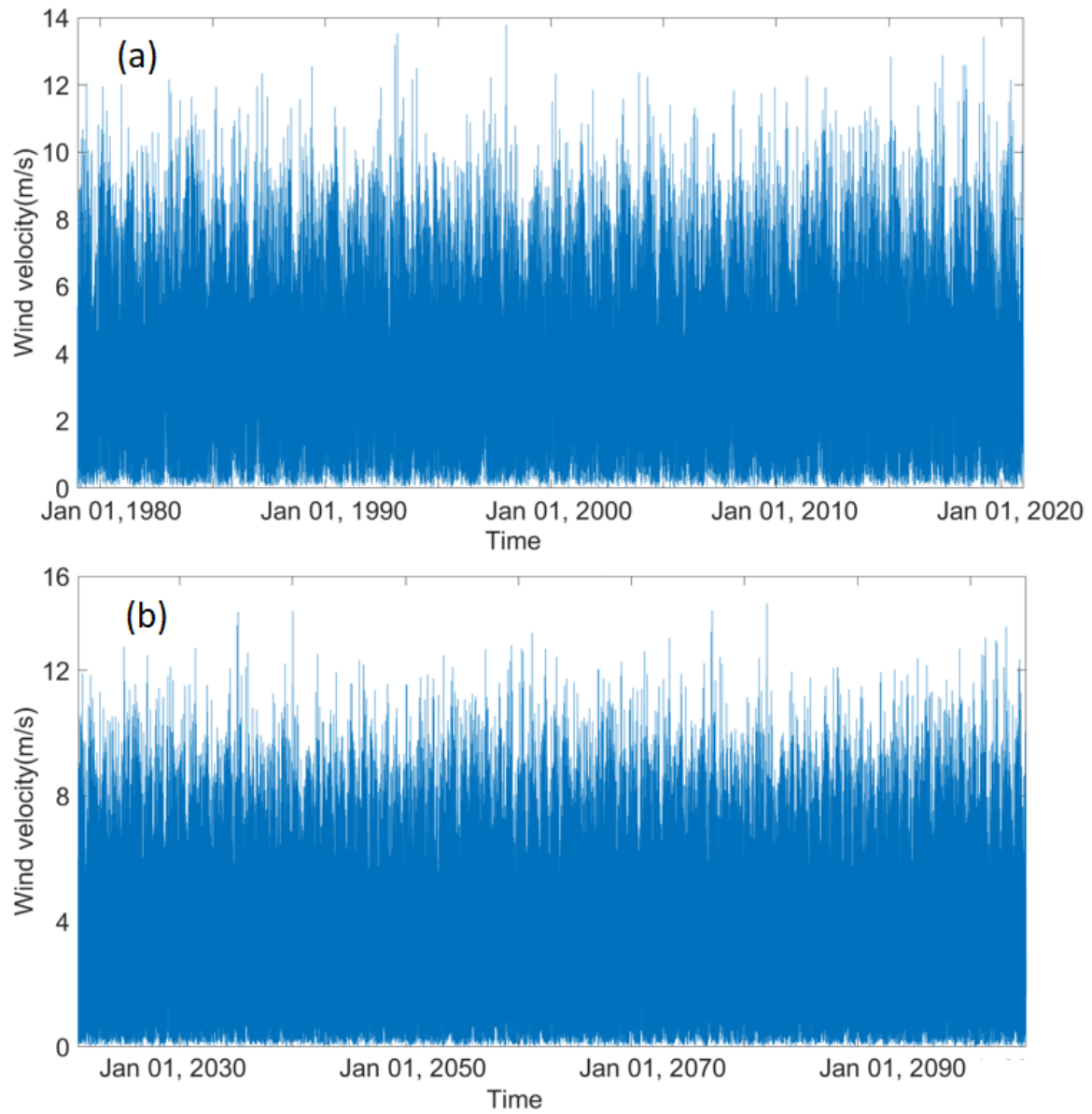


Figure 4.21: Time series of the ERA5 wind data at Bushehr port for the (a) past and (b) future period.

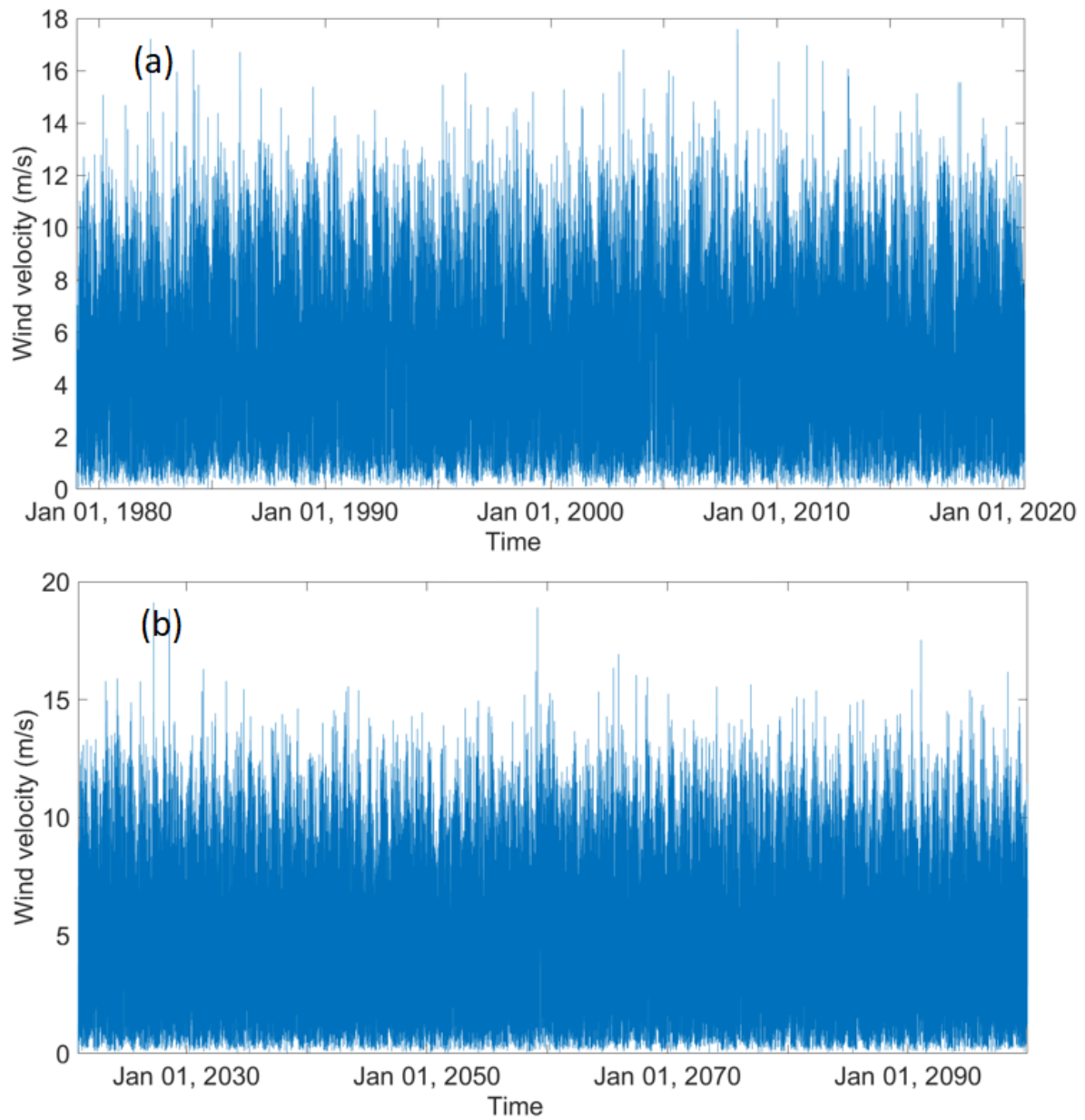


Figure 4.22: Time series of the REGCM wind data at Bushehr port for the (a) past and (b) future period.

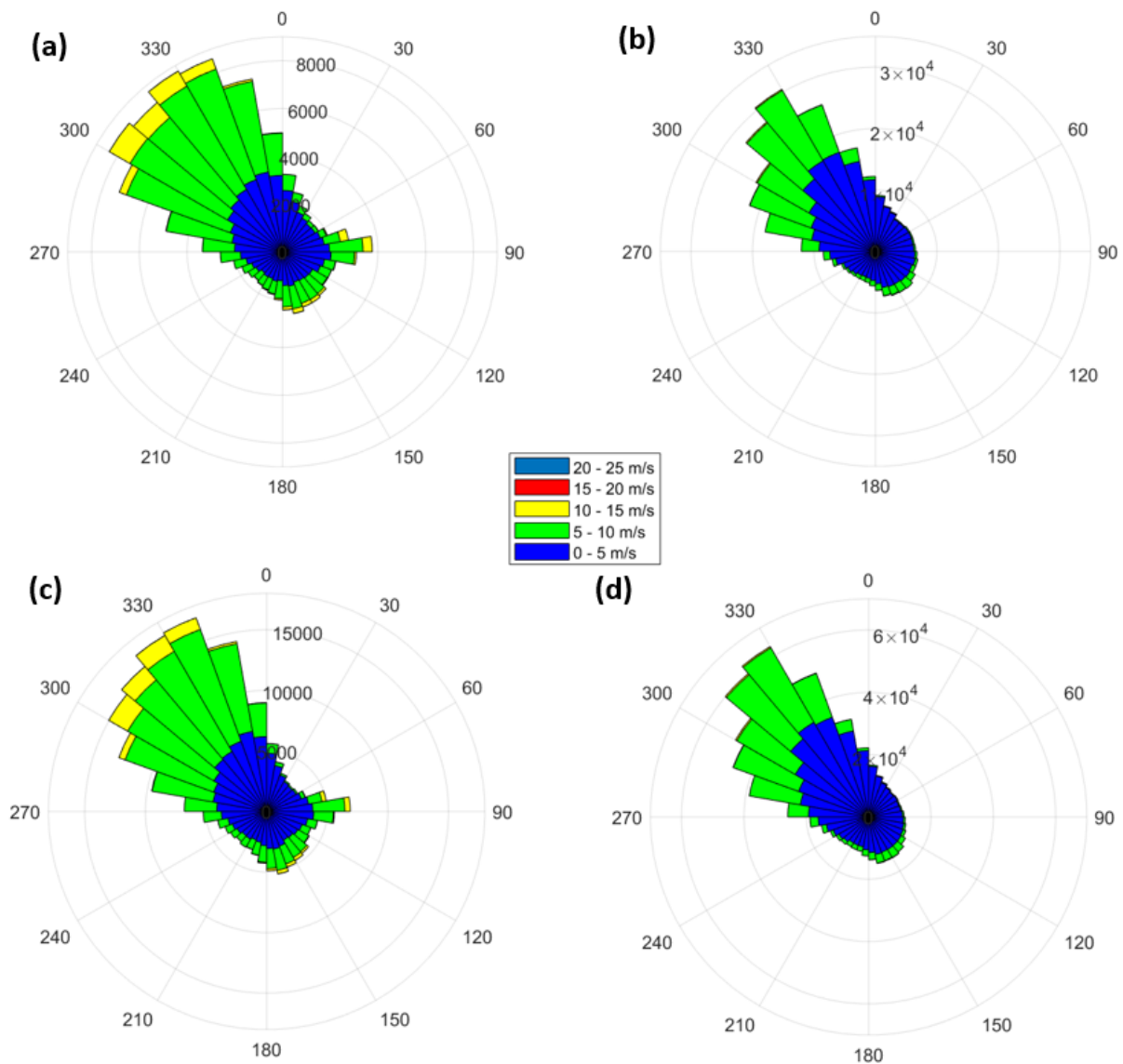


Figure 4.23: Wind rose diagrams of the ERA5 and REGCM wind data at Bushehr port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

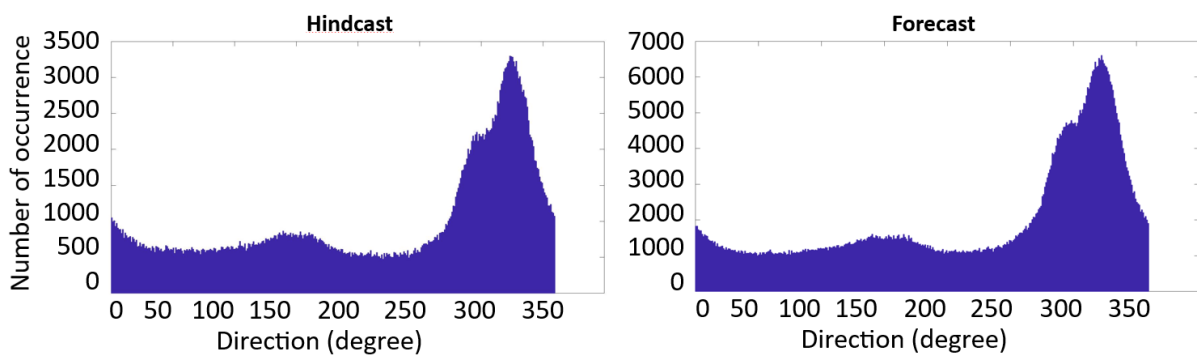


Figure 4.24: Histogram diagram of the ERA5 wind data at Bushehr port

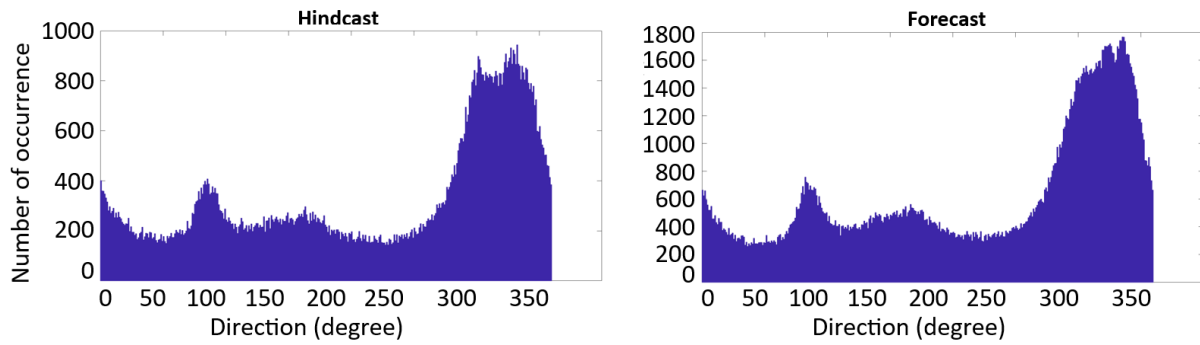


Figure 4.25: Histogram diagram of the REGCM wind data at Bushehr port

4.6 Analysis of Storm statistics

In this section, we present information about the statistics of extreme conditions in the wind data for both the ERA5 and REGCM models. Here we define storms as wind events with speeds higher than a threshold level. Because of the vastness of the Persian Gulf, the average wind velocity changes from point to point. Therefore, it does not make sense to consider a single threshold for all five points of study. Since we are interested in looking at the changes from past to future, we are less sensitive to the selection of the threshold wind level and chose it in such a way that we get a reasonable number of storms per year for each point ($1 < \text{storms/year} < 10$). This number of storms per year guarantees that the studied events are independent and the statistical analysis is valid.

Table 4.6 shows a comparison of the number of storms per year for different study points and the two investigated models. From this table, it appears that the REGCM and ERA5 models predict the change in the number of storms in opposite ways. From the REGCM data, it can be concluded that the number of storms per year in the future will be fewer than in the past. However, the ERA5 data predict that there will be more storms in the future. The origin of this discrepancy lies in the fact that Table 4.6 shows the number of storms, not the total number of storm hours. In order to make a fair comparison between the two models, one must look at the total number of storm hours, which is shown in Table 4.7. From this table, it is clear that both REGCM and ERA5 predict the same change from past to future. Based on both models, there are more storm hours in the future.

Table 4.6: Number of storms per year for different ports

Port	Number of storms/year				
	REGCM		ERA		
	Hindcast	Forecast	Hindcast	Forecast	
Lengeh	1.12	→ 0.96	2.15	→ 2.43	
Rajae	2.22	→ 2.13	1.29	→ 1.46	
Bahonar	2.29	→ 1.96	1.63	→ 1.79	
Asaluye	1.23	→ 1.12	1.09	→ 1.39	
Bushehr	2.04	→ 1.92	2.22	→ 2.51	

Table 4.7: Number of storm hours per year for different ports

Storm hours/year						
Port	REGCM			ERA		
	Hindcast		Forecast	Hindcast		Forecast
Lengeh	2.4	→	2.7	2.42	→	2.61
Rajae	8.94	→	9.43	1.74	→	2.13
Bahonar	2.8	→	3.3	2.42	→	2.61
Asaluye	4.1	→	4.7	2.12	→	2.97
Bushehr	9.4	→	9.1	6.06	→	6.75

Chapter 5

Wave simulation with SWAN

In this chapter, the simulation procedure for the wave conditions in the Persian Gulf for the whole period of interest is explained. We run the hindcast (1979 - 2020) and forecast (2021-2100) wave simulations using wind data provided by both the ERA5 and REGCM models.

As explained in Chapter 1, we limit our study area to five important ports as follows:

Point1: Lengeh port (54.896 E, 26.573N),

Point2: Rajaei port (56.205 E, 27.110 N),

Point3: Bahonar port (56.075 E, 27.079 N),

Point4: Asaluyeh port (52.590 E, 27.460 N),

Point5: Bushehr port (50.814 E, 29.009 N).

The locations of these points in the Persian Gulf are shown in Fig 5.1. The SWAN model is used to simulate the wave conditions.

5.1 SWAN model

The Simulating Waves Nearshore (SWAN) model is a third generation spectral wave model, which is an open source model developed at TU Delft to simulate wind –generated waves in the coastal regions as well as inland waters [98]. This simulation tool is especially suitable for large model areas and in shallow water regions [99]. The essential physical aspects of wave generation, propagation, interaction, and dissipation have been considered in the SWAN as follows:

(i) wave generation due to wind, (ii) wave propagation in time and space, (iii) shallow water processes such as shoaling and refraction due to currents and depth, (iv) interactions between three and four waves, (v) frequency shift due to currents and transient depth, (vi) frequency shift due to flow and transient depth, and (vii) dissipation due to white-capping, depth-limited breaking, soil friction, vegetation, etc. We can use the wave variance spectrum or energy density

$E(\sigma, \theta)$ to describe the sea surface. It shows the distribution of wave energy over frequencies σ and propagation directions θ . Wave simulation tools, including SWAN, usually use the action density $N(\vec{x}, t; \sigma, \theta)$ in space $\vec{x}$ and time, defined as follows:

$$N = \frac{E}{\sigma} \quad (5.1)$$

Main reason is that unlike the energy density, action density is conserved during the propagation of the wave. SWAN solves the equation for the wave action balance with sources and sinks [100]:

$$\frac{\partial}{\partial t} N(\sigma, \theta) + \nabla_{\vec{x}} \cdot [c_{\vec{x}} N(\sigma, \theta)] + \frac{\partial}{\partial \sigma} [c_{\sigma} N(\sigma, \theta)] + \frac{\partial}{\partial \theta} [c_{\theta} N(\sigma, \theta)] = \frac{S(\sigma, \theta)}{\sigma} \quad (5.2)$$

where $c_{\vec{x}}$ is the group velocity of the wave, while c_{σ} and c_{θ} represent the propagation velocities in spectral space (σ, θ) . $S(\sigma, \theta)$ is the source term which is determined by the wind.

SWAN can be run in spherical or Cartesian coordinates on a regular or curved or triangular mesh. It can be simulated in stationary or non-stationary modes, and both linear and non-linear deep and shallow water can be taken into account. For the discretization of the governing equation, SWAN uses the finite difference method.

5.2 Nesting approach

As can be seen in Fig 5.1, the study points from the east to west coasts of the Persian Gulf are far from each other. Therefore, it is necessary to perform the wave simulation for the whole area of the Persian Gulf. We will see in the next section that, in order to have precise simulations, we must have a computational mesh size which is close to the resolution of the bathymetry data. However, due to the vastness of the Persian Gulf, such a resolution results in more than 4 million mesh cells in the computational grid, which takes several days for a short-time simulation. Since we are only interested in the wave conditions at the few points mentioned above (for the sake of validation and later wave condition investigation), we do not need a fine resolution over the whole area of the Persian Gulf. There are two ways to have a non-uniform mesh size. The first option is to use an unstructured mesh. An example of an unstructured mesh is shown in Fig 5.2. As can be seen in this figure, with this option, one can use a finer mesh around the points of interest. However, this type of mesh is not compatible with the MPI parallel solver. Since we definitely need a parallel simulation considering the long time period of the study (over 120 years), we chose the second method to have a finer mesh in the study points, which is the nested mesh approach. In this approach, the simulation is performed in two (or more) steps. In the last step, a small area around the study point is simulated with the required mesh size. However, boundary conditions should be provided for the boundary of the computational domain. Such information is obtained from the previous step, which is run for a larger area with coarser cells. Therefore, we use the nested approach to have a finer mesh size in the five selected ports as explained in Chapter 4. Two levels of nesting are applied to achieve a mesh size of about 550 meters at the target points. In the first run, the whole area is simulated with about a 0.2 degree mesh size, which provides the boundary conditions for the next step. In this step, we simulate the wave in three subdomains as shown in Fig 5.3. The first subdomain includes



Figure 5.1: location of the study points in the Persian Gulf

points $P1, P2$ and $P3$ while the other two subdomains are dedicated to points $P4$ and $P5$. The mesh resolution in this step is 0.05 degree. As in the previous step, the simulation results are used as the boundary conditions for the last step, in which we have five subdomains for each target point with a resolution of 0.005 degree. This procedure is shown in Fig 5.4.

As it can be seen, in order to have final results for all five points of interest, we have to run nine SWAN codes. On the other hand, it doesn't make sense to run the whole period at once, since any interruption in the used computer nodes could lead to the loss of all data and force to redo the simulations. Therefore, we divided the simulation period into 8-year intervals and ran the simulations for each interval separately. SWAN offers the possibility to save the results at the end of the simulation time and to use them as initial conditions for the next time interval. Splitting the simulation time results in six time intervals for the hindcast simulations and ten intervals for the forecast simulations, 16 in total.

Since all nine runs have to be performed for each time interval, we needed a total of 144 separate simulations. Considering that we are interested in the wave generated by both the ERA5 and REGCM models, a total of 288 SWAN runs were performed. Even if we ignore computational limitations, it is also clear that most of these simulations cannot be run in parallel because they require the output of the previous time interval or the last nesting step to be started.

It has to be noted that ERA5 model provides wind data in spherical coordinates while REGCM wind data is in Cartesian coordinates. Therefore, the coordinate system of the SWAN simulation has to be adapted based on the model. All other input information such as bathymetrical data or coordinates of the points must also converted from spherical to Cartesian coordinate.

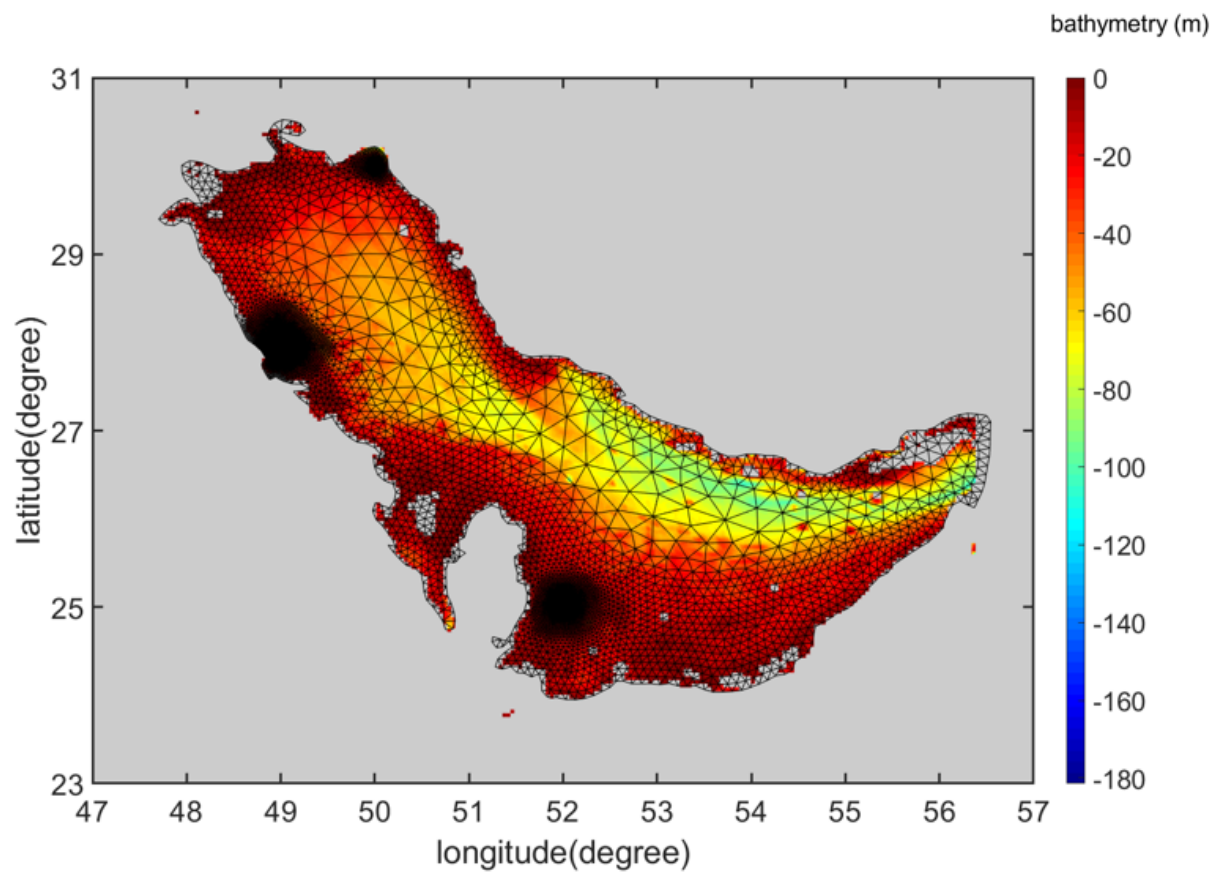


Figure 5.2: Example of an unstructured mesh in the Persian Gulf to have finer mesh size in special points

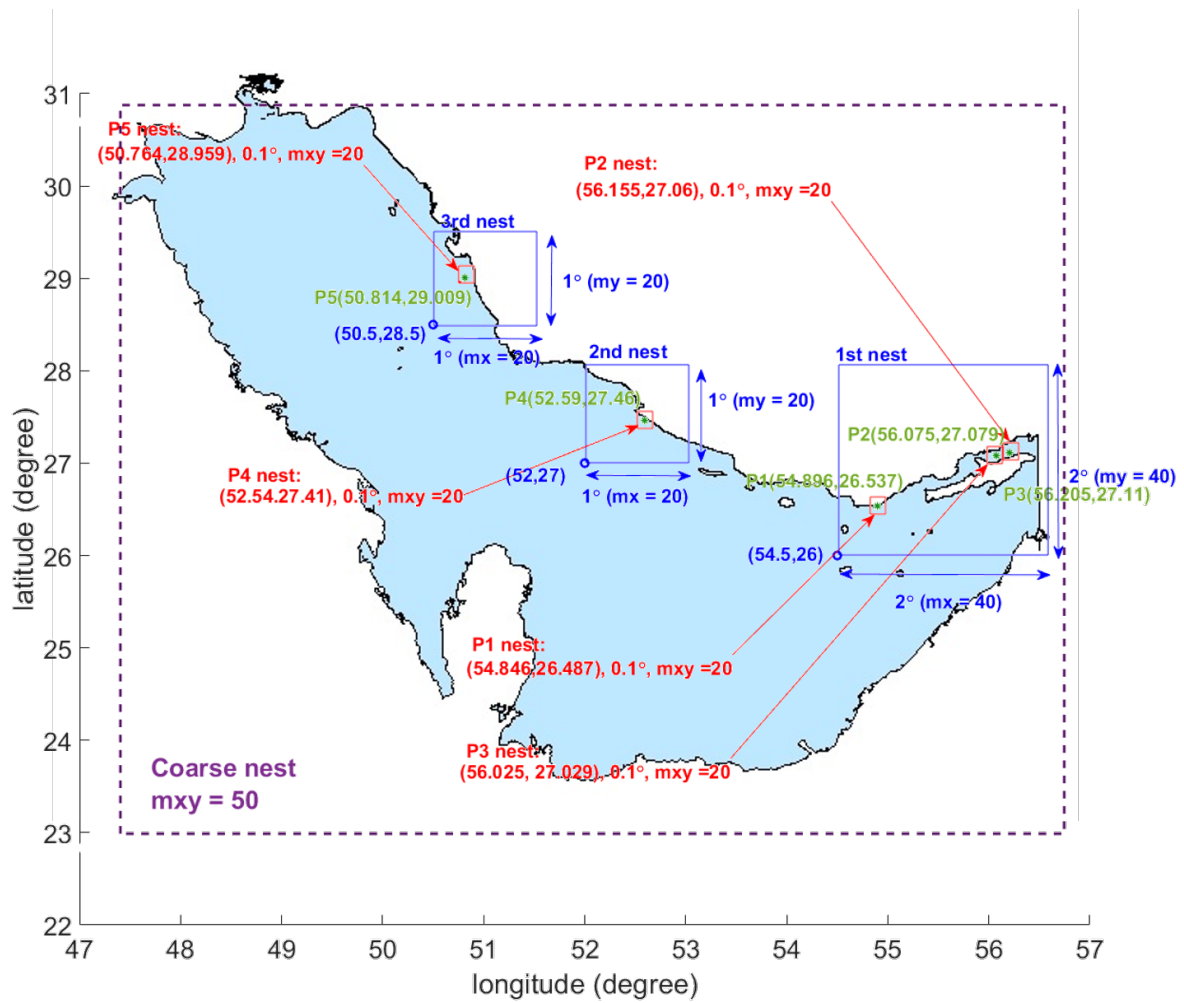


Figure 5.3: Coordinates of the study points as well as nests that are used for the wave simulations.

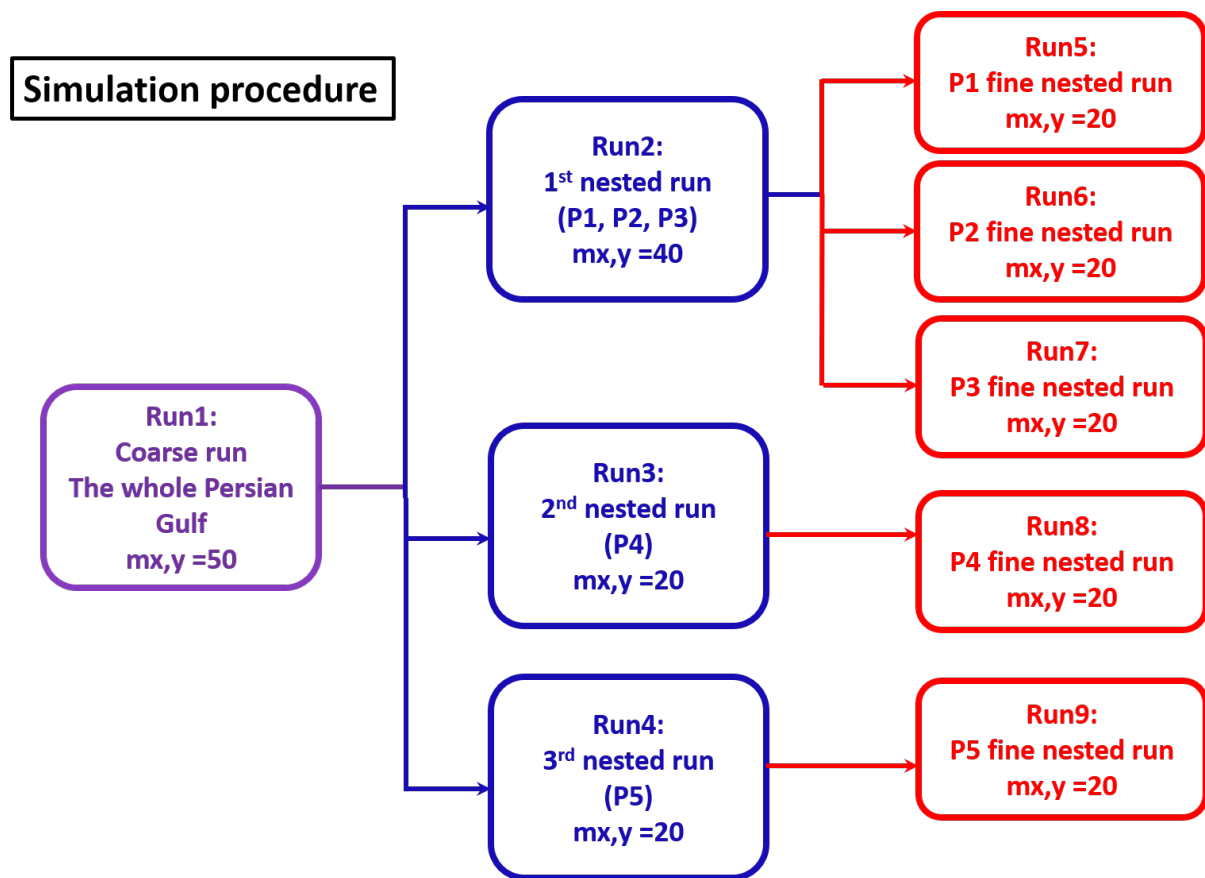


Figure 5.4: procedure of the SWAN simulations using nesting approach

5.3 Validation and Sensitivity analysis of the SWAN model

5.3.1 Sensitivity analysis

The General Bathymetric Chart of the Oceans (GEBCO) releases the global bathymetry grid, which has been provided by the international group of experts in ocean mapping [101]. In our study, we have used the GEBCO_2020 grid, which is a global ocean and land terrain model providing elevation data in meters on a 15 arc second grid. The data can be downloaded in netCDF, or Esri ASCII raster, or GeoTiff from the GEBCO website. These data have a resolution of 0.00417 degrees (corresponds to 15 arc seconds) for both latitude and longitude in spherical coordinates. This resolution corresponds to a grid size of about 450 meters. We considered the entire area of the Persian Gulf, which extends from 47° E to 56.4° E in the longitude and from 23° N to 31° N in the latitude. Therefore, we have a 2225×1919 matrix representing the bathymetric data of the study area. Fig 5.5 shows the bathymetric data used for the Persian Gulf.

Since the resolution of the bathymetry data is about 450 meters, which is much higher than the resolution of the wind data, one has to perform some sensitivity analysis on the mesh size to find the required fineness of the mesh cells for the SWAN simulation.

We repeated the simulation for different mesh sizes from 2.2 km down to 300 m and looked at the convergence results to find the required mesh resolution. Such results are shown in Fig 5.6. As can be seen from these curves, a coarser mesh size leads to an underestimation of the significant wave height. On the other hand, there is no significant change in the results when the mesh size is reduced from 550 meters to 300 meters. Therefore, we conclude that a mesh size of about 550 meters should be sufficient to simulate the wave conditions in the Persian Gulf. It also makes sense since such a resolution is the same as what we have for the bathymetric data.

5.3.2 SWAN model validation

It is necessary to validate the SWAN model by comparing its results with the observation data. For this purpose, we have performed the validation of the model for two buoy stations where measurement data for the wave properties are available for a short period of time as follows:

Station 1, near Bushehr port: coordinates (50.50° E, 28.58° N), depth: 56 m,

Station 2, near Asaluyeh port: coordinates (52.55° E, 27.51° N), depth: 50 m.

These two stations are shown in Fig 5.7 by red and green stars. The actual data of the waves at these points are available for 2008. Therefore, we ran the simulations for a three-month period from April to June 2008. As mentioned above, sensitivity analysis showed that a mesh size of 550 meters is fine enough to ensure an accurate simulation. Therefore, we validate our SWAN model with this mesh size. As explained before, a nested approach is applied to achieve such a resolution in the For the validation we performed a two-level nesting approach which is illustrated in Fig 5.8. In the first step a coarse nest of 0.2 degree (around 20 km) is used to simulate the entire area of the Persian Gulf. The results of this step provided the boundary conditions of the first nested mesh which has 0.05-degree (around 5.5 km) resolution. Finally, the last step would be two high resolution simulation around the target point with 0.005 degree (around 550 meters) mesh size.

Fig 5.9 shows a comparison between the simulation results and the observed data for the signifi-

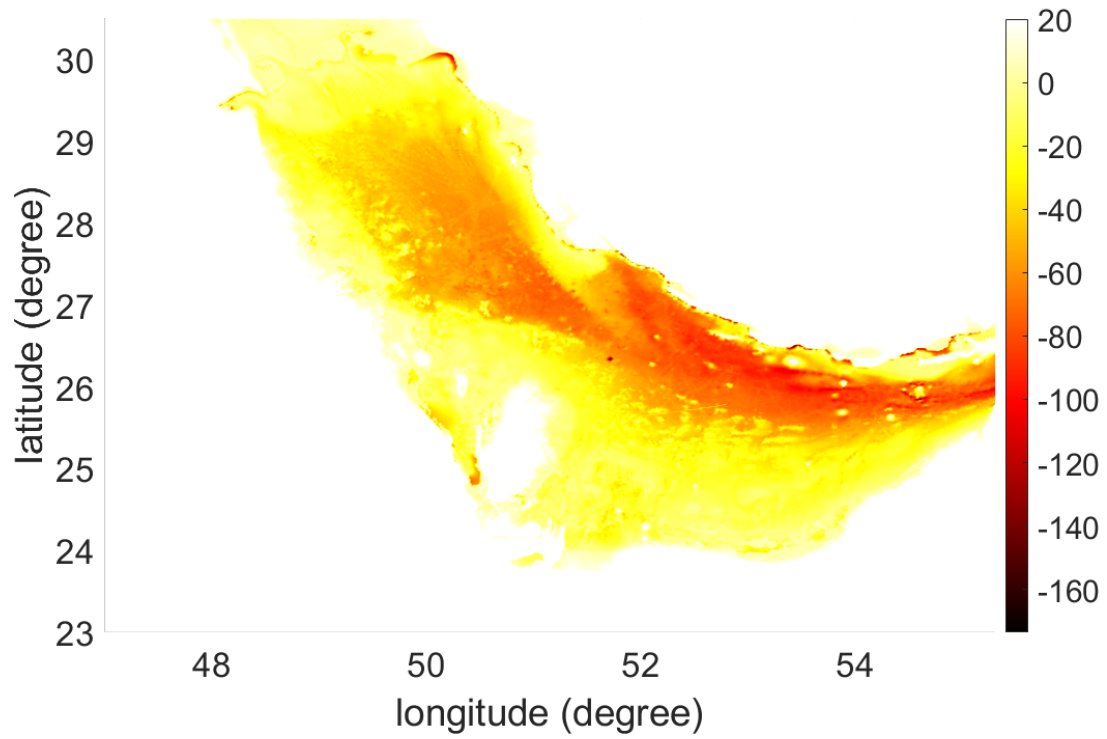


Figure 5.5: Bathymetric data of the Persian Gulf

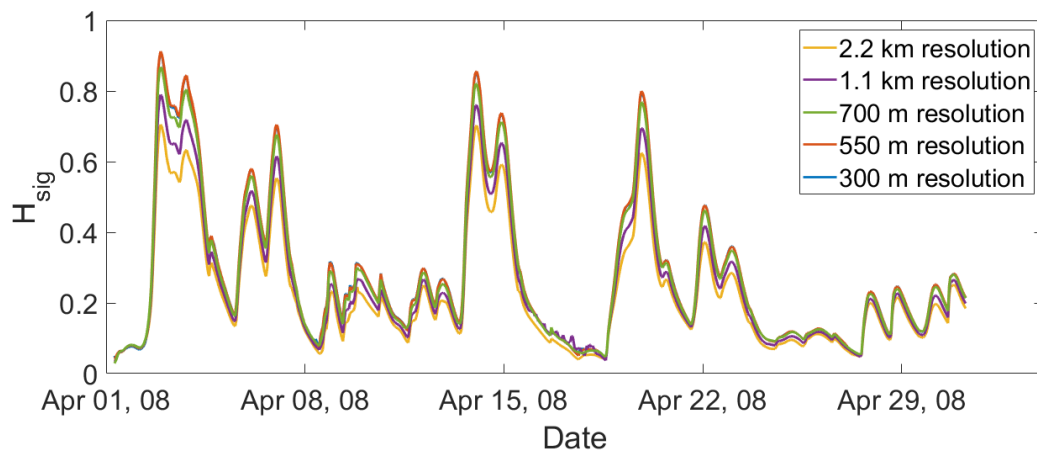


Figure 5.6: Sensitivity analysis of the SWAN model to the mesh resolution



Figure 5.7: Location of the stations for which measurement data is available and can be used for the sensitivity analysis and validation.

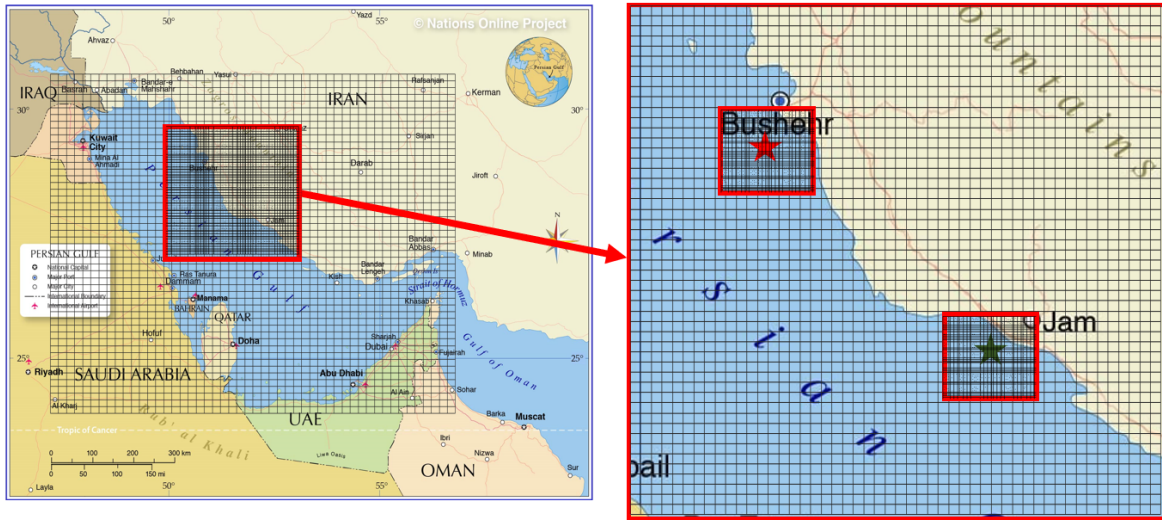


Figure 5.8: Nested approach used for the validation and sensitivity analysis

cant wave height H_{sig} at the first validation point (Bushehr) for a period of three months from the beginning of April to the end of June 2008. As can be seen, there is a very good agreement between simulation and measurement. Fig 5.10 shows the wind data provided by the ERA5 model together with the actual data measured for this time period. It can be seen that the two set of data are fitting very well for most of the times.

Peak period of the wave at this point is also depicted in Fig 5.11 for both simulation and observation.

For a better statistical comparison between simulation and observation data, they can be plotted as horizontal and vertical axes of a curve and the Root Mean Square Error (RMSE) for the significant wave height and peak period and the Mean Average Error (MAE) for the wave direction can be calculated. Such curves are shown in Fig 5.12 It can be seen that the points are mainly around the unity line. The RMSE for the significant wave height is 0.28 m and for the peak period is 1.01 s, while the MAE for the wave direction is 25 degrees. All these values show the good agreement between the simulations and the observations. It also shows that the wind data provided by the ERA5 model are very close to the reality. It is also shown Fig 5.13 which illustrates a statistical comparison between the actual wind data and the information provided by the ERA5 model at Bushehr.

We repeated the same procedure for the second validation point (Asaluyeh). Fig 5.14 shows the simulation and observation data for the significant wave height at this point. As with the Bushehr station, there is a good agreement between the simulation and observation data. Fig 5.15 shows a comparison between the wind data of the ERA5 model and the measured values while Fig 5.16 shows the peak period for the two sets of data. As with the Bushehr point, here we made a statistical comparison between the observed and simulated wave and wind properties which are shown in Fig. 5.17.

In summary, for both study points there is a good agreement between the observational data

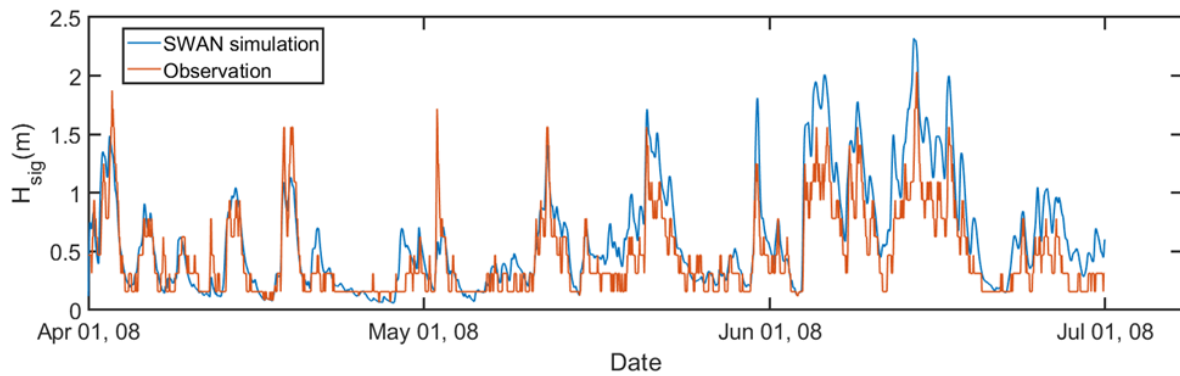


Figure 5.9: Comparison between the simulation and measurement data for significant wave height at Busher

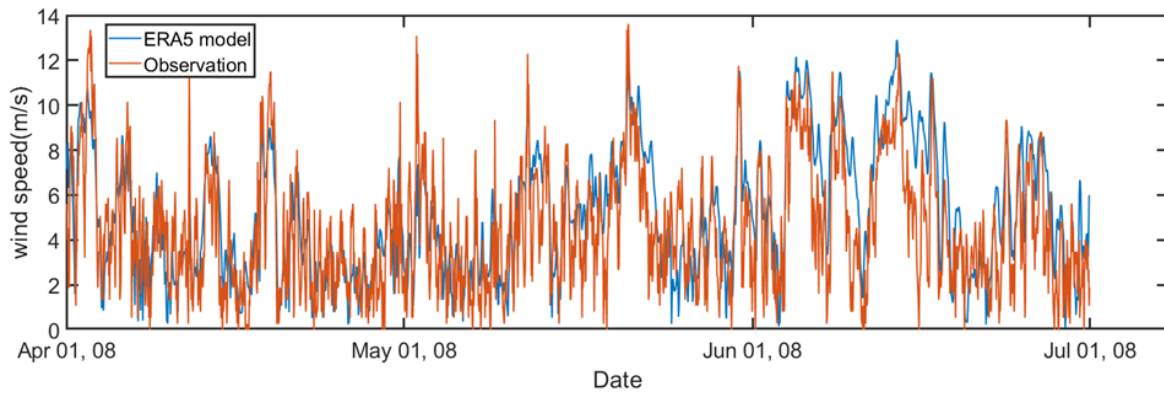


Figure 5.10: Comparison between the wind speed values provided by ERA5 model and the measurement data at Bushehr

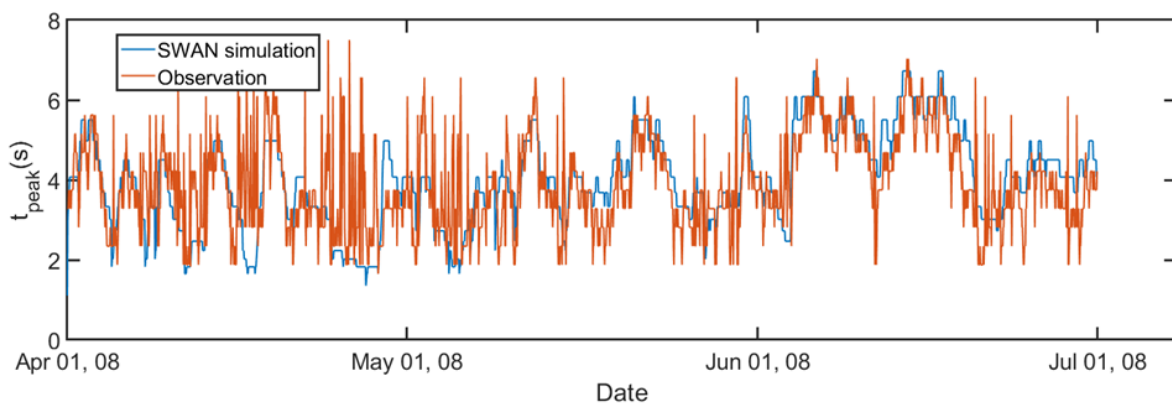


Figure 5.11: Comparison between the simulation and measurement data for peak period at Bushehr

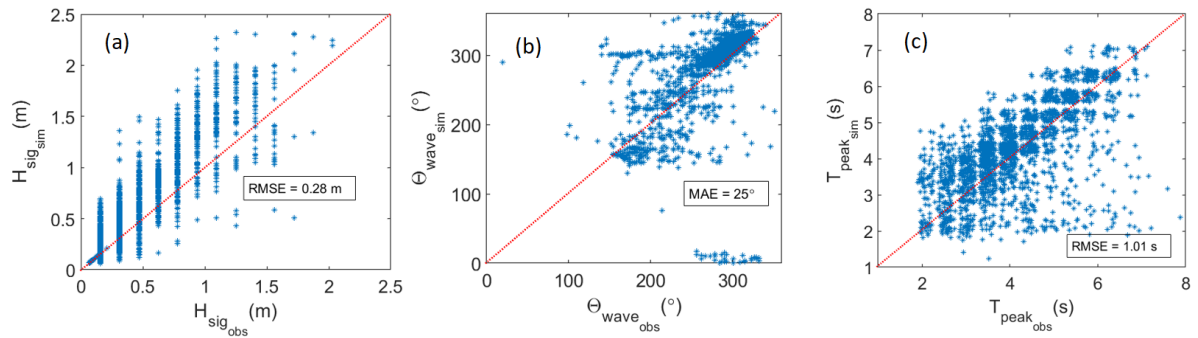


Figure 5.12: Comparison between the simulation and measurement data for (a) significant wave height, (b) wave direction, and (c) peak period at Busher

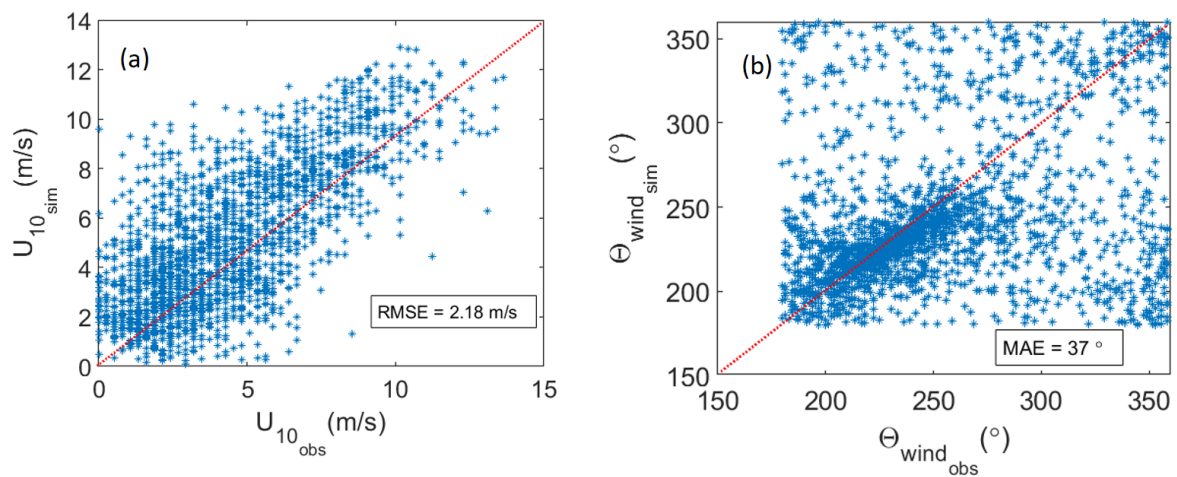


Figure 5.13: Comparison between the (a) wind speed and (b) wind direction values provided by ERA5 model and the observed data at Busher

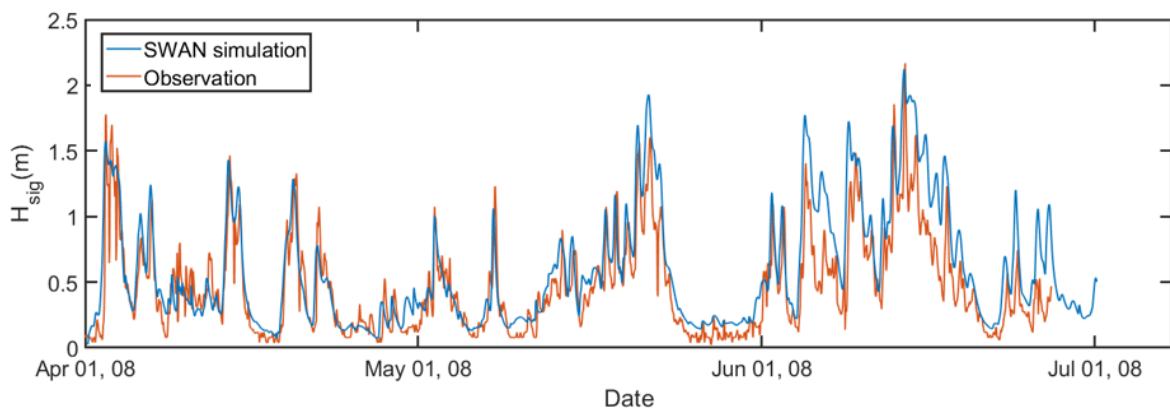


Figure 5.14: Comparison between the simulation and measurement data for significant wave height at Asaluve

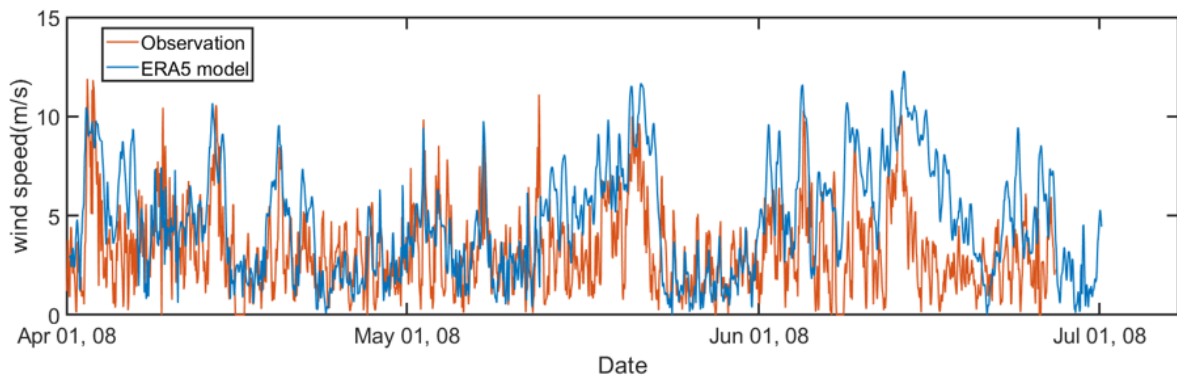


Figure 5.15: Comparison between the wind speed values provided by the ERA5 model and the measurement data at Asaluye

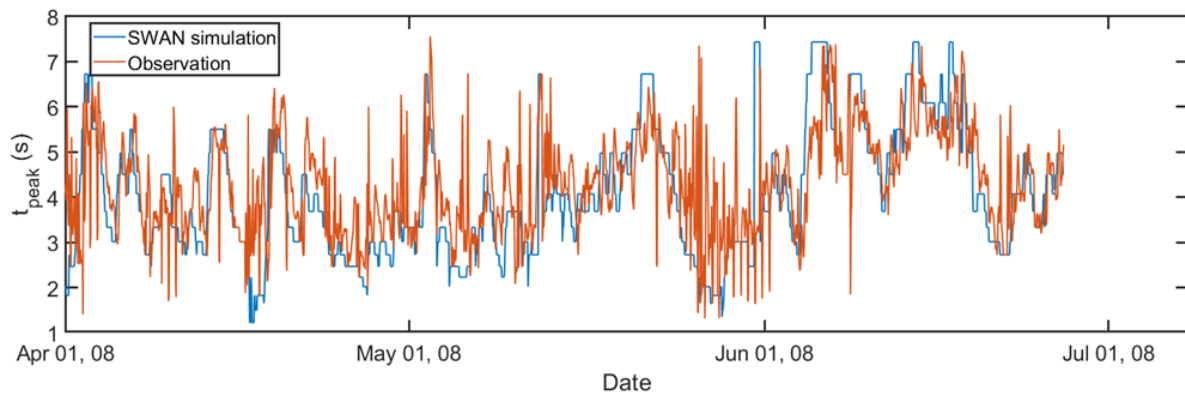


Figure 5.16: Comparison between the simulation and measurement data for peak period at Asaluye

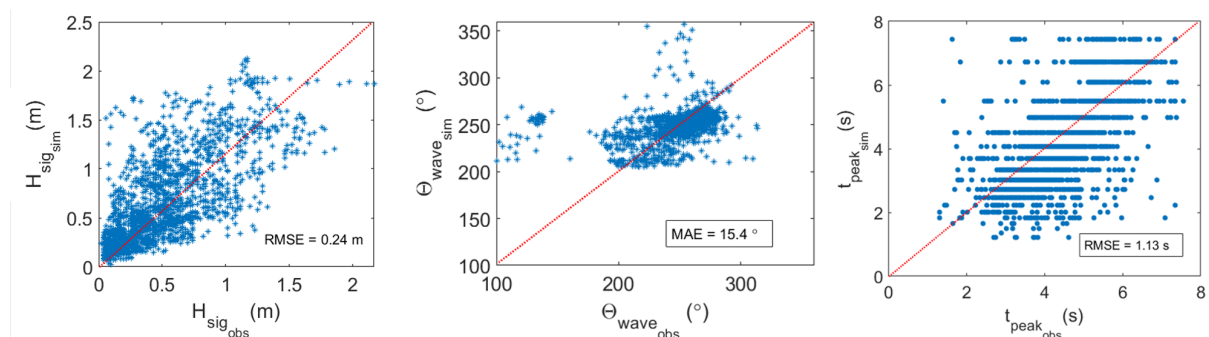


Figure 5.17: Comparison between the simulation and measurement data for (a) significant wave height, (b) wave direction, and (c) peak period at Asaluye

and the results of the simulation by SWAN, which validates the model used as well as the nested approach and the mesh size chosen.

5.4 Wave simulation results

After validation of the SWAN model we performed the simulations to find the wave properties at five study points using both ERA5 and REGCM wind data. In the following we present the simulation results.

5.4.1 P1 - Lengeh port

Fig 5.18 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of the significant wave height H_{sig} at Lengeh port from the ERA5 model, while such time series for the REGCM model are shown in Fig 5.19.

Fig 5.20 shows the waverose of these four data sets. Note that these curves show the direction from which the wind is blowing. As can be seen from the waveroses, at this port the waves generated by the ERA5 wind data come mainly from one direction. However, simulations with the REGCM wind predict two classes of waves based on their direction. We will discuss the possible reasons for this difference in the next section in detail. Fig 5.21 and 5.22 show histogram plots of the waves, which also illustrate the contribution of each direction to the overall data. Fig 5.23 and 5.24 show the peak period of the waves generated by ERA5 and REGCM wind, respectively.

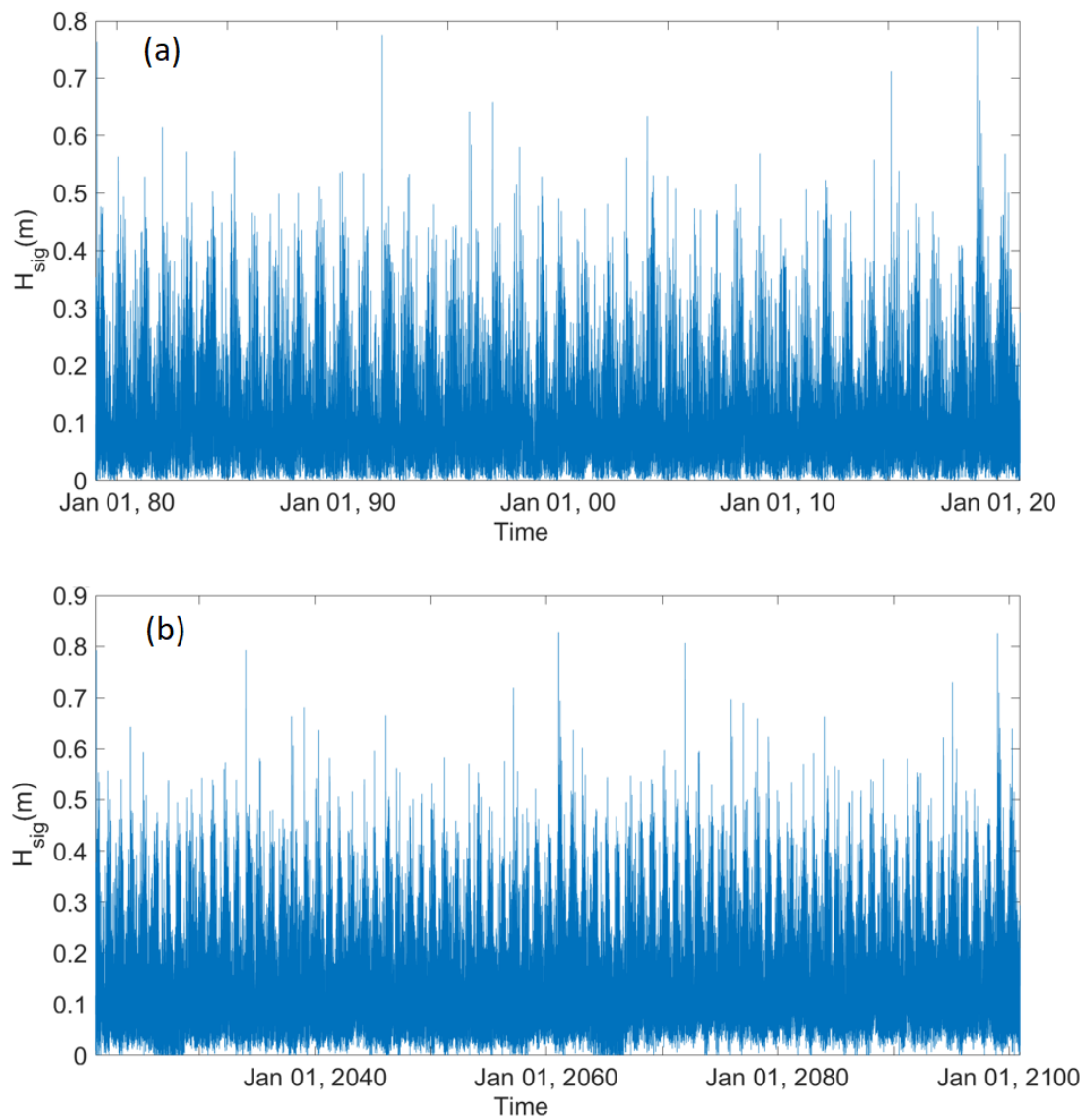


Figure 5.18: Time series of the significant wave height simulated using ERA5 wind data at Lenghe port for (a) past and (b) future period.

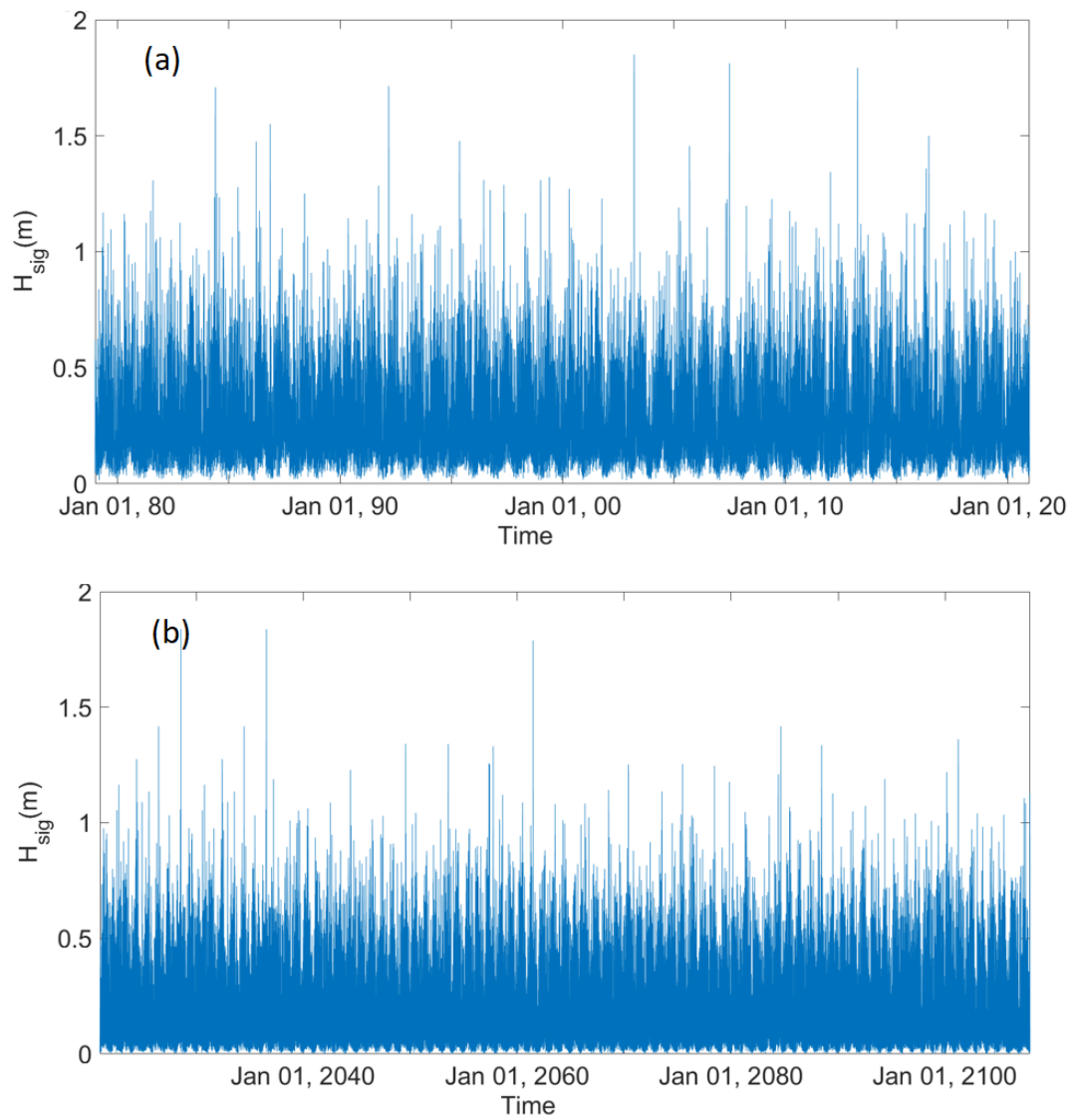


Figure 5.19: Time series of the significant wave height simulated using REGCM wind data at Lenghe port for (a) past and (b) future period.

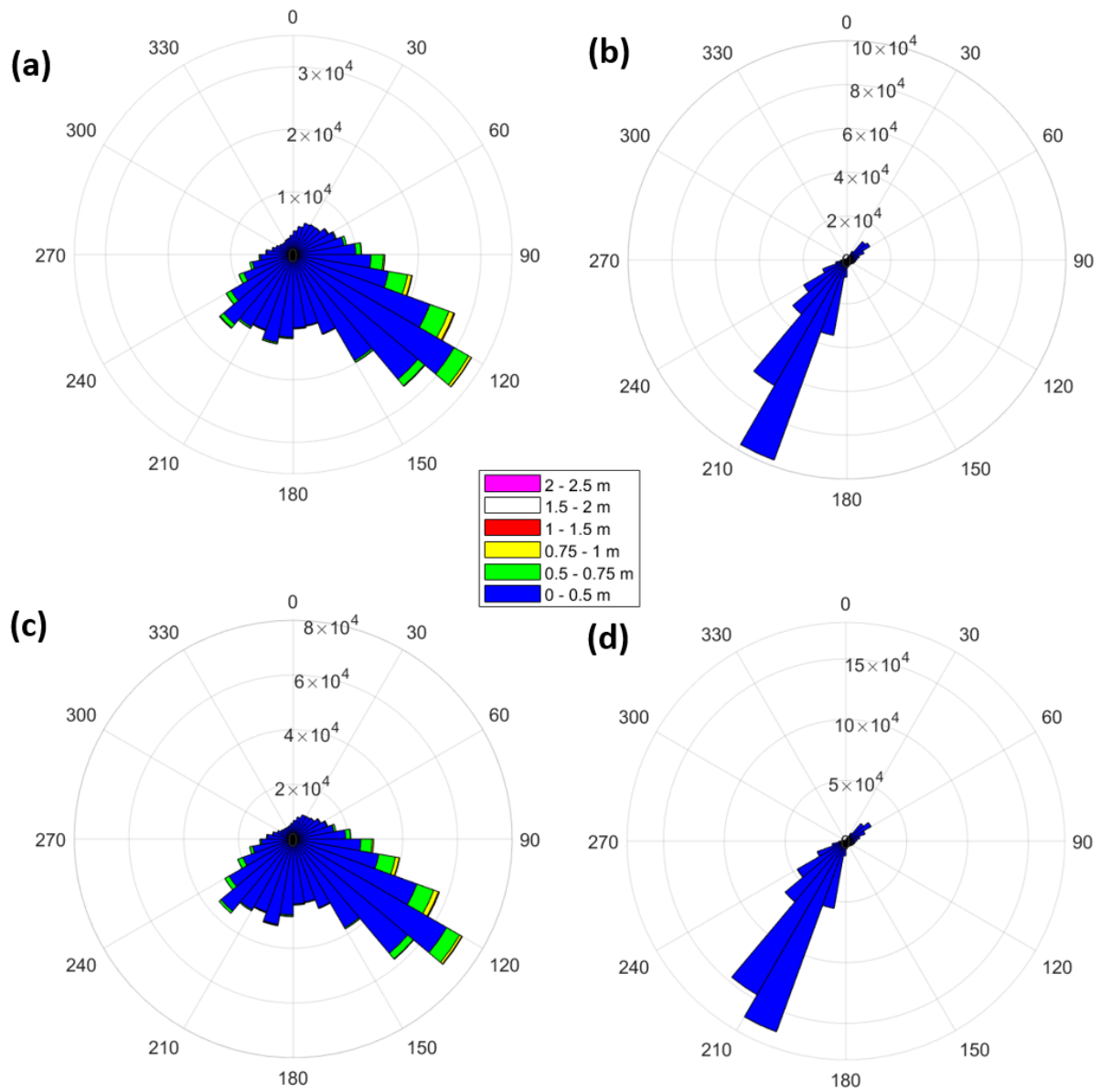


Figure 5.20: Waverose diagrams of the ERA5 and REGCM wave data at Lengeh port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

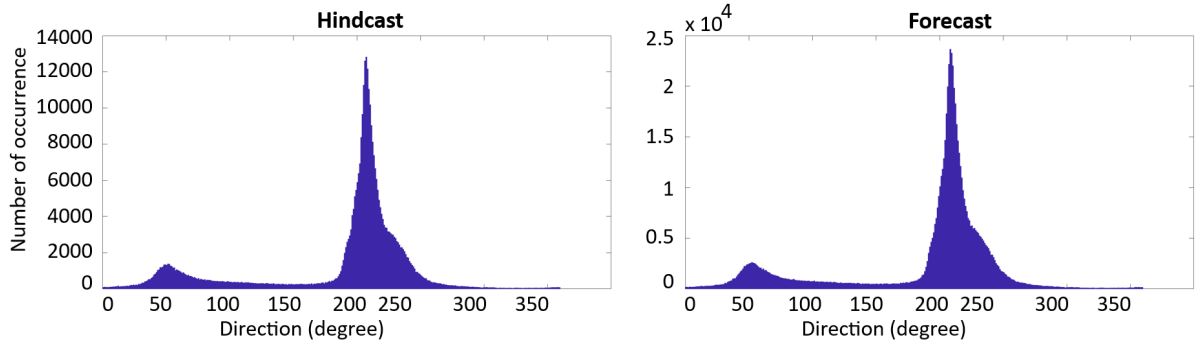


Figure 5.21: Histogram diagram of the ERA5 wave data at Lengeh port

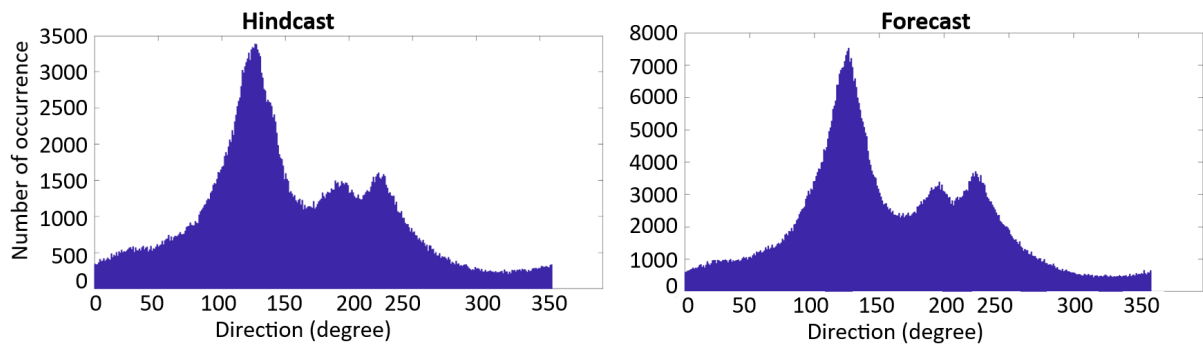


Figure 5.22: Histogram diagram of the REGCM wave data at Lengeh port

5.4.2 P2 - Rajae port

Fig 5.25 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of the significant wave height H_{sig} at Rajae port from the ERA5 model, while such time series for the REGCM model are shown in Fig 5.26.

Fig 5.27 shows the waveroses of these four data sets. As with the Lengeh port, it can be seen from the waveroses that the waves generated by the ERA5 wind data come mainly from one direction. However, simulations with the REGCM wind predict a broader range of wave directions. Fig 5.28 and 5.29 show histogram plots of the waves, which also illustrate the contribution of each direction to the overall data. Fig 5.30 and 5.31 show the peak period of the waves generated by ERA5 and REGCM wind, respectively.

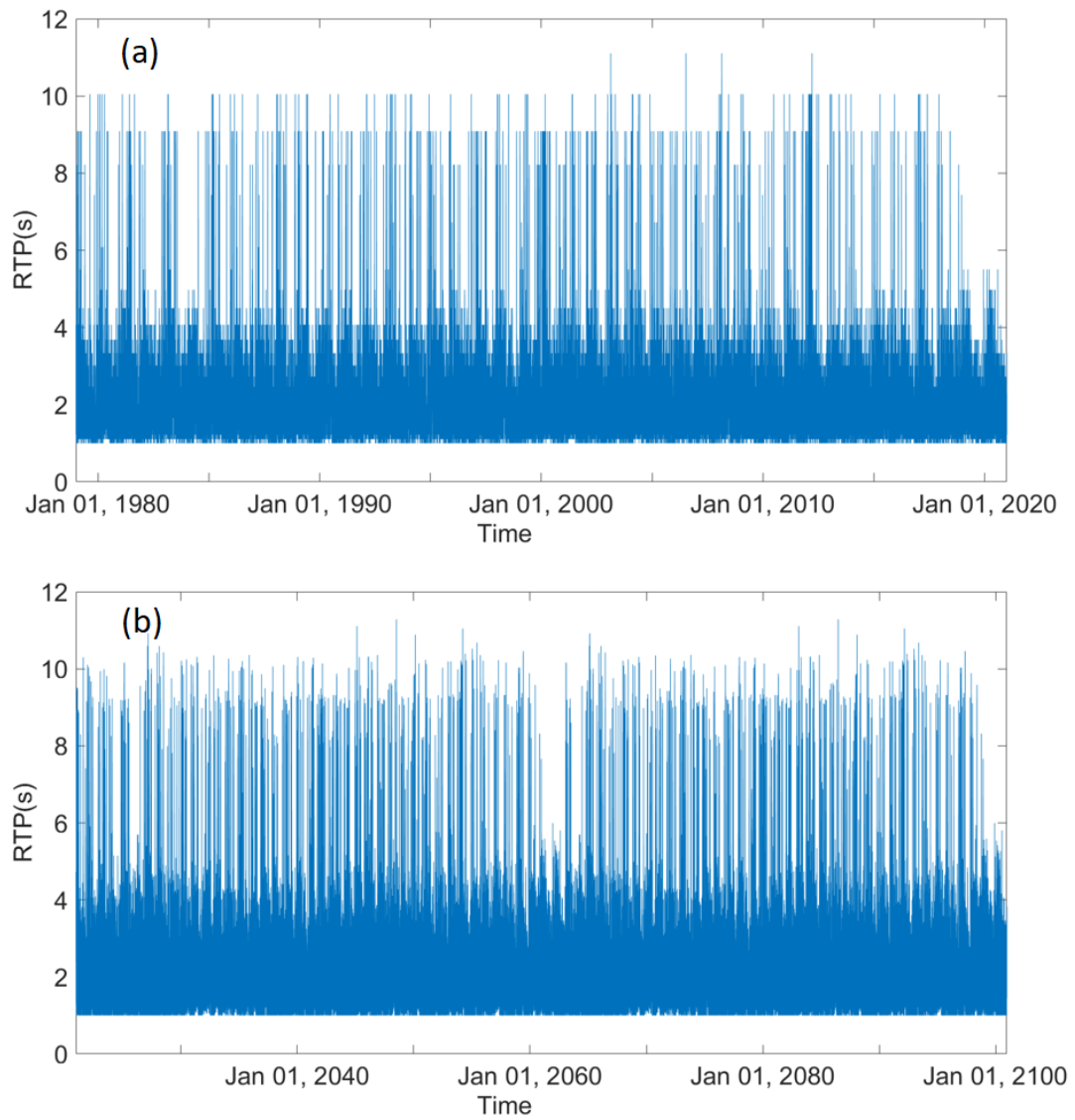


Figure 5.23: Time series of the peak wave period simulated using ERA5 wind data at Lengeh port for (a) past and (b) future period.

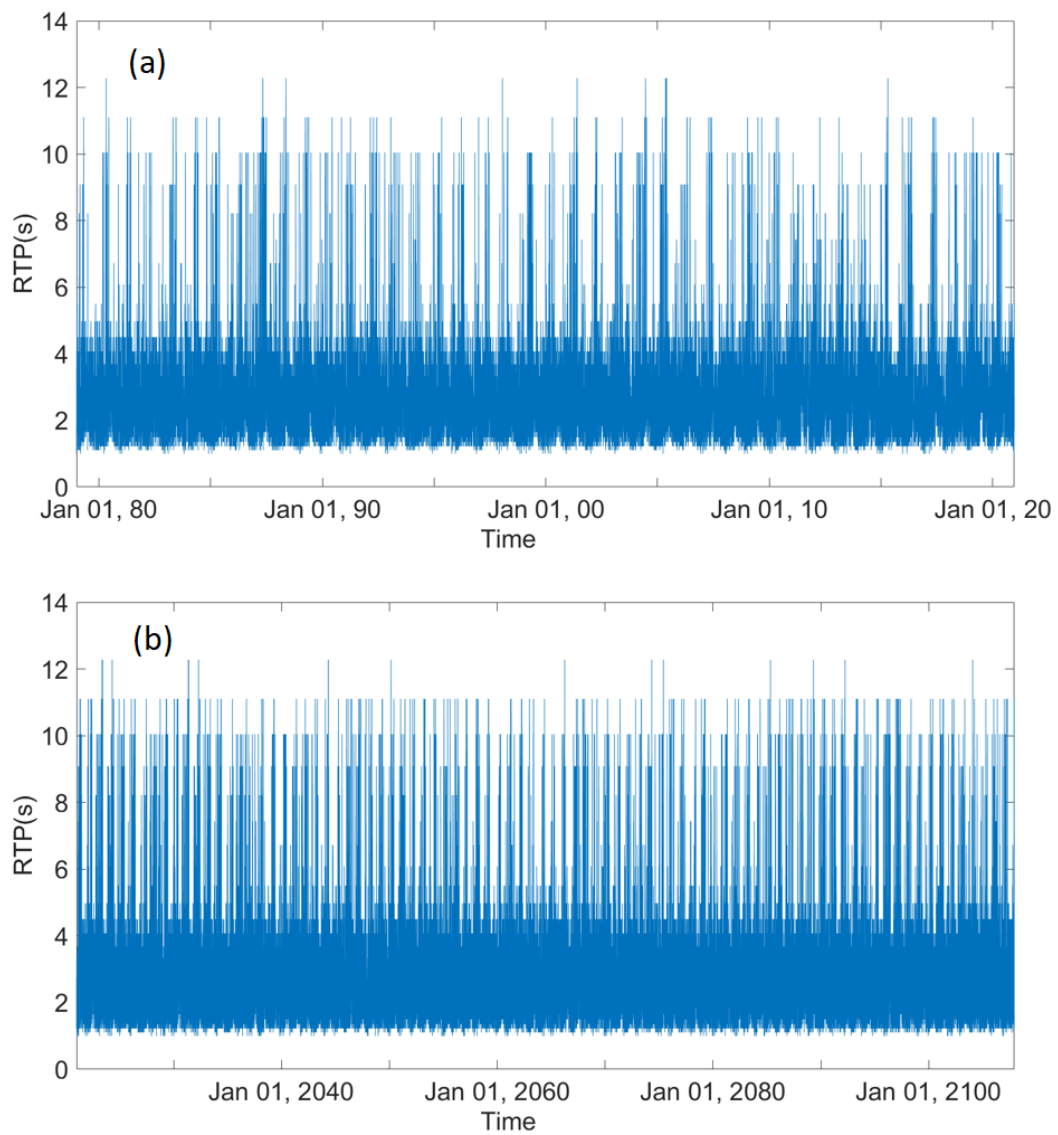


Figure 5.24: Time series of the peak wave period simulated using REGCM wind data at Lengeh port for (a) past and (b) future period.

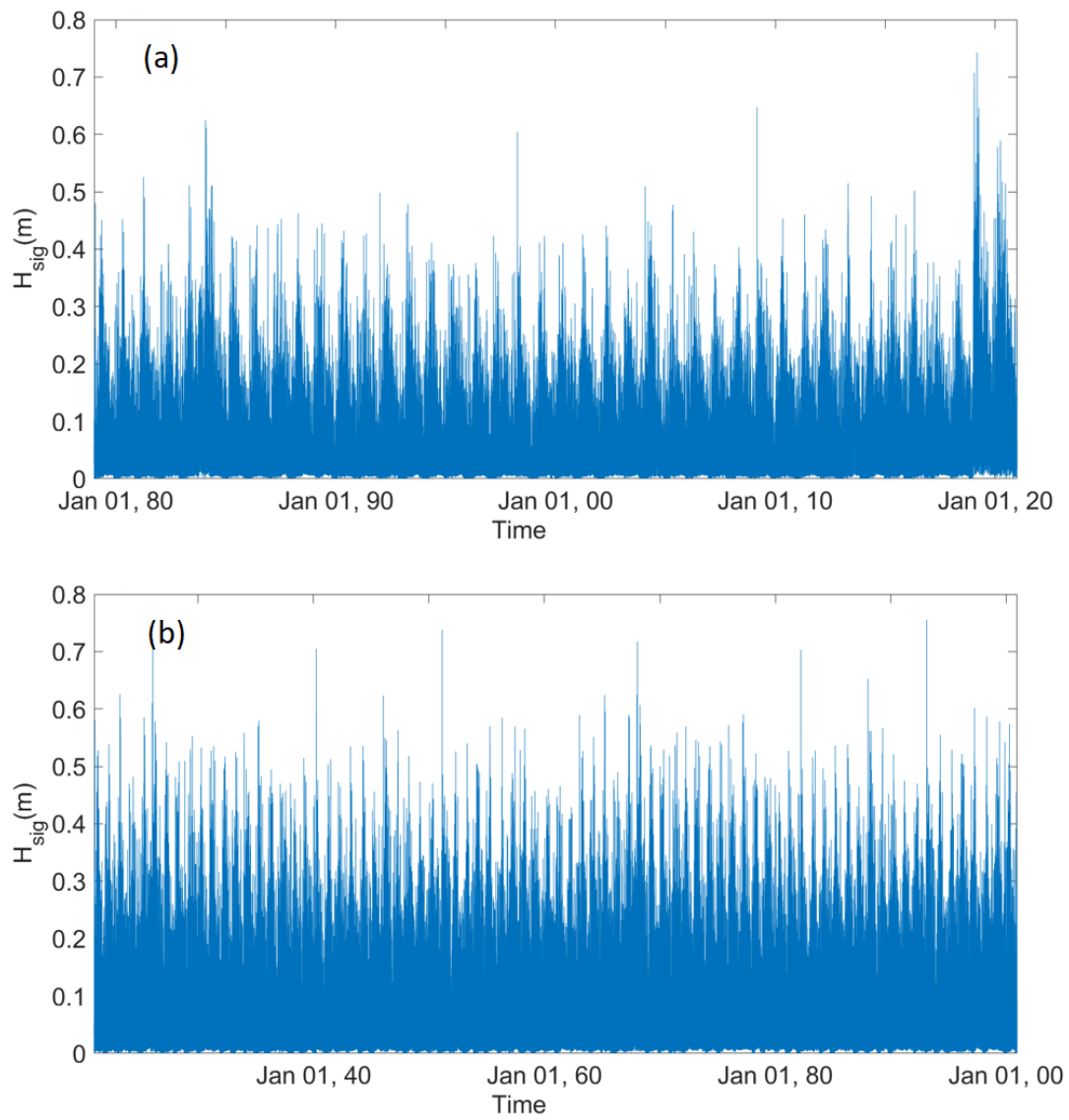


Figure 5.25: Time series of the significant wave height simulated using ERA5 wind data at Rajae port for (a) past and (b) future period.

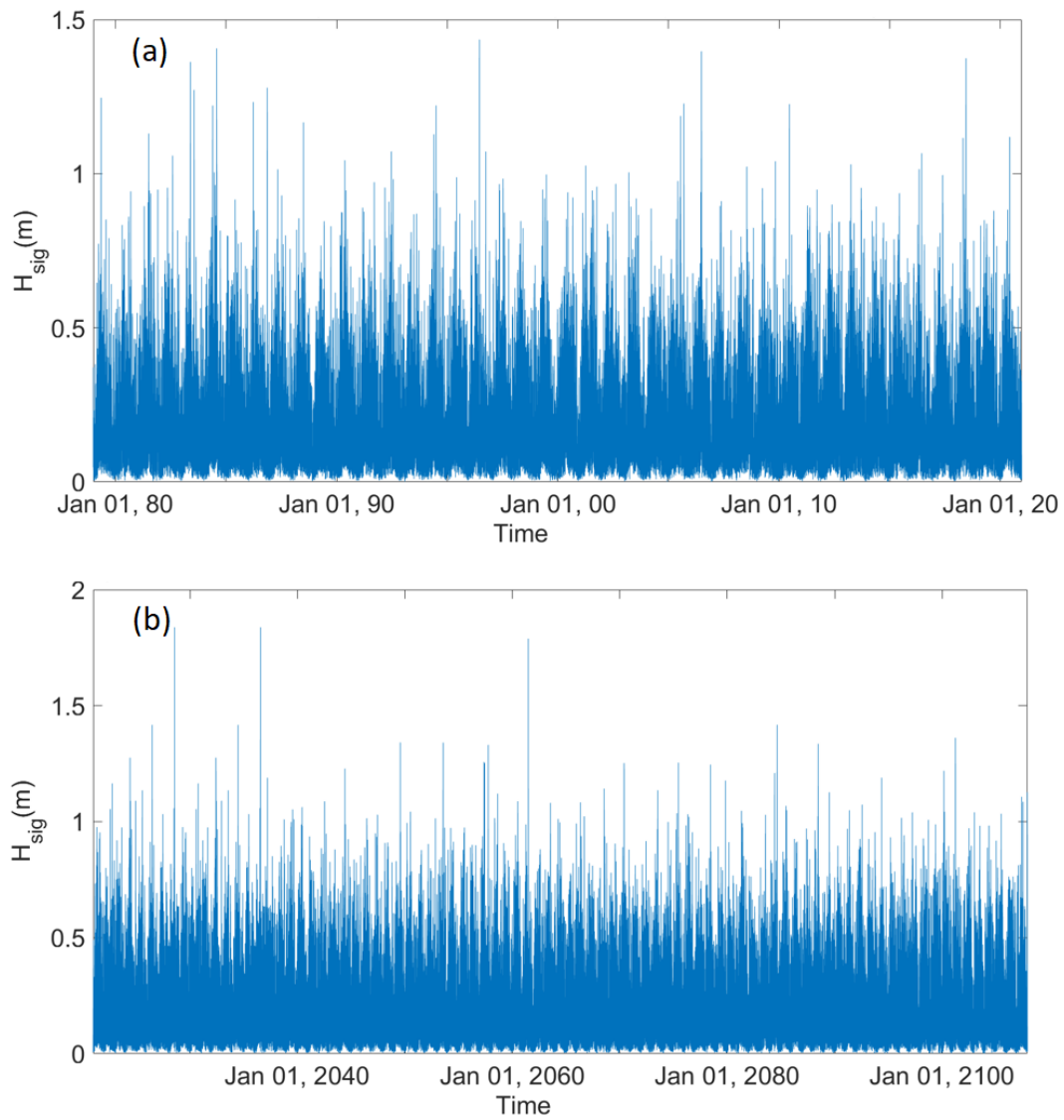


Figure 5.26: Time series of the significant wave height simulated using REGCM wind data at Rajae port for (a) past and (b) future period.

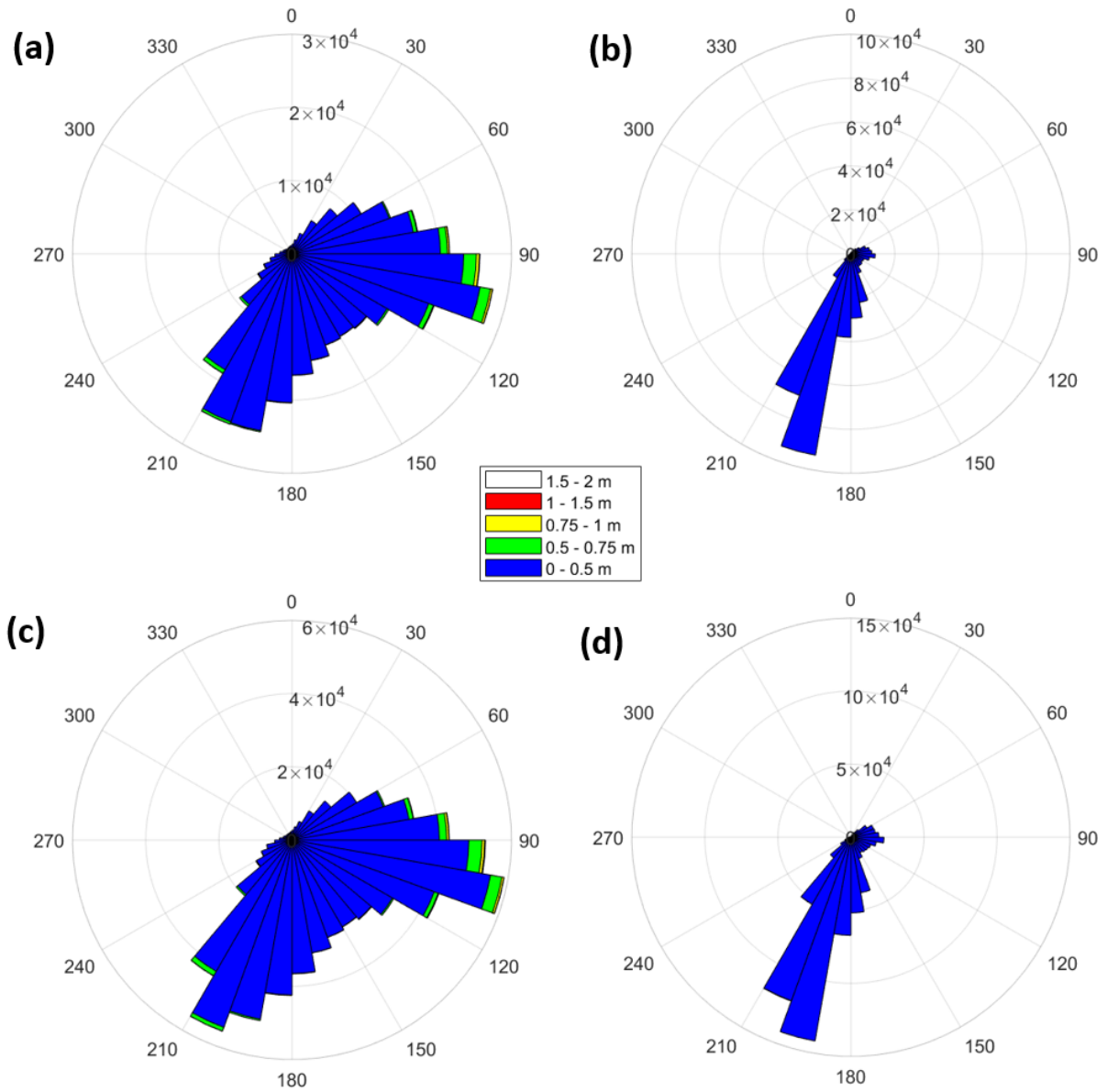


Figure 5.27: Waverose diagrams of the ERA5 and REGCM wave data at Rajae port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

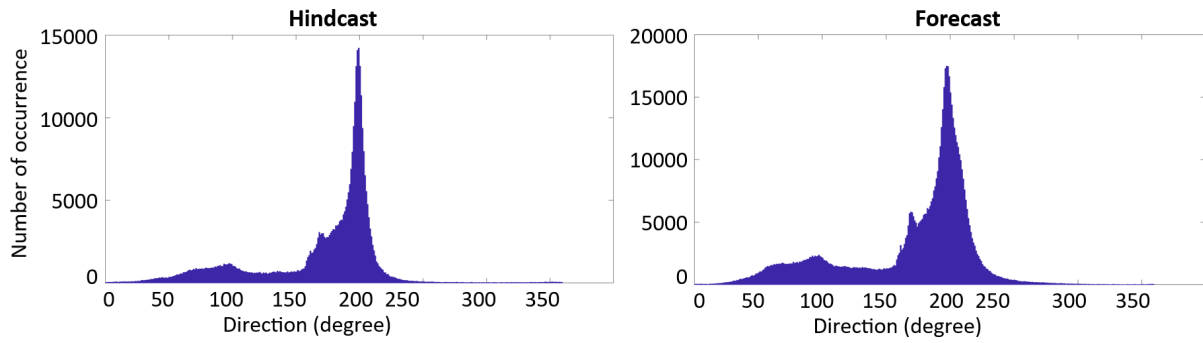


Figure 5.28: Histogram diagram of the ERA5 wave data at Rajae port

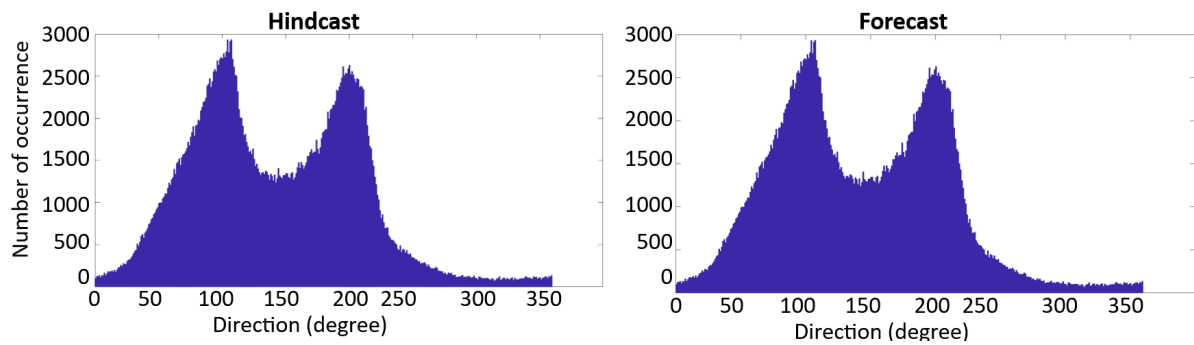


Figure 5.29: Histogram diagram of the REGCM wave data at Rajae port

5.4.3 P3 - Bahonar port

Fig 5.32 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of the significant wave height H_{sig} at Bahonar port from the ERA5 model, while such time series for the REGCM model are shown in Fig 5.33.

Fig 5.34 shows the waverose of these four data sets. Again, it can be seen from the waveroses that the waves generated by the ERA5 wind data come mainly from one directions. However, simulations with the REGCM wind predict a broader range of wave direction. Figures 5.35 and 5.36 show histogram plots of the waves, which also illustrate the contribution of each direction to the overall data. Fig 5.37 and 5.38 show the peak period of the wave generated by ERA5 and REGCM wind, respectively.

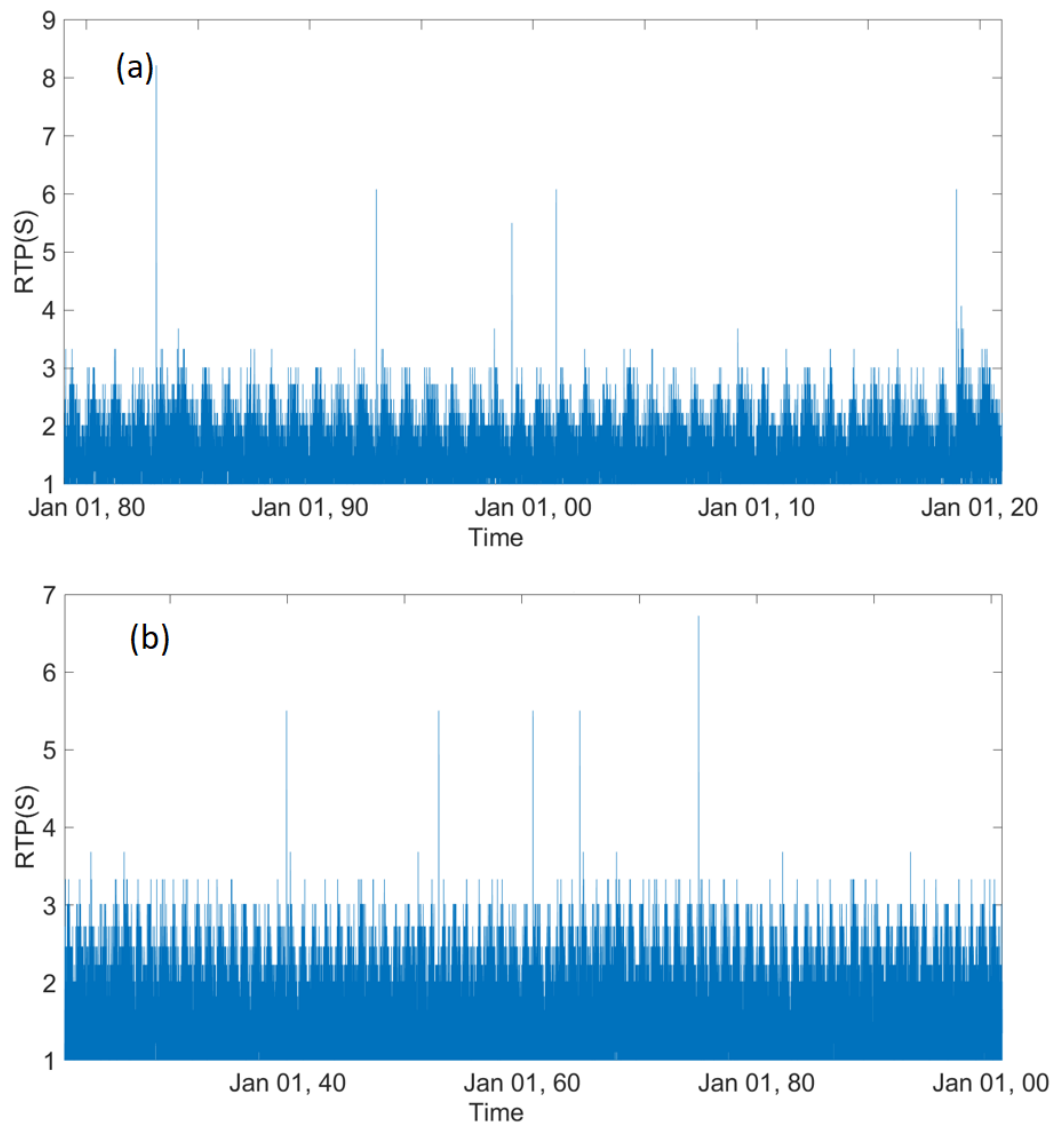


Figure 5.30: Time series of the peak wave period simulated using ERA5 wind data at Rajae port for (a) past and (b) future period.

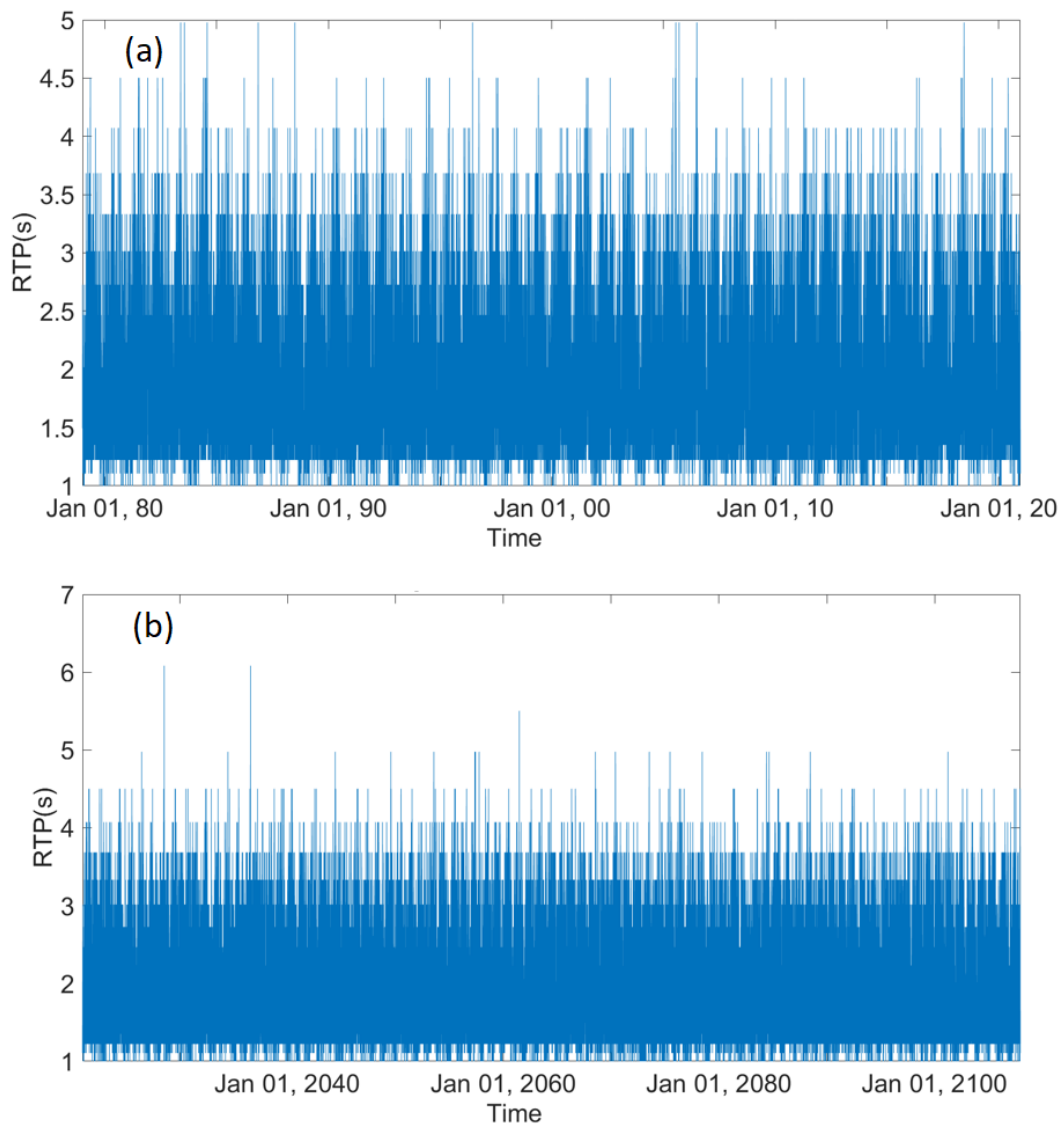


Figure 5.31: Time series of the peak wave period simulated using REGCM wind data at Rajae port for (a) past and (b) future period.

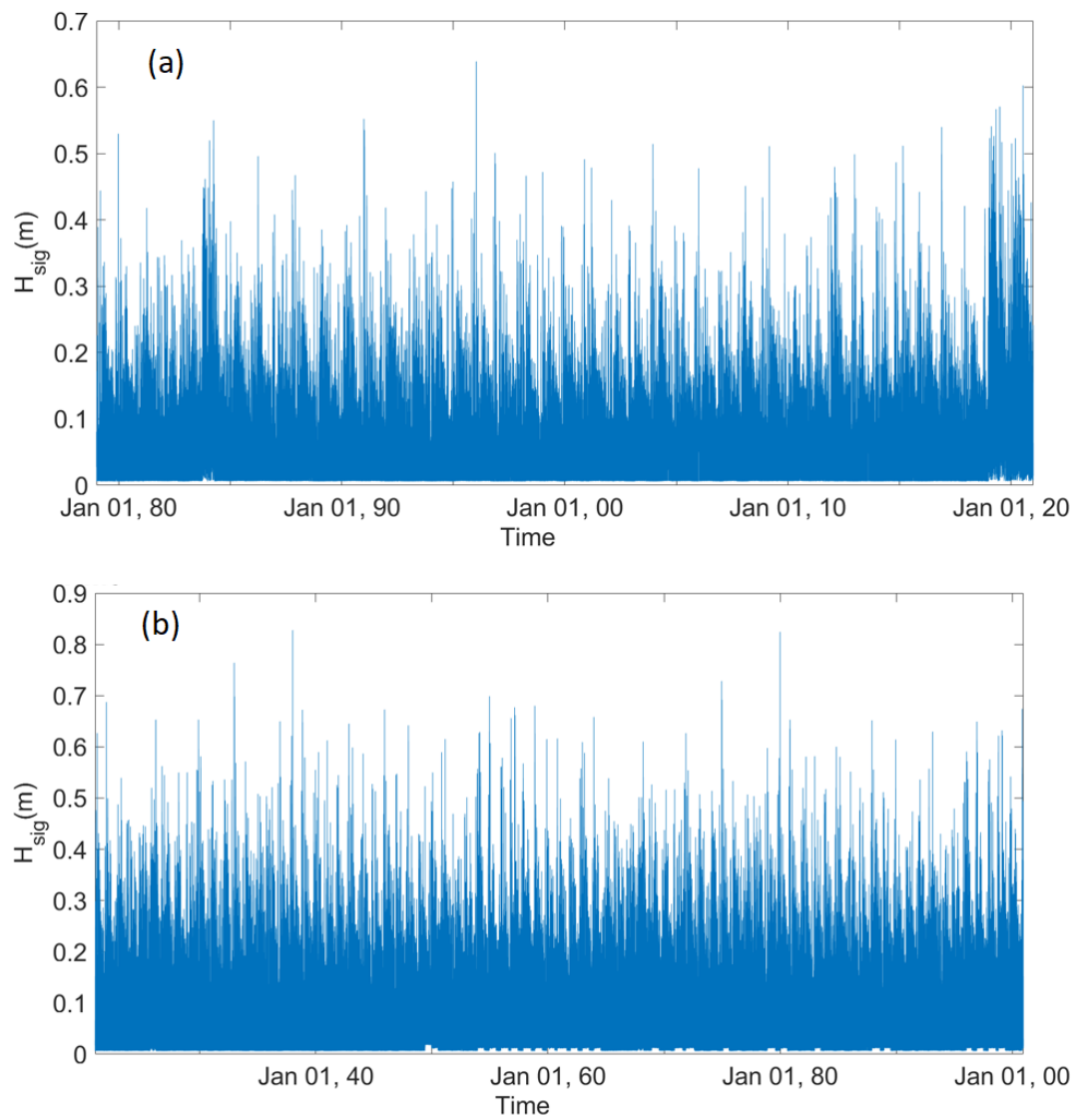


Figure 5.32: Time series of the significant wave height simulated using ERA5 wind data at Bahonar port for (a) past and (b) future period.

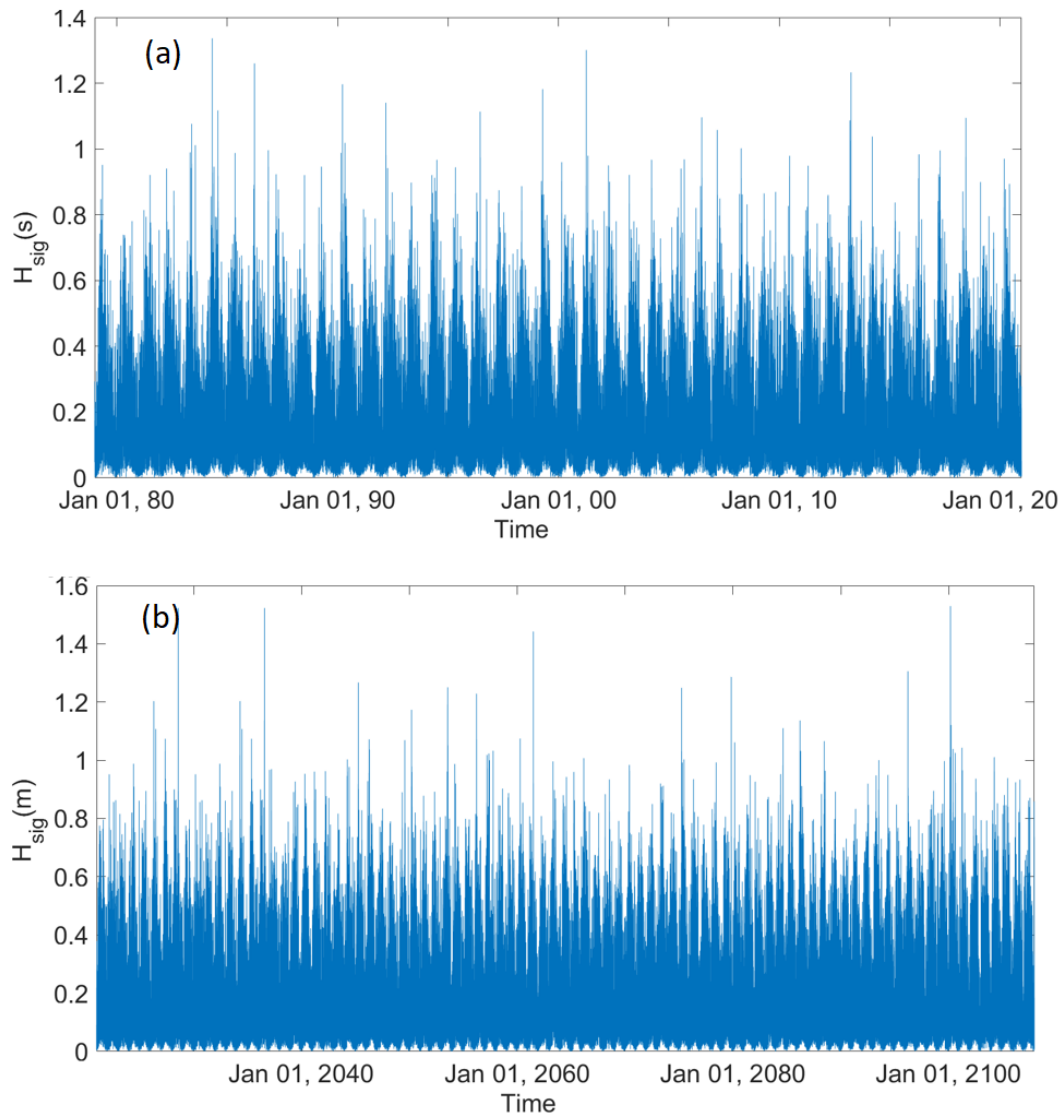


Figure 5.33: Time series of the significant wave height simulated using REGCM wind data at Bahonar port for (a) past and (b) future period.

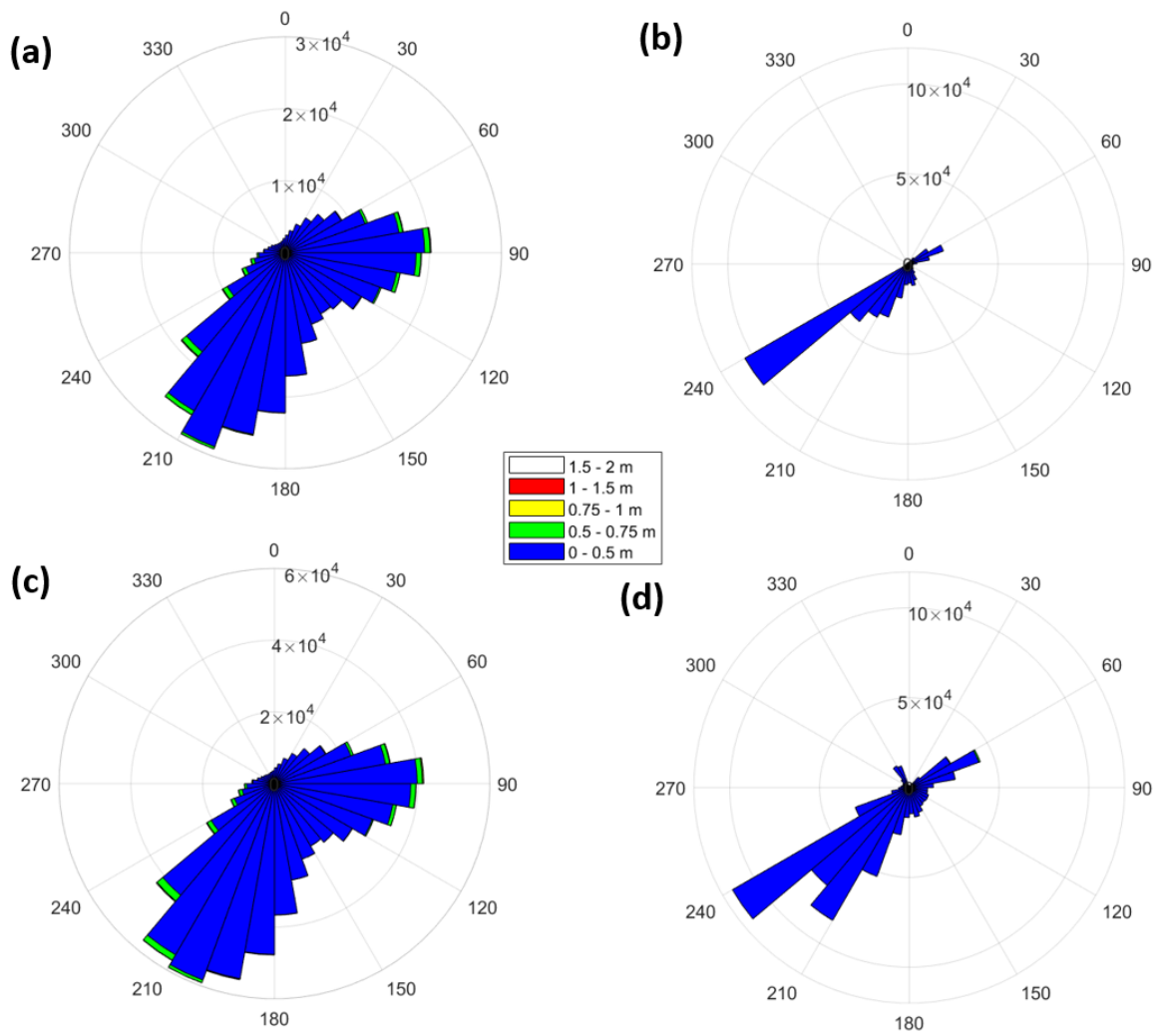


Figure 5.34: Waverose diagrams of the ERA5 and REGCM wave data at Bahonar port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

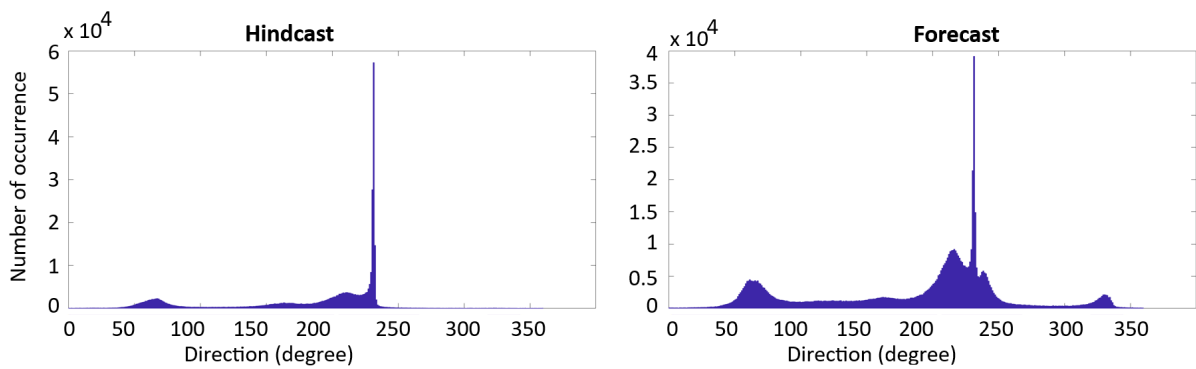


Figure 5.35: Histogram diagram of the ERA5 wave data at Bahonar port

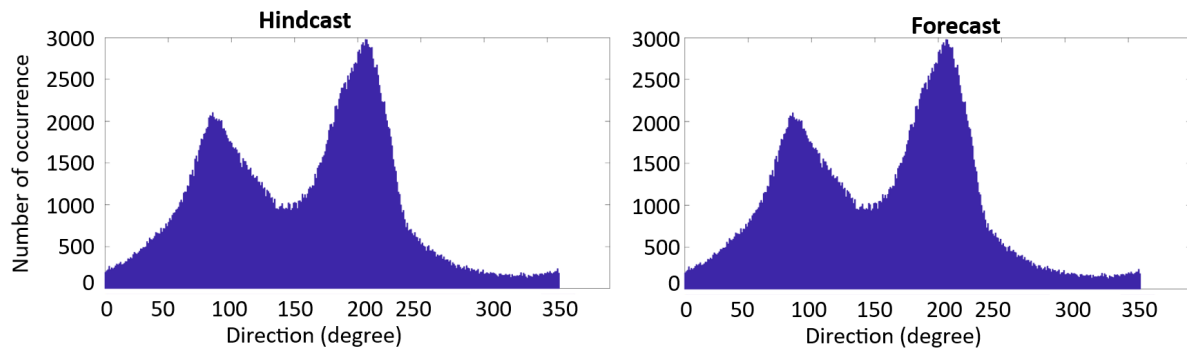


Figure 5.36: Histogram diagram of the REGCM wave data at Bahonar port

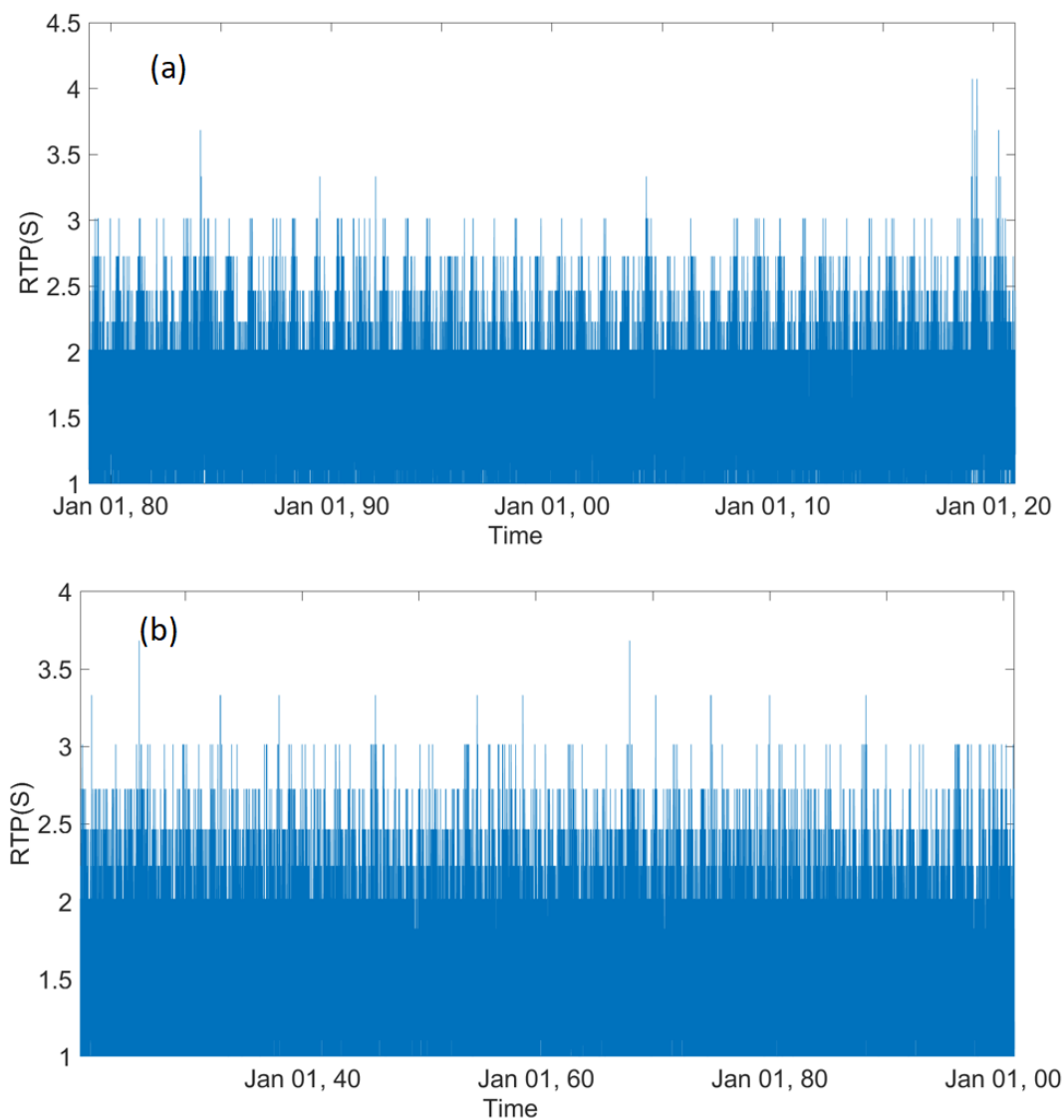


Figure 5.37: Time series of the peak wave period simulated using ERA5 wind data at Bahonar port for (a) past and (b) future period.

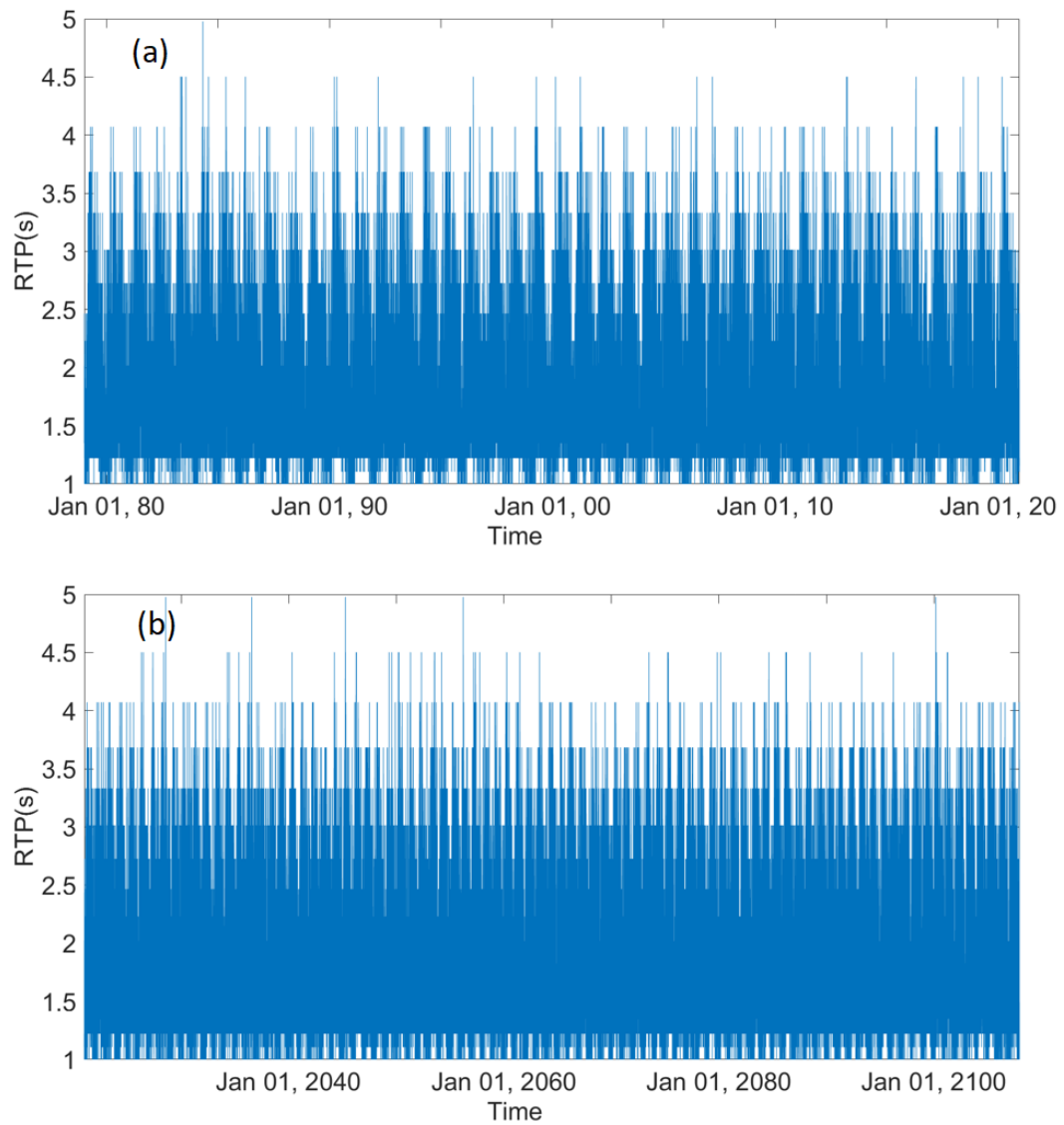


Figure 5.38: Time series of the peak wave period simulated using REGCM wind data at Bahunar port for (a) past and (b) future period.

5.4.4 P4 - Asaluve port

Fig 5.39 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of the significant wave height H_{sig} at Asaluve port from the ERA5 model, while such time series for the REGCM model are shown in Fig 5.40.

Fig 5.41 shows the waveroses of these four data sets. Unlike the other three ports, for Asaluve both ERA5 and REGCM wind data generate waves which mainly come from one direction. Fig 5.42 and 5.43 show histogram plots of the waves, which also illustrate the contribution of each direction to the overall data. Fig 5.44 and 5.45 show the peak period of the waves generated by ERA5 and REGCM wind, respectively.

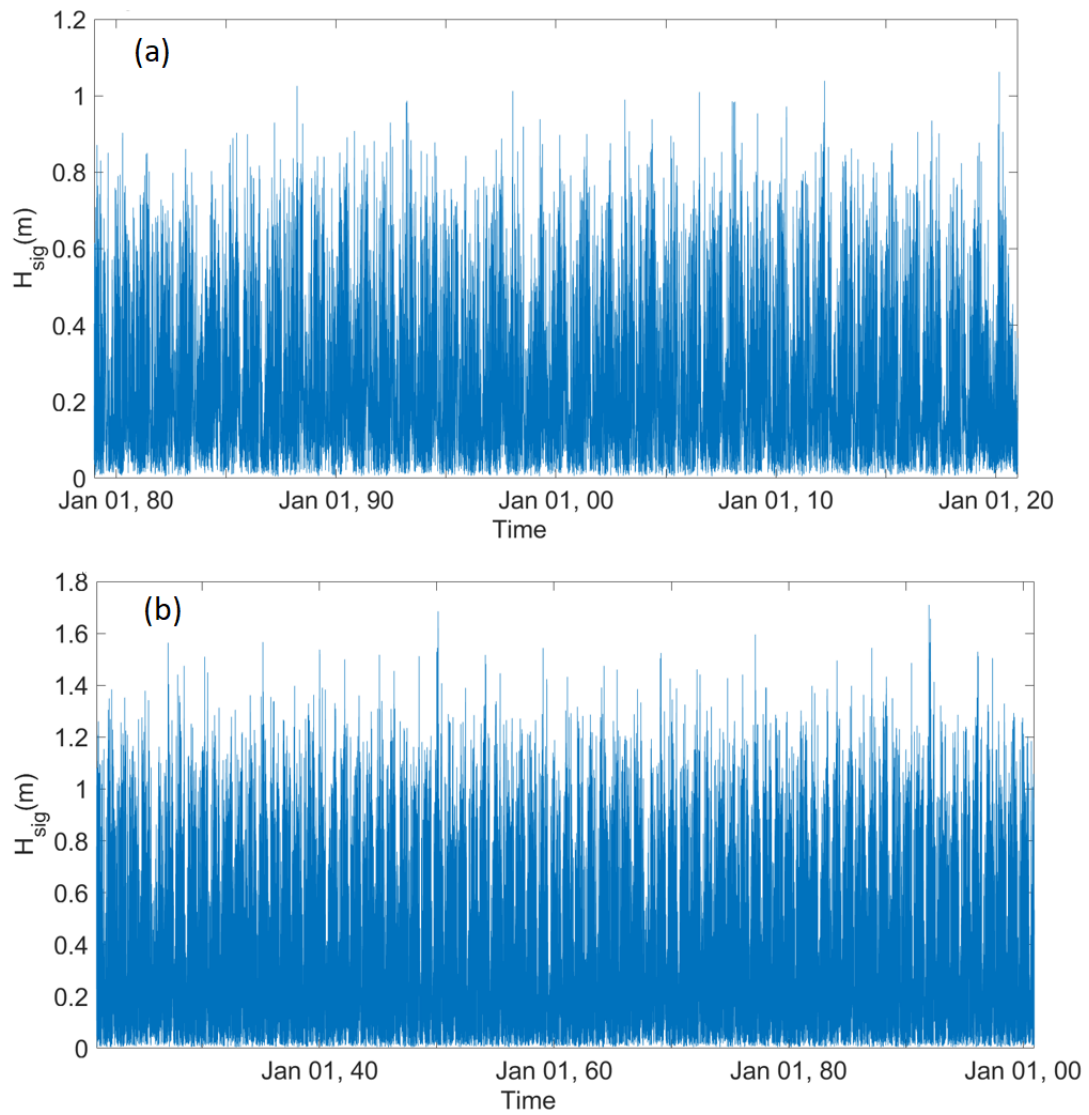


Figure 5.39: Time series of the significant wave height simulated using ERA5 wind data at Asaluye port for (a) past and (b) future period.

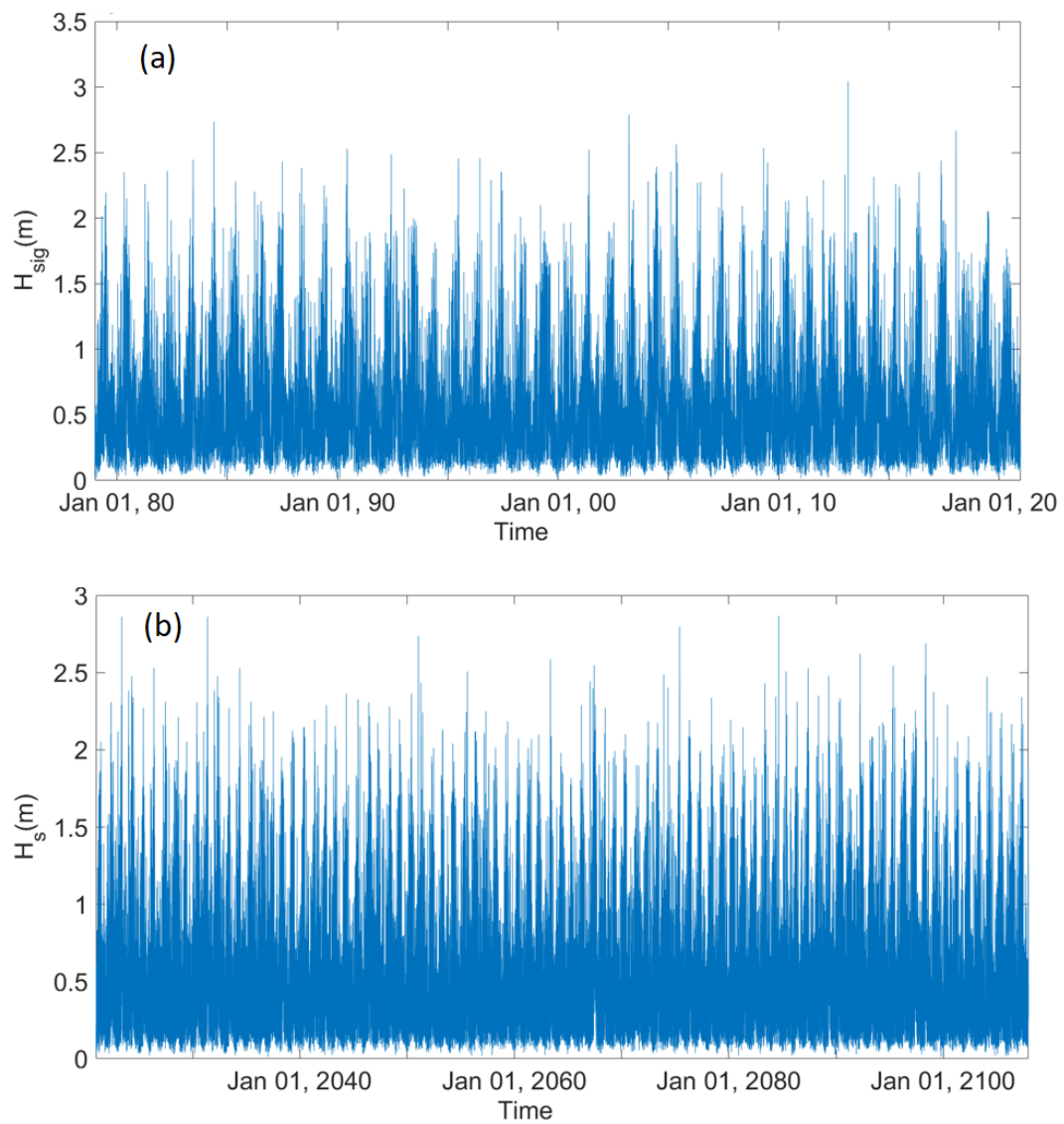


Figure 5.40: Time series of the significant wave height simulated using REGCM wind data at Asaluje port for (a) past and (b) future period.

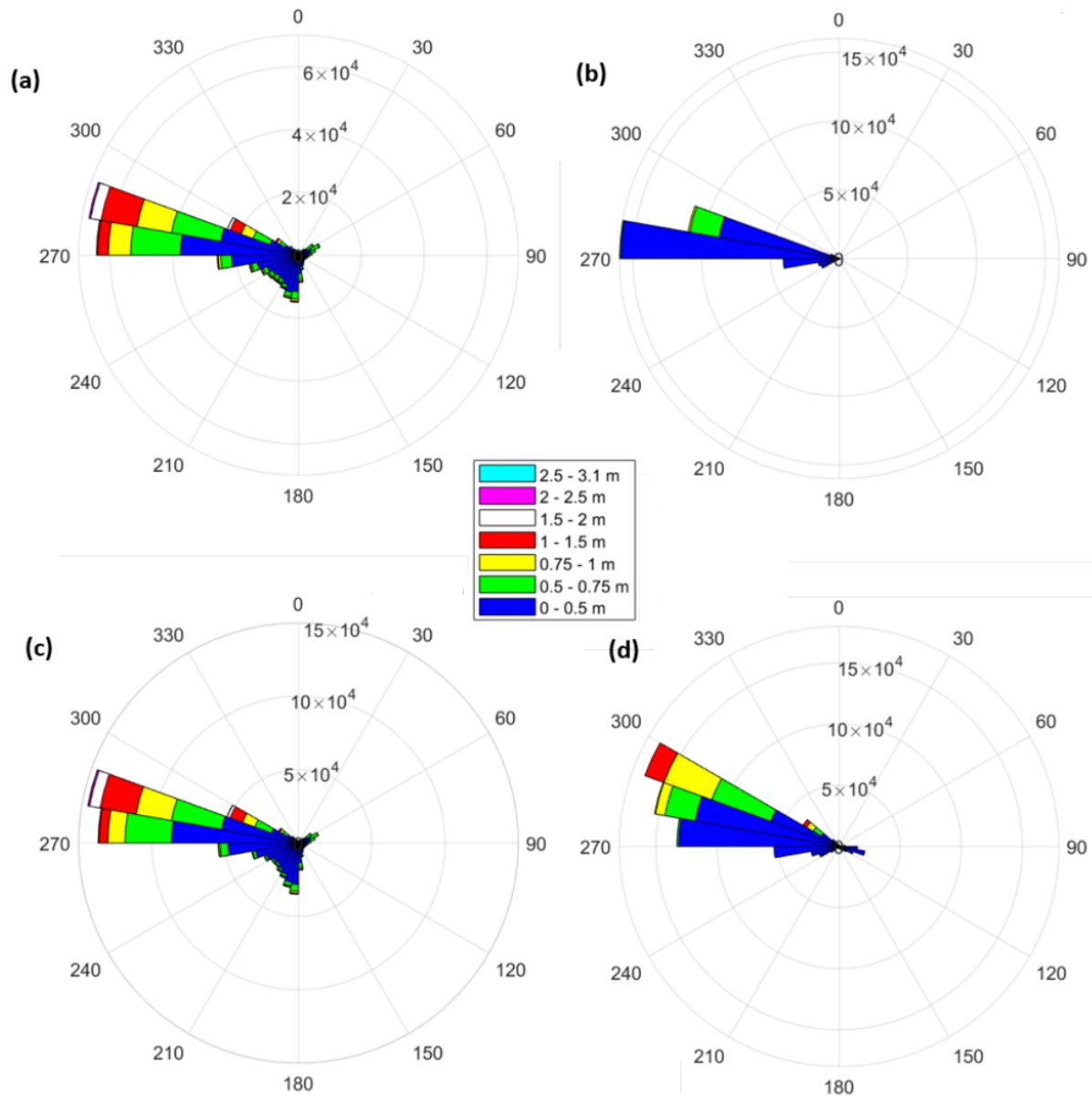


Figure 5.41: Waverose diagrams of the ERA5 and REGCM wave data at Asaluye port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

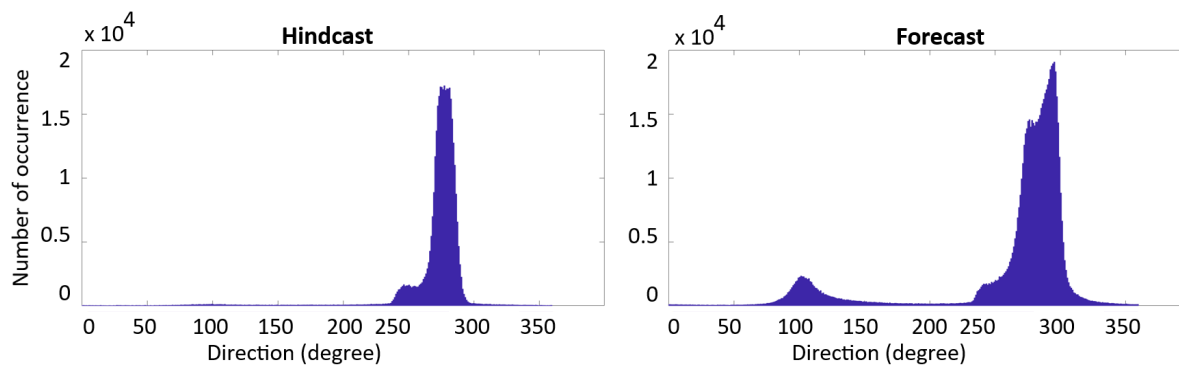


Figure 5.42: Histogram diagram of the ERA5 wave data at Asaluve port

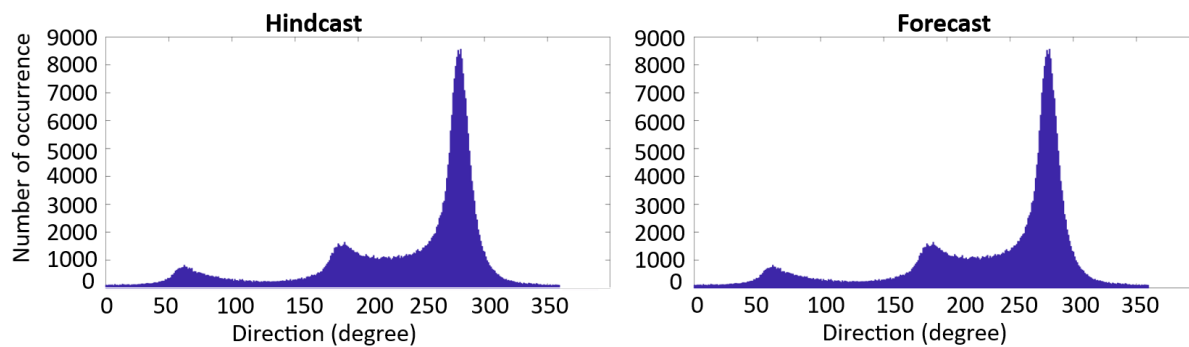


Figure 5.43: Histogram diagram of the REGCM wave data at Asaluve port

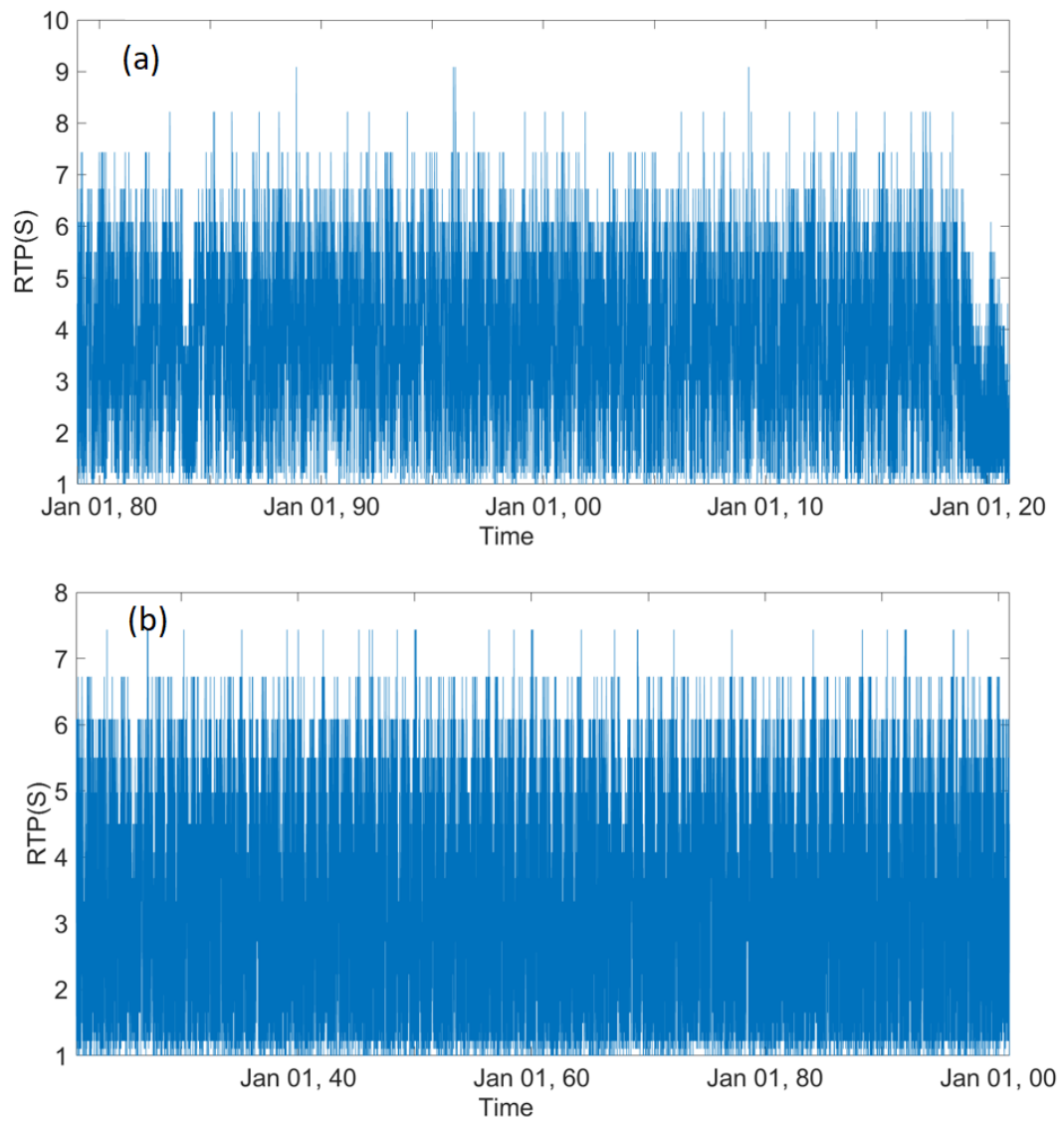


Figure 5.44: Time series of the peak wave period simulated using ERA5 wind data at Asalupe port for (a) past and (b) future period.

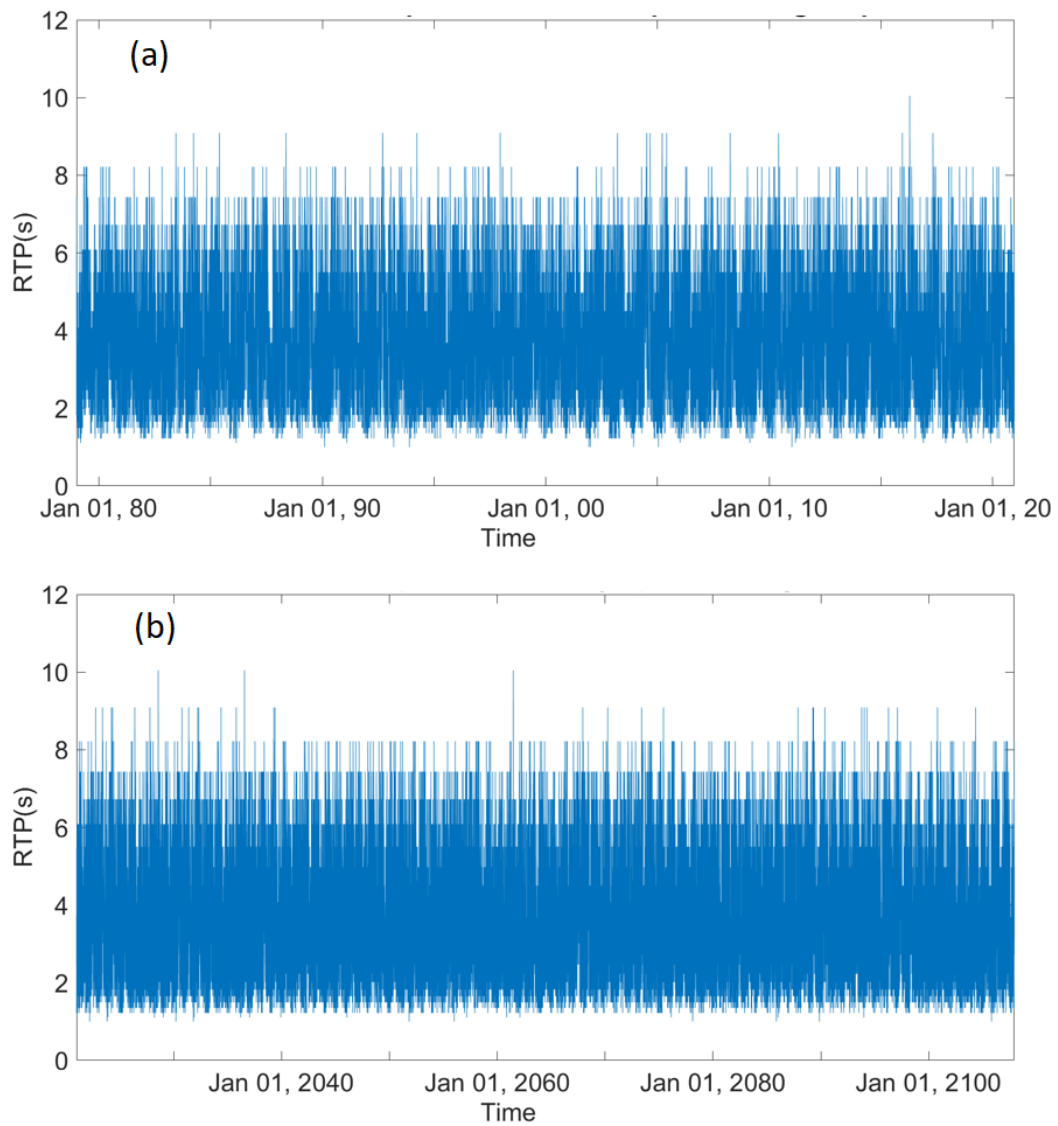


Figure 5.45: Time series of the peak wave period simulated using REGCM wind data at Asaluve port for (a) past and (b) future period.

5.4.5 P5 - Bushehr port

Fig 5.46 shows the hindcast (1979 - 2020) and the forecast (2021 - 2100) time series of the significant wave height H_{sig} at Bushehr port from the ERA5 model, while such time series for the REGCM model are shown in Fig 5.47.

Fig 5.48 shows the waveroses of these four data sets. As with Asaluye, both ERA5 and REGCM wind data generate waves which mainly come from one direction. Fig 5.49 and 5.50 show histogram plots of the waves, which also illustrate the contribution of each direction to the overall data. Fig 5.51 and 5.52 show the peak period of the waves generated by ERA5 and REGCM wind, respectively.

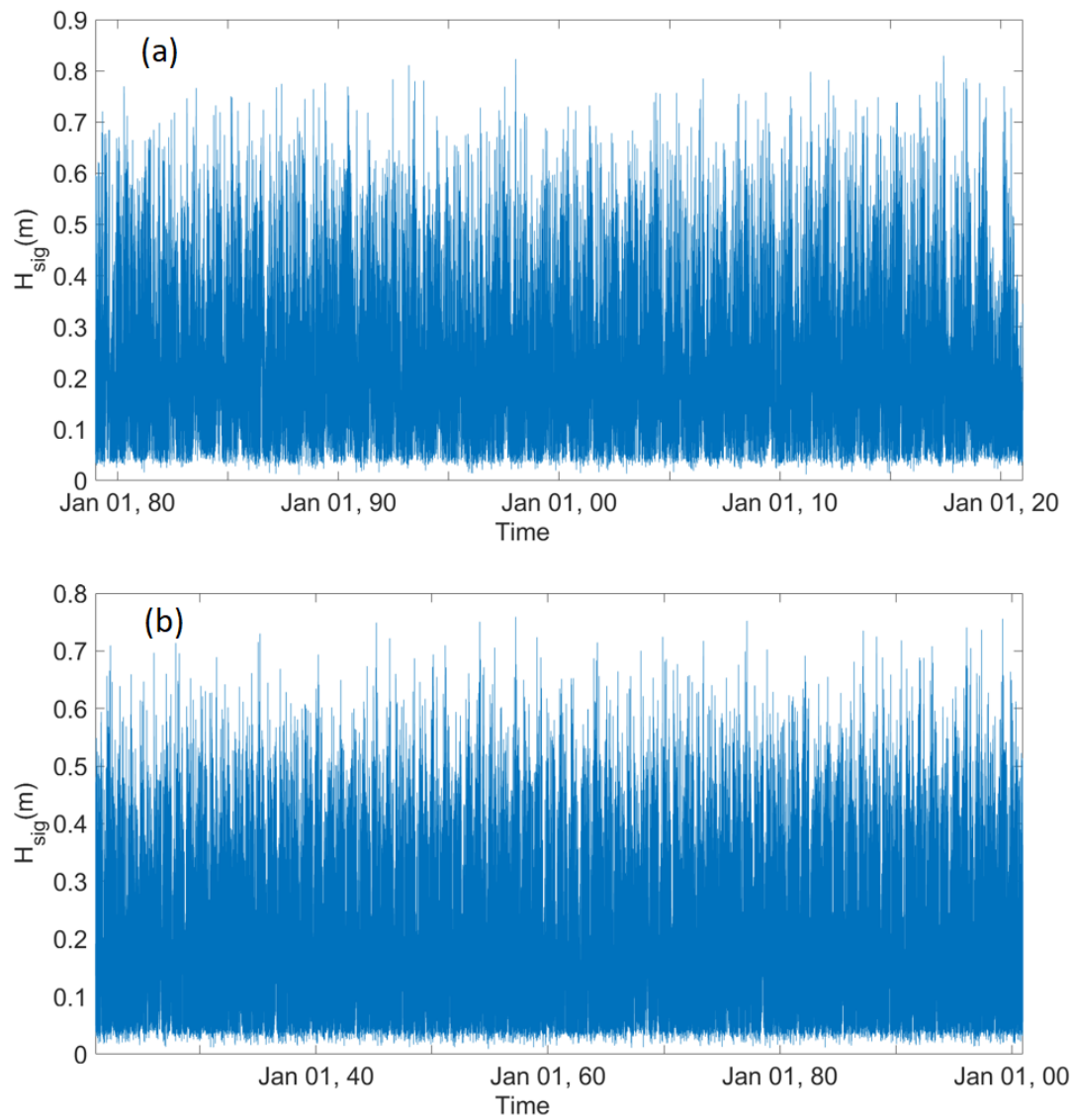


Figure 5.46: Time series of the significant wave height simulated using ERA5 wind data at Bushehr port for (a) past and (b) future period.

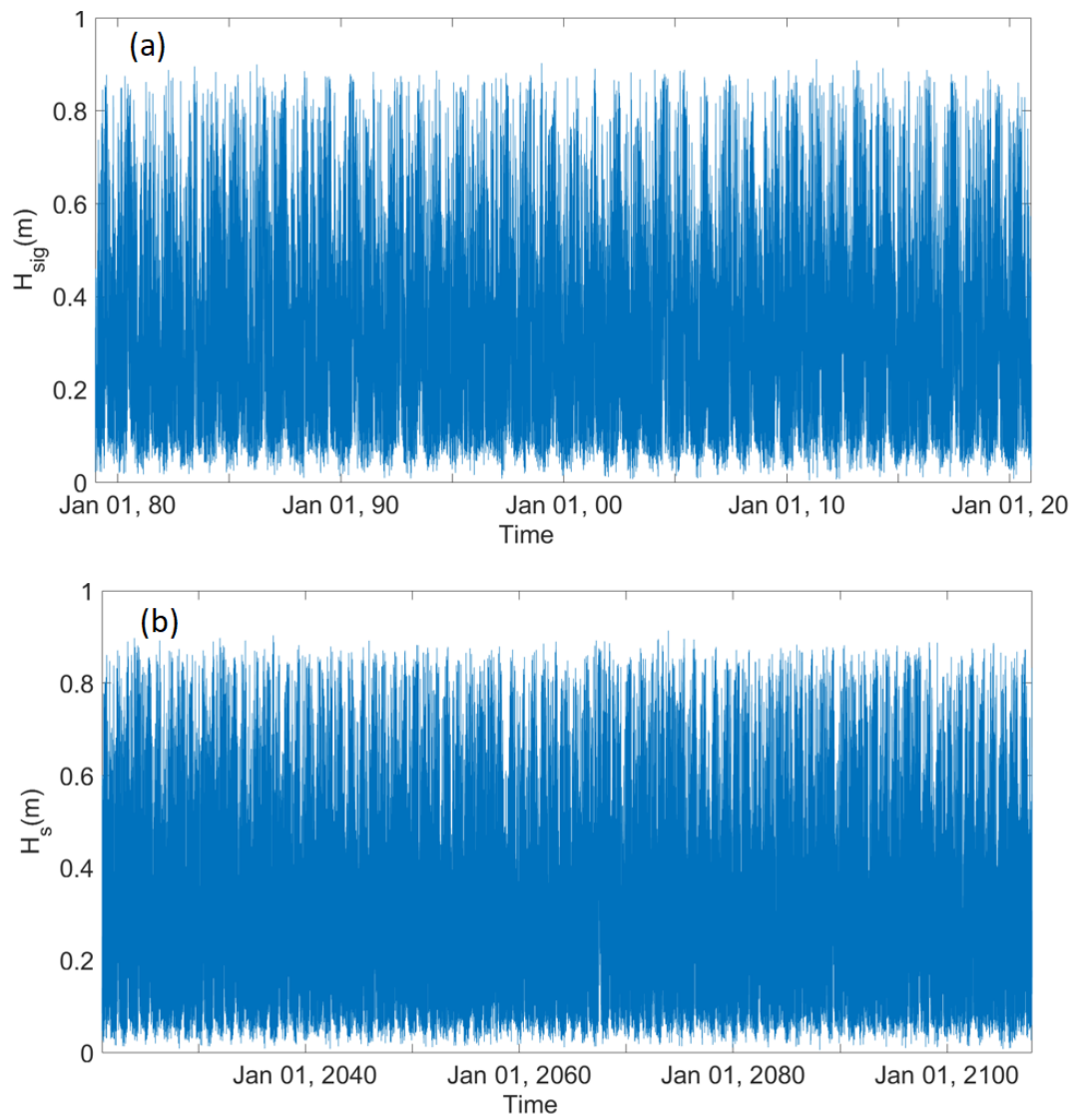


Figure 5.47: Time series of the significant wave height simulated using REGCM wind data at Bushehr port for (a) past and (b) future period.

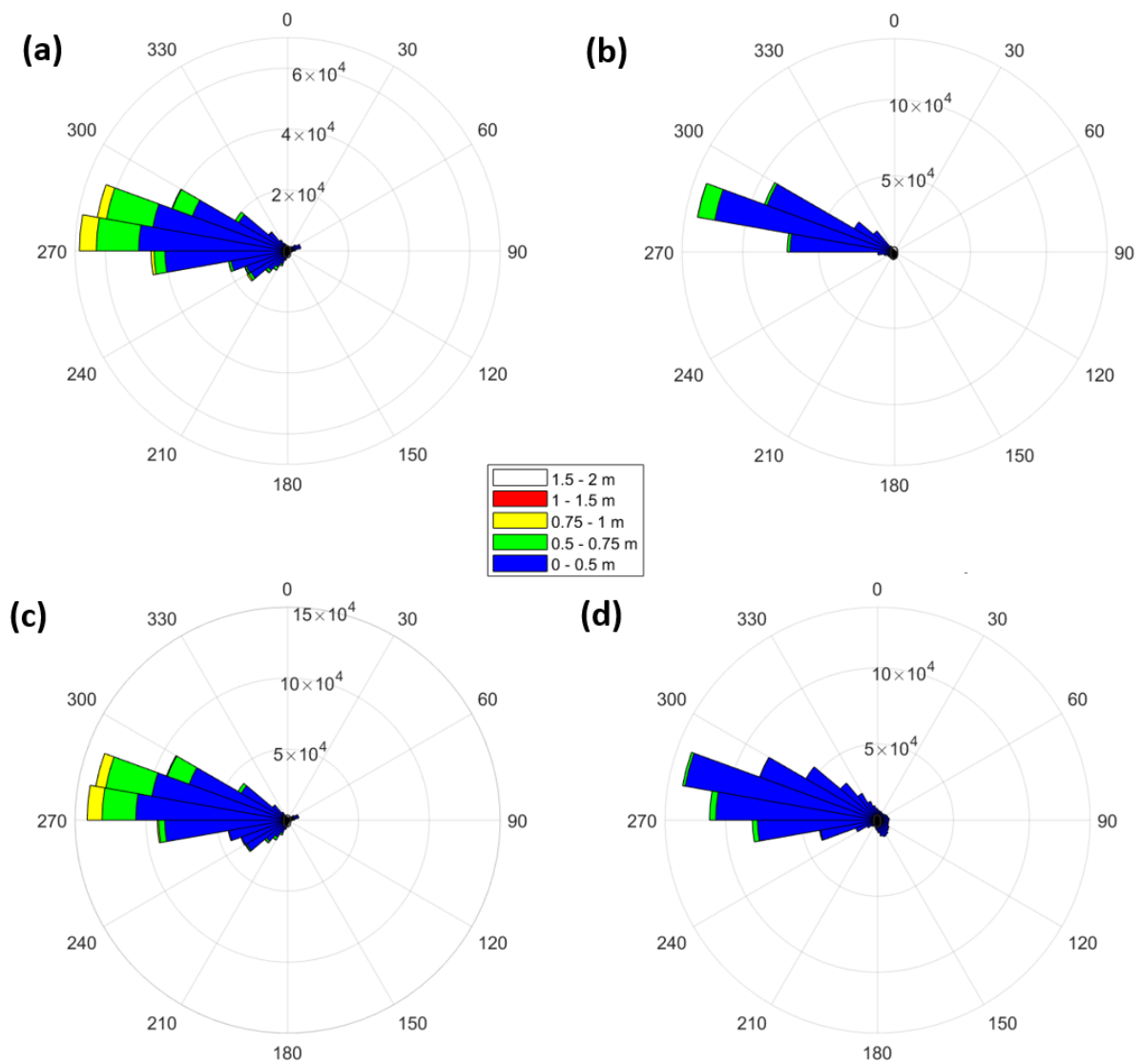


Figure 5.48: Waverose diagrams of the ERA5 and REGCM wave data at Bushehr port: (a) REGCM past, (b) ERA5 past, (c) REGCM future, and (d) ERA5 future

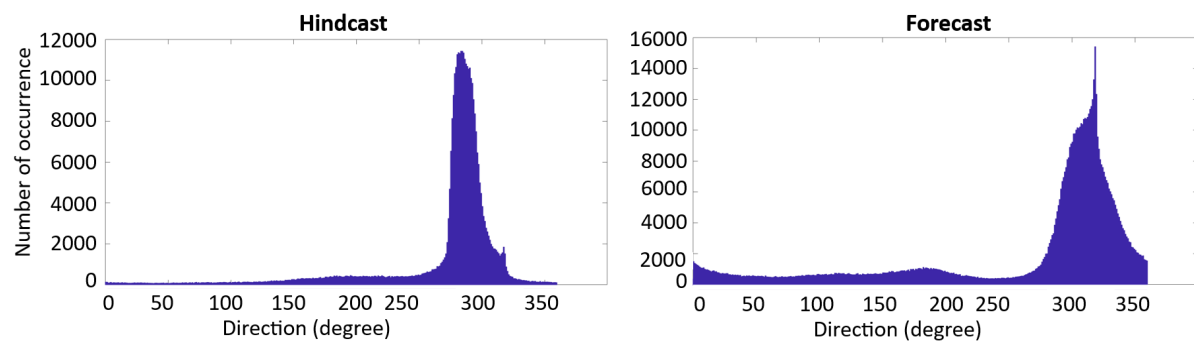


Figure 5.49: Histogram diagram of the ERA5 wave data at Bushehr port

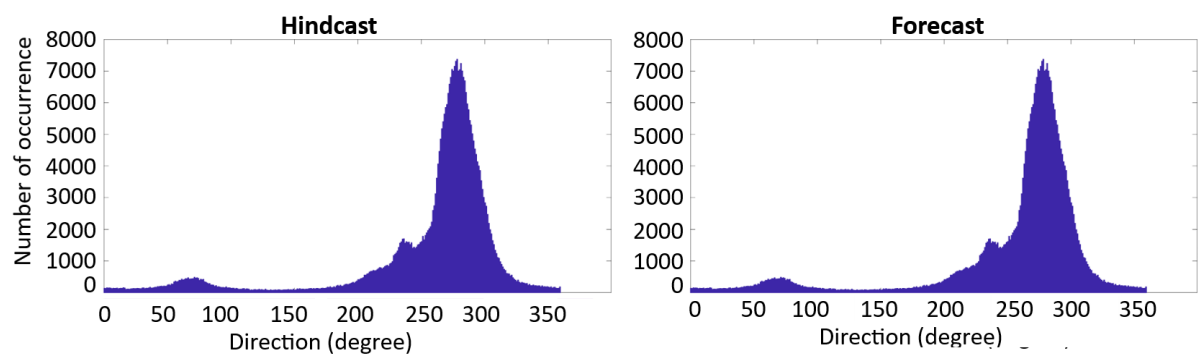


Figure 5.50: Histogram diagram of the REGCM wave data at Bushehr port

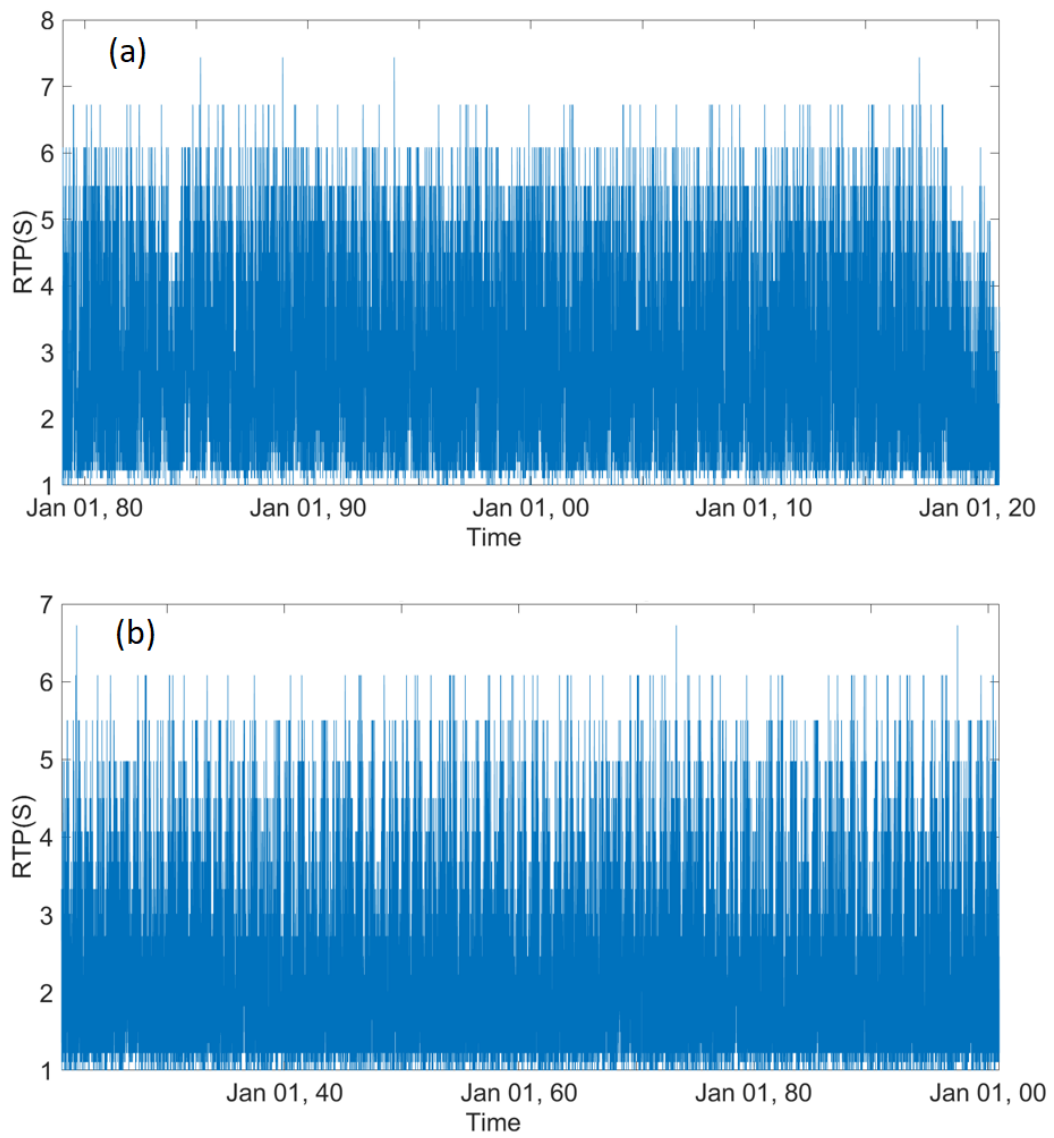


Figure 5.51: Time series of the peak wave period simulated using ERA5 wind data at Bushehr port for (a) past and (b) future period.

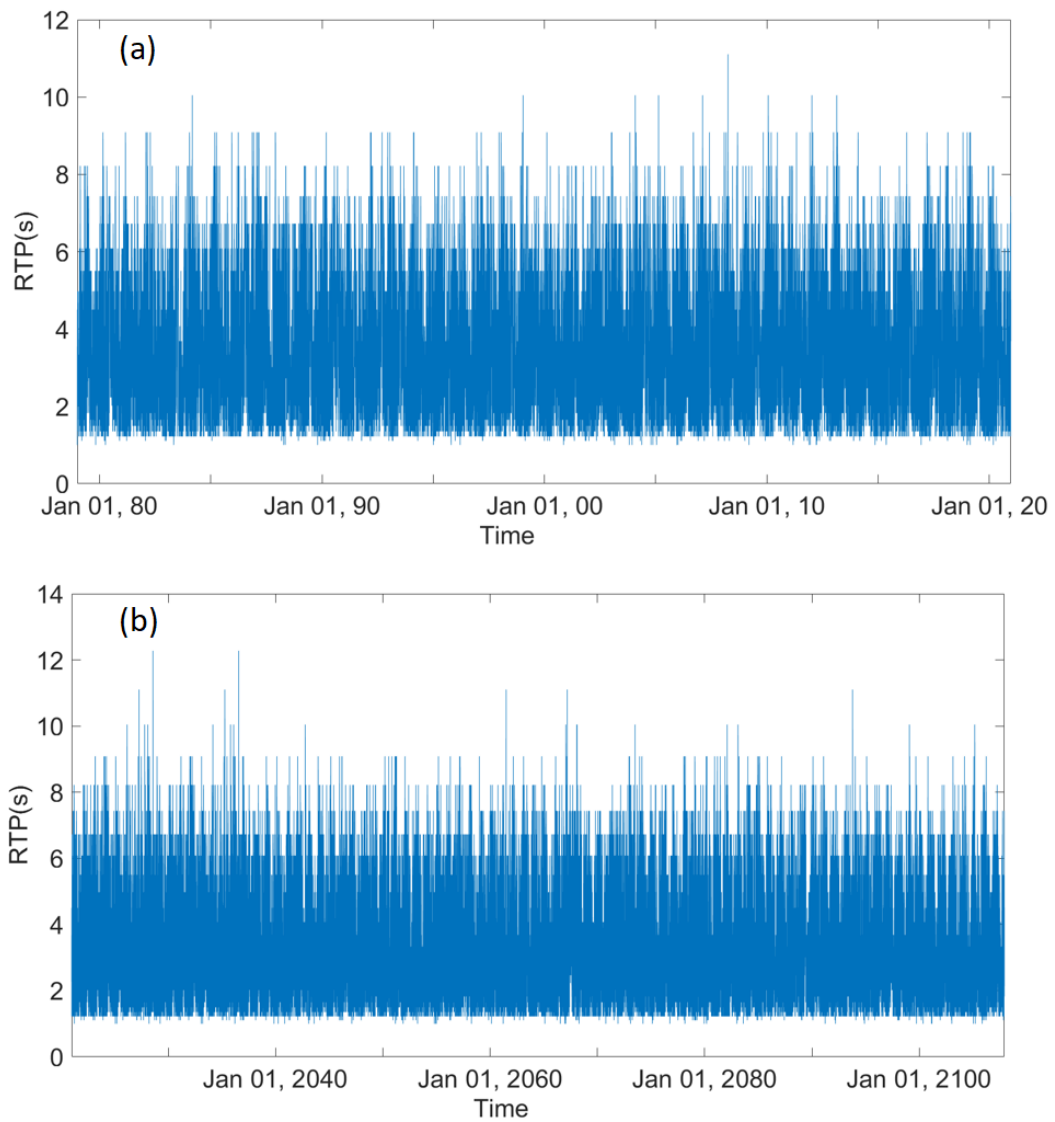


Figure 5.52: Time series of the peak wave period simulated using REGCM wind data at Bushehr port for (a) past and (b) future period.

5.5 Analysis of the results

As shown in the previous section, there is a discrepancy between the direction of the waves generated by ERA5 and REGCM wind data at the first three study points. We have seen that the ERA5 wind generates waves mainly in one direction, while the waves generated by REGCM cover a wide range of directions. This phenomenon does not occur for the other two ports located on the northwestern coast of the Persian Gulf. Therefore, we took a closer look at the results and the dynamics of the wind at the study points.

In Chapter 4 we analyzed the wind information at different points and saw that for the first three points both ERA5 and REGCM models predict the wind blowing from two main directions. However, it should be noted that the REGCM model provides wind data with a time resolution of three hours, while the time step of the SWAN simulation is one hour. Therefore, in the case of the REGCM simulation, SWAN has to generate wind data in between by interpolating the existing information. It is also clear that the wind information obtained from the models is for certain grid points which are different from the computational grid points. Thus, spatial interpolation is also required to calculate the wind information in the computational grid.

When simulating with ERA5 wind data, spatial interpolation is still required, but temporal interpolation is not necessary since its time resolution is similar to the simulation time step.

Fig 5.53 shows a comparison between the histogram of the wind direction generated by SWAN and the original wind data provided by the REGCM model at the port of Lengeh (point 1). It can be seen that SWAN broadens the range of wind directions due to the interpolation. The reason for this is that the variation of the wind direction in this region is rather fast (a few times per day). Therefore, for each variation, SWAN adds two intermediate directions to the original wind data (to downscale from 3-hour to 1 hour time resolution). Using the interpolated wind data, SWAN predicts the wave to come from a wide range of directions. For the ERA5 wind data, on the other hand, there would be no variation in the wind direction provided by the model. Therefore, two distinct peaks can be seen in the wind direction histogram. Since one of the directions has a larger contribution and the duration of the winds blowing from the other direction as well as the number of their occurrences is smaller than the main direction, these winds are not strong enough to generate significant waves in their directions.

Unlike the northeastern ports, in the northwestern coast of the Persian Gulf, for example, Asaluye port, the dynamics of the wind are different. In this region, the wind direction changes much slower than on the other side. Therefore, the temporal interpolation of SWAN doesn't have a significant effect on the wind direction histogram, as can be seen in Fig 5.54. Fig 5.55 and Fig 5.56 show the windroses of the above-mentioned data in these two ports which better show the broadening caused by SWAN interpolation in Lengeh port.

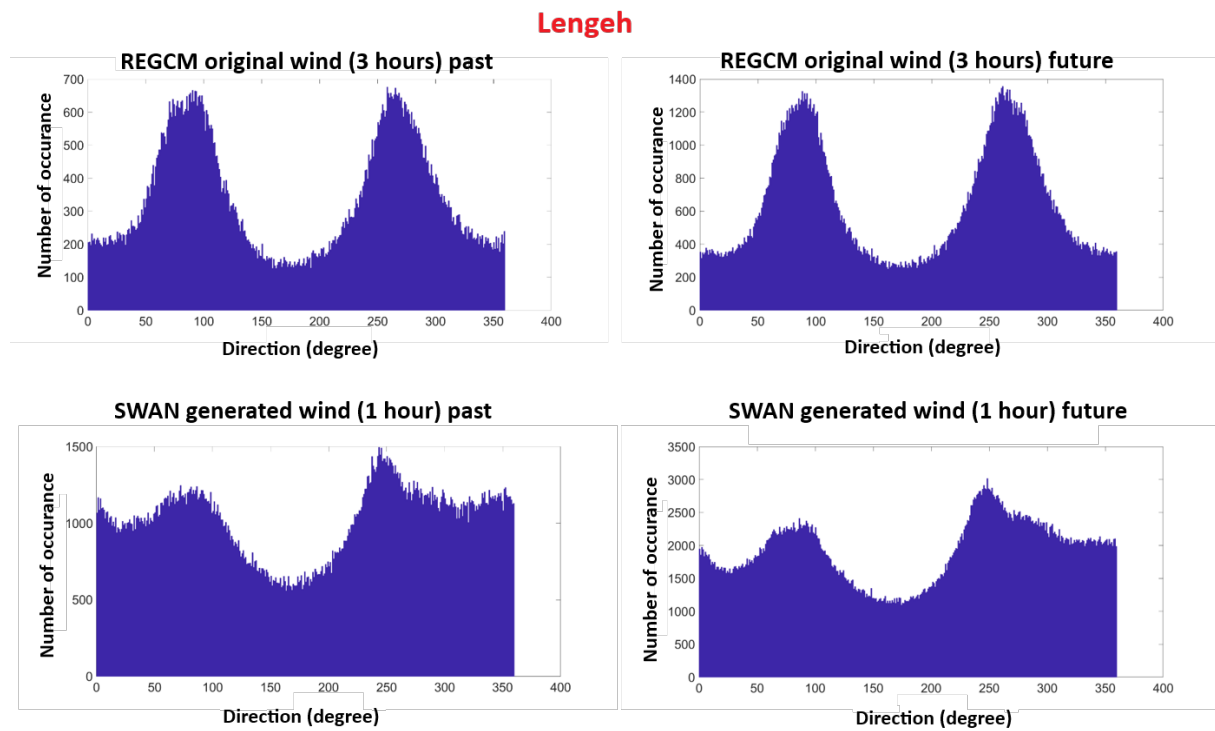


Figure 5.53: Comparison between wave direction interpolated by SWAN and the original wind data provided by the REGCM model at Lengeh port.

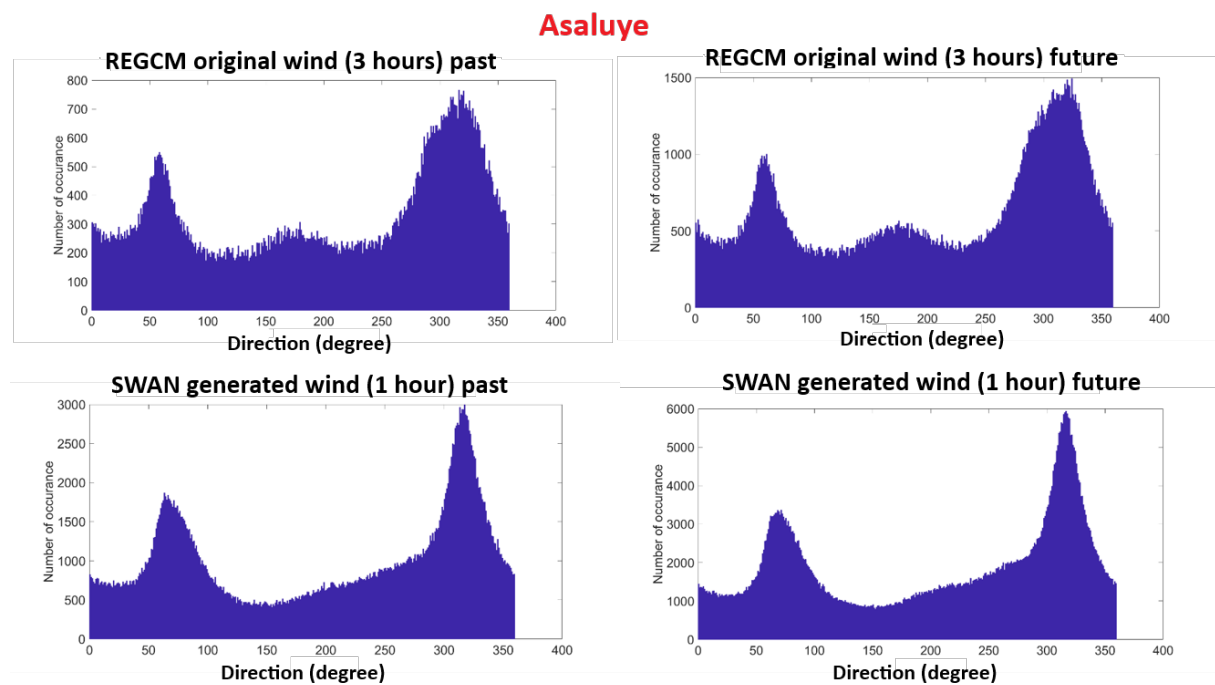


Figure 5.54: Comparison between wave direction interpolated by SWAN and the original wind data provided by the REGCM model at Asaluwe port.

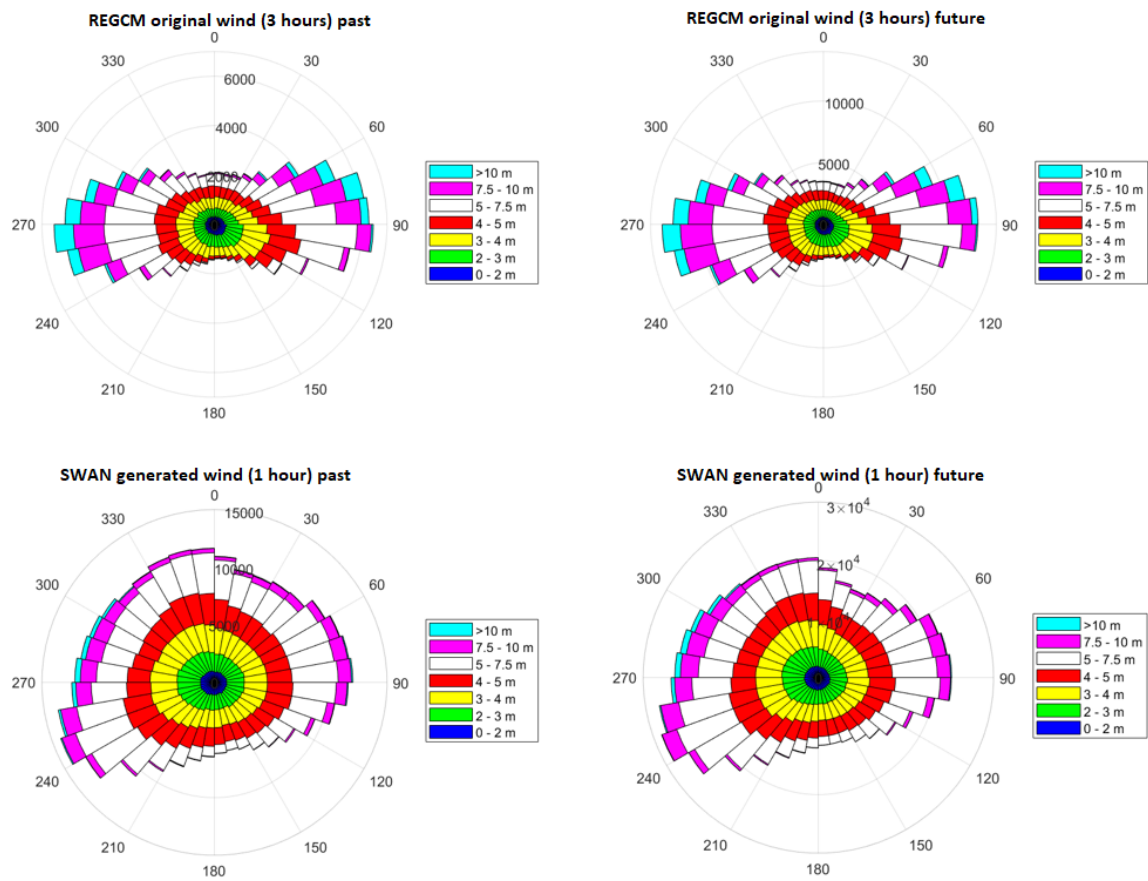


Figure 5.55: Windrose diagrams of the data generated by SWAN as well as the original data provided by the REGCM model at Lengeh.

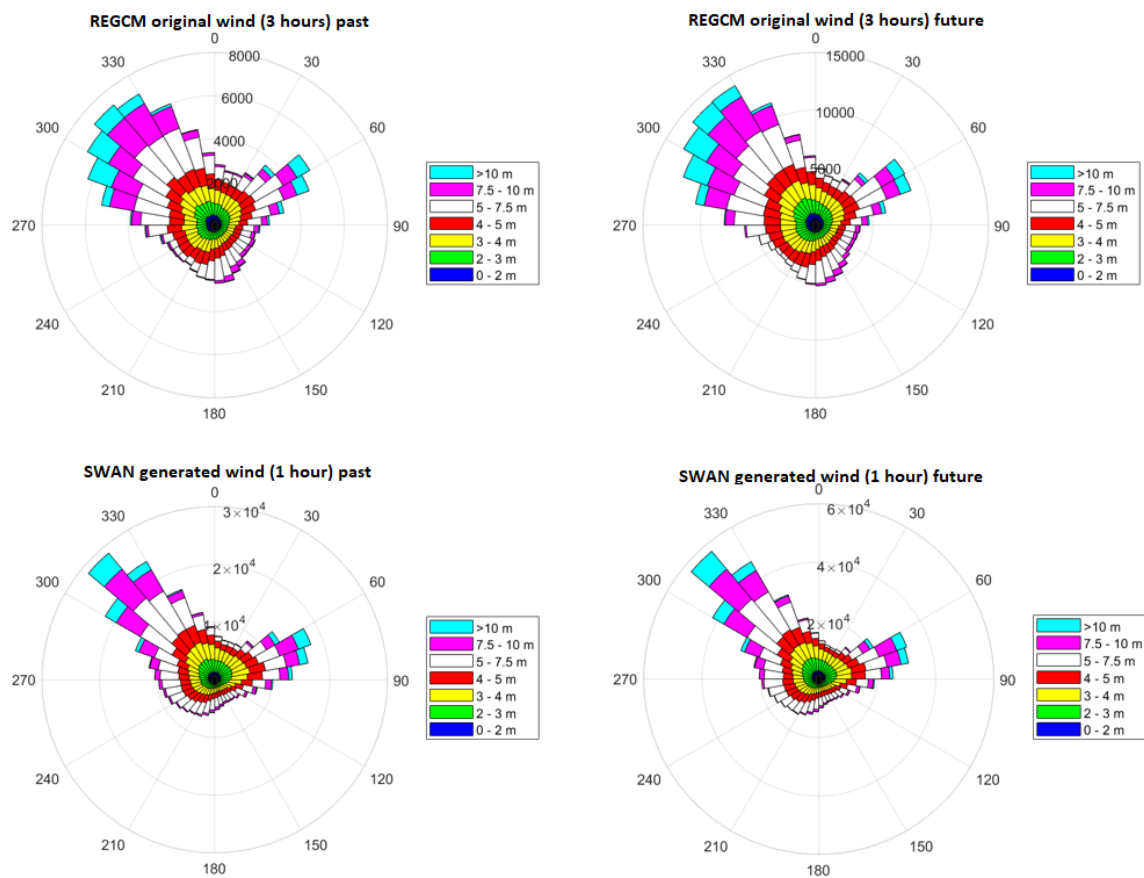


Figure 5.56: Windrose diagrams of the data generated by SWAN as well as the original data provided by the REGCM model at Asaluje.

Chapter 6

Wave condition analysis

To determine the impact of climate change on wave conditions in the Persian Gulf, we study the influence of waves on coastal structures. Wave-structure interactions can be studied from two perspectives. First, the hydraulic response of the waves, such as wave run-up, wave overtopping, reflection, refraction, and diffraction. Another aspect is the effect of the waves on the structure, including the load on the structure and its response to that load. In this study, we focus on this latter aspect and investigate the variation of wave loading caused by climate change on typical coastal structures at the study points in the Persian Gulf.

For this purpose, we calculate the wave loads on different structures for short and long return periods, including [1, 2, 5, 10, 20, 50, 100, 200]-year return periods. The next section explains the method used for this statistical analysis.

6.1 Statistical analysis of the extreme conditions

The prerequisite for an accurate statistical analysis is that the individual data points be statistically independent. However, such independence is not met in the wave data shown in the previous chapter, since the wave height and direction at each instant depend on the previous waves at that point. Therefore, in order to make the analysis more reliable, it is necessary to extract the independent data from the original dataset by separating the extreme conditions. The Peak Over Threshold (POT) method is used to provide such an independent data set [100, 102]. In this method, we limit our study to the data points that exceed a certain value called a threshold. It should be noted that the extracted extreme conditions do not necessarily represent real storms that could have a harmful impact on the coastal structures. Fig 6.1 explains this better. In this figure, the significant wave height generated by ERA5 wind data at Lengeh port is shown for a period of one month in January 2000. Using the POT method and an arbitrarily chosen threshold of 0.15 m for the significant wave height H_t , results in 8 time intervals where the wave height is greater than H_t . We take the maximum wave height in each interval as independent data points. It is clear that these 8 time intervals, which occurred during one month, do not represent real storms, because 0.15 m is not a considerable wave height. However, for the purpose of statistical analysis, they can be considered as independent data points. Of course, the threshold can be

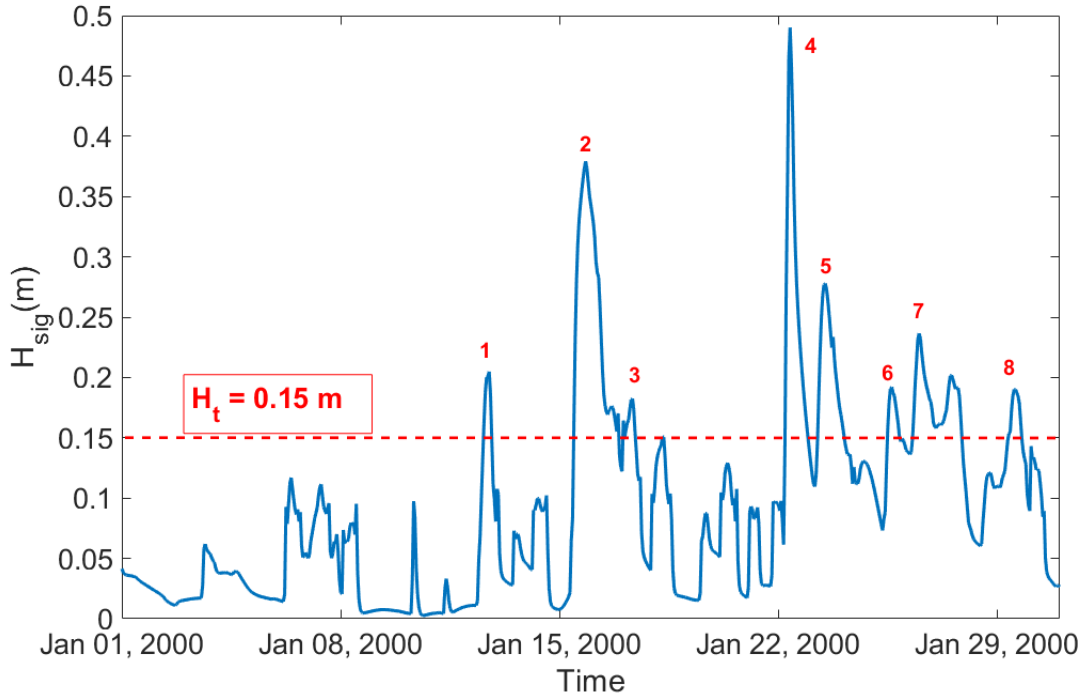


Figure 6.1: Significant wave height at Lengeh port in January 2000. Using a threshold wave height of 0.15m results in 8 independent data points.

chosen arbitrarily, as long as the independence condition of the data points is met. To verify that this condition is met, one needs to find the wave height for different return periods and for a set of values for the threshold wave height. We use the following method to find the wave height for different return periods:

After extracting the extreme values (data points greater than the threshold value), one should plot the Cumulative Distribution Function (CDF) of the new data set as shown in Fig 6.2. To generate this plot, we used the significant wave height at Lengeh port simulated using ERA5 wind data over a 42-year time period (1979-2020). The threshold value of the wave height is assumed to be $H_t = 0.4$ m, as can be seen from the horizontal axis. From the CDF, one can determine the probability that a wave exceeds a certain height. For example, if the CDF of $H_{sig} = 0.5$ is 0.9, it means that the probability of having a wave with a significant height greater than 0.5 is $1 - 0.9 = 0.1$ (10%):

$$CDF(H') = P(H < H') = 1 - P(H > H') \quad (6.1)$$

Since the CDF is plotted based on a discrete data set, interpolation and extrapolation are required to find the CDF of all possible values. One can try different distributions to see which one fits to the CDF better. The distributions that are usually used for this purpose are the Log-Normal, Gumbel, and Weibull distributions. We try all these possibilities to find the best fitting one. The results are shown in Fig 6.3. Although all three distributions seem to provide a good fit to the actual data, since we are more interested in the extrapolation of the CDF, it makes

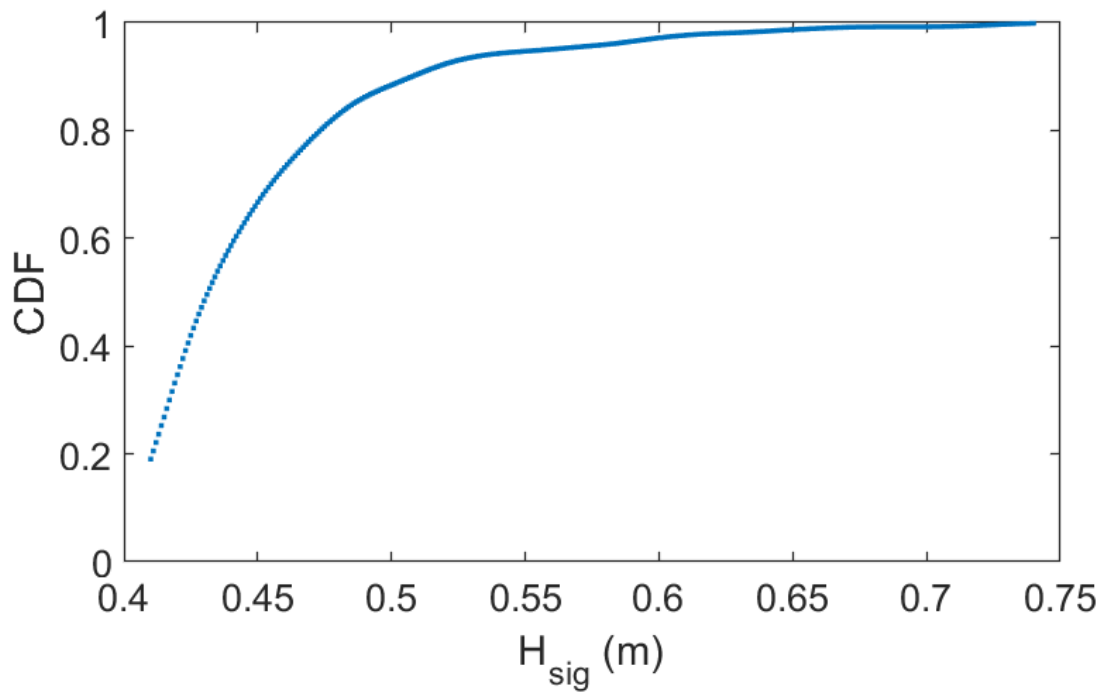


Figure 6.2: CDF of significant wave height at Lengeh port for a period of 42 years.

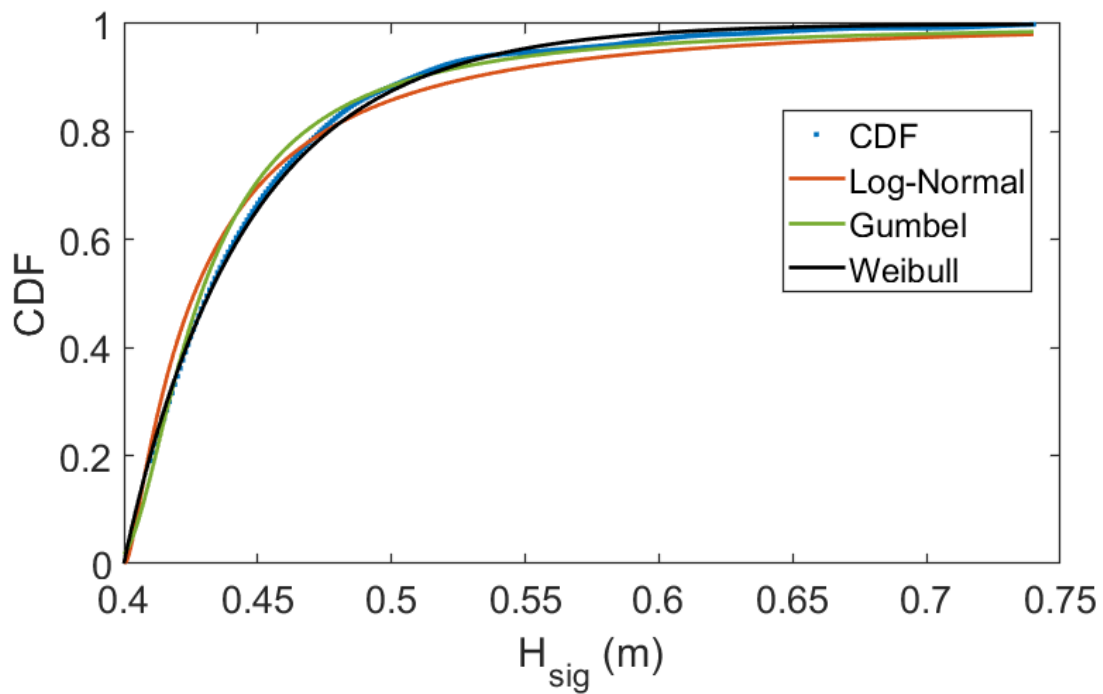


Figure 6.3: Fitting the CDF shown in Fig. 6.2 using different distributions, including Log-Normal, Gumbel, and Weibull.

more sense to choose a distribution that provides the best fit at high values. Thus, from Fig 6.3 we can conclude that the Weibull distribution is the best choice here.

Suppose we have the total number of data points n . Then we define the normalized number of events N which shows data points per year:

$$N = \frac{n}{42} \quad (6.2)$$

Remember that we investigate data points over a 42-year time period. Now we want to find the wave height for a certain return period T_R , shown by H_R . By definition, H_R is the wave height that likely happens once in T_R years. Therefore, the probability of having a wave with a height equal to or higher than H_R would be:

$$P(H \geq H_R) = \frac{1}{NT_R} \quad (6.3)$$

Thus, the CDF of H_R has to be:

$$CDF(H_R) = 1 - P(H \geq H_R) = 1 - \frac{1}{NT_R} \quad (6.4)$$

From the fitted distribution, one can then find the H_R .

As mentioned before, the threshold value can be arbitrarily selected. We repeated the calculations with a set of values for the threshold wave height and found the H_{sig} for different return periods. The results of these calculations are shown in Table 6.1.

Table 6.1: Significant wave height (m) at Lengeh port using different values for the threshold wave height.

$T_R(\text{years}) \backslash H_t(m)$	1	5	10	20	50	100	200
0.1	0.47	0.63	0.71	0.79	0.91	0.99	1.07
0.2	0.39	0.52	0.59	0.64	0.74	0.81	0.88
0.3	0.35	0.46	0.52	0.57	0.66	0.72	0.78
0.35	0.34	0.45	0.51	0.56	0.64	0.70	0.76
0.4	0.34	0.45	0.51	0.56	0.64	0.70	0.76

As can be seen from this table, by increasing H_t , the calculated wave height values for all the return periods converge in such a way that the values calculated for $H_t = 0.35m$ are equal to the case where H_t is $0.4m$. It means that $H_t = 0.35m$ is large enough to make the data points independent and can be used to analyze this data set. Such a procedure should be followed in all other analyses where we are interested in finding the value of each parameter for different return periods.

6.2 Analysis of wave parameters

In this section, we present an analysis of the following wave parameters:

- Significant wave height.
- Peak period.
- Wave number and wavelength.

The values of the above parameters are calculated for a set of return periods [1,5,10,20,50,100,200] years using the past and future waves simulated by ERA5 and REGCM wind data. Significant wave height and peak period are got directly from the SWAN simulations. We use linear wave theory (Airy theory) to calculate the wavelength and wavenumber. According to Airy theory, the dispersion equation of the wave which relates the angular frequency ω to the wavenumber k can be written as follows:

$$\omega = \sqrt{g \cdot \tanh(kd)} \rightarrow \tanh(kd) = \frac{\omega^2}{gk} \quad (6.5)$$

Where d is the depth of water and g is the Earth's gravitational acceleration, which is about $9.8m/s^2$. Angular frequency ω can be found from the wave period T as follows:

$$\omega = \frac{2\pi}{T} \quad (6.6)$$

So, to find the wavenumber, one needs to find the intersection of the following two curves as shown in Fig 6.4. In this figure, we assume a water depth of $10m$ and find the wavenumber for a wave with a period of $5s$.

$$f_1(k) = \tanh(kd), \quad f_2(k) = \frac{4\pi^2}{gkT^2} \quad (6.7)$$

Wavelength L can also be easily calculated from the wavenumber using the following equation:

$$L = \frac{2\pi}{k} \quad (6.8)$$

6.2.1 Point1 - Lengeh port

Table 6.2 shows the wave parameters for different return periods at Lengeh port. The values are calculated for both past and future waves simulated using ERA5 data. We have also calculated the change in each parameter from the past to the future to gain a better insight into the effects of the climate change.

Same results are shown in Table 6.3 for the waves simulated with REGCM wind data. It can be seen that both models predict an increase in wave height and wave period, but a decrease in

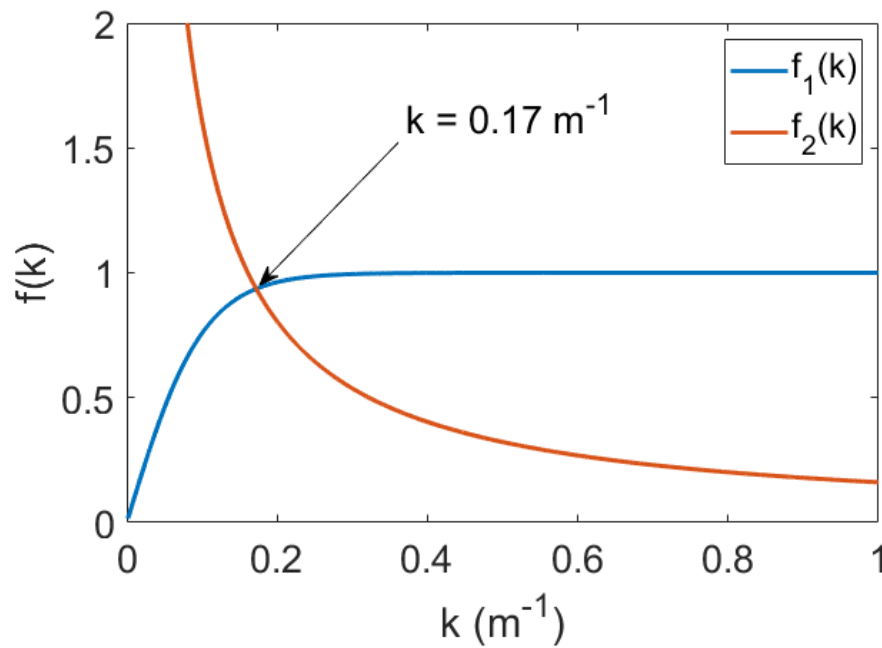


Figure 6.4: Finding the wavenumber from the intersection point of the two functions introduced in Eq. 6.7.

wavenumber in the future. However, the ERA5 model predicts a higher increase, especially for the significant wave height.

Table 6.2: Wave parameters at Lengeh port simulated by ERA5 wind data

Significant wave height H_{sig} for ERA5 at Lengeh (m)							
Return Period	1	5	10	20	50	100	200
Past	0.34	0.45	0.51	0.56	0.64	0.70	0.76
Future	0.41 (+21%)	0.48 (+7%)	0.56 (+10%)	0.65 (+16%)	0.78 (+22%)	0.88 (+26%)	1.00 (+32%)
Peak period T for ERA5 at Lengeh (s)							
Return Period	1	5	10	20	50	100	200
Past	6.12	7.48	8.24	9.04	10.13	10.99	11.89
Future	6.4 (+5%)	8.2 (+10%)	9.0 (+9%)	9.80 (+8%)	10.90 (+8%)	11.82 (+7%)	12.71 (+7%)
Wavenumber (Wavelength) $k(L)$ for ERA5 at Lengeh ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	3.9 (1.61)	5.1 (1.25)	5.5 (1.14)	6.0 (0.96)	6.6 (0.96)	7.0 (0.90)	7.4 (0.85)
Future	3.7 (1.69) (+5%)	4.6 (1.37) (+10%)	5.1 (1.24) (+9%)	5.6 (1.13) (+8%)	6.0 (1.04) (+8%)	6.5 (0.96) (+7%)	6.9 (0.91) (+7%)

Table 6.3: Wave parameters at Lengeh port simulated by REGCM wind data

Significant wave height H_{sig} for REGCM at Lengeh (m)							
Return Period	1	5	10	20	50	100	200
Past	1.01	1.34	1.51	1.68	1.92	2.12	2.33
Future	1.14 (+13%)	1.50 (+12%)	1.67 (+9%)	1.85 (+10%)	2.11 (+10%)	2.32 (+9%)	2.54 (+9%)
Peak period T for REGCM at Lengeh (s)							
Return Period	1	5	10	20	50	100	200
Past	6.20	7.46	8.50	9.68	11.48	13.07	14.87
Future	6.53 (+5%)	8.50 (+14%)	10.08 (+19%)	11.47 (+18%)	13.01 (+13%)	13.72 (+5%)	15.43 (+4%)
Wavenumber (Wavelength) $k(L)$ for REGCM at Lengeh ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	4.3 (1.44)	6.2 (1.01)	7.1 (0.88)	8.1 (0.77)	9.6 (0.65)	10.9 (0.58)	12.2 (0.52)
Future	4.2 (1.50) (+4%)	6.0 (1.05) (+4%)	6.9 (0.91) (+3%)	7.8 (0.80) (+4%)	9.3 (0.68) (+4%)	10.5 (0.60) (+3%)	11.7 (0.54) (+4%)

6.2.2 Point2 - Rajae port

The wave parameters for different return periods at Rajae port are shown in Tables 6.4 and ?? for ERA5 and REGCM wind data respectively.

Same as Lengeh port, wave height and peak period will increase in the future while wave number doesn't change considerably.

Table 6.4: Wave parameters at Rajae port simulated by ERA5 wind data

Significant wave height H_{sig} for ERA5 at Rajae (m)							
Return Period	1	5	10	20	50	100	200
Past	0.35	0.50	0.56	0.61	0.69	0.75	0.82
Future	0.38 (+9%)	0.53 (+6%)	0.60 (+7%)	0.66 (+8%)	0.75 (+9%)	0.82 (+9%)	0.89 (+9%)
Peak period T for ERA5 at Rajae (s)							
Return Period	1	5	10	20	50	100	200
Past	2.99	3.31	3.45	3.6	3.77	3.91	4.05
Future	3.18 (+6%)	3.51 (+6%)	3.65 (+6%)	3.8 (+6%)	3.98 (+6%)	4.12 (+5%)	4.26 (+5%)
Wavenumber (Wavelength) $k(L)$ for ERA5 at Rajae ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	4.1 (1.53)	4.6 (1.38)	4.7 (1.33)	4.9 (1.28)	5.1 (1.23)	5.3 (1.20)	5.4 (1.17)
Future	4.2 (1.50) (-2%)	4.6 (1.37) (-1%)	4.8 (1.31) (-1%)	4.9 (1.27) (-1%)	5.1 (1.22) (-1%)	5.3 (1.19) (-1%)	5.4 (1.16) (-1%)

Table 6.5: Wave parameters at Rajae port simulated by REGCM wind data

Significant wave height H_{sig} for REGCM at Rajae (m)							
Return Period	1	5	10	20	50	100	200
Past	0.72	1.01	1.16	1.33	1.58	1.79	2.03
Future	0.84 (+17%)	1.16 (+15%)	1.33 (+15%)	1.51 (+14%)	1.79 (+13%)	2.02 (+13%)	2.29 (+13%)
Peak period T for REGCM at Rajae (s)							
Return Period	1	5	10	20	50	100	200
Past	3.94	4.58	4.83	5.06	5.35	5.56	5.77
Future	4.25 (+8%)	4.85 (+6%)	5.09 (+5%)	5.32 (+5%)	5.60 (+5%)	5.80 (+4%)	6.00 (+4%)
Wavenumber (Wavelength) $k(L)$ for REGCM at Rajae ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	4.0 (1.57)	4.6 (1.38)	4.8 (1.31)	5.0 (1.26)	5.3 (1.19)	5.5 (1.15)	5.7 (1.11)
Future	4.2 (1.49) (-6%)	4.7 (1.32) (-4%)	5.0 (1.27) (-3%)	5.2 (1.22) (-3%)	5.4 (1.16) (-3%)	5.6 (1.12) (-3%)	5.8 (1.09) (-2%)

6.2.3 Point3 - Bahonar port

The wave parameters for different return periods at Rajae port are shown in Tables 6.6 and 6.7 for ERA5 and REGCM wind data respectively.

For this port, both ERA5 and REGCM model show that wave height increases in the future and unlike the wave number that decreases. On the other hand, prediction of the peak period is changing in two opposite ways.

Table 6.6: Wave parameters at Bahonar port simulated by ERA5 wind data

Significant wave height H_{sig} for ERA5 at Bahonar (m)							
Return Period	1	5	10	20	50	100	200
Past	0.34	0.46	0.51	0.56	0.63	0.68	0.74
Future	0.45 (+32%)	0.59 (+28%)	0.65 (+27%)	0.71 (+27%)	0.78 (+24%)	0.85 (+25%)	0.91 (+23%)
Peak period T for ERA5 at Bahonar (s)							
Return Period	1	5	10	20	50	100	200
Past	2.41	3.18	3.39	3.76	4.29	4.71	5.23
Future	2.18 (-9%)	2.76 (-13%)	3.04 (-10%)	3.35 (-11%)	3.80 (-11%)	4.19 (-11%)	4.61 (-12%)
Wavenumber (Wavelength) $k(L)$ for ERA5 at Bahonar ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	4.0 (1.58)	4.5 (1.40)	4.7 (1.35)	4.9 (1.29)	5.1 (1.23)	5.3 (1.20)	5.4 (1.16)
Future	4.2 (1.49) (-6%)	4.7 (1.35) (-4%)	4.8 (1.30) (-4%)	5.0 (1.26) (-2%)	5.2 (1.21) (-2%)	5.3 (1.18) (-2%)	5.5 (1.15) (-1%)

Table 6.7: Wave parameters at Bahonar port simulated by REGCM wind data

Significant wave height H_{sig} for REGCM at Bahonar (m)							
Return Period	1	5	10	20	50	100	200
Past	0.70	0.92	1.02	1.12	1.27	1.39	1.52
Future	0.81 (+16%)	1.04 (+13%)	1.14 (+12%)	1.26 (+12%)	1.41 (+11%)	1.54 (+11%)	1.68 (+11%)
Peak period T for REGCM at Bahonar (s)							
Return Period	1	5	10	20	50	100	200
Past	3.67	4.30	4.55	4.78	5.06	5.27	5.46
Future	4.02 (+10%)	4.62 (+7%)	4.85 (+7%)	5.07 (+6%)	5.35 (+6%)	5.55 (+5%)	5.74 (+5%)
Wavenumber (Wavelength) $k(L)$ for REGCM at Bahonar ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	4.3 (1.46)	4.9 (1.28)	5.1 (1.22)	5.4 (1.16)	5.7 (1.10)	5.9 (1.06)	6.1 (1.03)
Future	4.5 (1.39) (-5%)	5.1 (1.23) (-4%)	5.3 (1.18) (-3%)	5.6 (1.13) (-3%)	5.9 (1.07) (-3%)	6.1 (1.04) (-2%)	6.3 (1.00) (-3%)

6.2.4 Point4 - Asaluye port

The wave parameters for different return periods at Asaluye port are shown in Tables 6.8 and 6.9 for ERA5 and REGCM wind data respectively.

In Asaluye, ERA5 predicts a significant change in wave height for the future while the increase in wave height in REGCM model is less severe. From the results it can be concluded that the increase of wave energy in REGCM model causes increase of both wave height and peak period, but in ERA5 model it is mainly reflected in wave height.

Table 6.8: Wave parameters at Asaluye port simulated by ERA5 wind data

Significant wave height H_{sig} for ERA5 at Asaluye (m)							
Return Period	1	5	10	20	50	100	200
Past	0.65	0.86	0.93	1.00	1.10	1.17	1.25
Future	1.01 (+55%)	1.28 (+49%)	1.46 (+57%)	1.63 (+63%)	1.85 (+68%)	2.02 (+73%)	2.18 (+75%)
Peak period T for ERA5 at Asaluye (s)							
Return Period	1	5	10	20	50	100	200
Past	6.58	7.96	8.51	9.04	9.73	10.23	10.73
Future	6.46 (-2%)	7.24 (-10%)	7.53 (-12%)	7.80 (-14%)	8.13 (-15%)	8.37 (-18%)	8.59 (-20%)
Wavenumber (Wavelength) $k(L)$ for ERA5 at Asaluye ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	3.7 (1.71)	6.9 (0.90)	8.2 (0.77)	9.0 (0.70)	9.6 (0.65)	9.9 (0.64)	10.0 (0.63)
Future	4.2 (1.48) (+13%)	8.3 (0.78) (+13%)	8.6 (0.73) (+5%)	8.9 (0.71) (+2%)	9.1 (0.68) (+5%)	9.2 (0.68) (+6%)	9.3 (0.67) (+6%)

Table 6.9: Wave parameters at Asaluye port simulated by REGCM wind data

Significant wave height H_{sig} for REGCM at Asaluye (m)							
Return Period	1	5	10	20	50	100	200
Past	1.01	1.63	1.93	2.26	2.74	3.14	3.57
Future	1.25 (+24%)	1.90 (+17%)	2.22 (+15%)	2.57 (+14%)	3.07 (+12%)	3.49 (+11%)	3.93 (+10%)
Peak period T for REGCM at Asaluye (s)							
Return Period	1	5	10	20	50	100	200
Past	7.70	8.63	9.00	9.36	9.82	10.15	10.48
Future	7.08 (-8%)	8.31 (-4%)	8.83 (-2%)	9.34 (-0%)	10.01 (+2%)	10.53 (+4%)	11.06 (+6%)
Wavenumber (Wavelength) $k(L)$ for REGCM at Asaluye ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	3.0 (2.08)	4.2 (1.48)	4.9 (1.29)	5.5 (1.14)	6.5 (0.97)	7.3 (0.86)	8.2 (0.76)
Future	3.6 (1.74) (-16%)	4.9 (1.27) (-14%)	5.6 (1.12) (-13%)	6.4 (0.99) (-13%)	7.4 (0.85) (-12%)	8.3 (0.76) (-12%)	9.3 (0.68) (-11%)

6.2.5 Point5 - Bushehr port

The wave parameters for different return periods at Bushehr port are shown in Tables 6.10 and 6.11 for ERA5 and REGCM wind data respectively. Unlike the other ports in Bushehr, wave height and period don't have significant change from past to future and the variation of wave number is stronger.

In the following sections, we investigate the influence of parameter variations on the wave loading on the coastal structures.

Table 6.10: Wave parameters at Bushehr port simulated by ERA5 wind data

Significant wave height H_{sig} for ERA5 at Bushehr (m)							
Return Period	1	5	10	20	50	100	200
Past	0.53	0.66	0.71	0.76	0.82	0.87	0.91
Future	0.52 (-2%)	0.63 (-5%)	0.69 (-3%)	0.73 (-4%)	0.79 (-4%)	0.85 (-3%)	0.88 (-3%)
Peak period T for ERA5 at Bushehr (s)							
Return Period	1	5	10	20	50	100	200
Past	5.17	6.34	6.76	7.15	7.61	7.95	8.26
Future	3.44 (-33%)	4.68 (-26%)	5.34 (-21%)	6.08 (-15%)	7.23 (-5%)	8.23 (+4%)	9.38 (+14%)
Wavenumber (Wavelength) $k(L)$ for ERA5 at Bushehr ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	3.9 (1.59)	4.6 (1.38)	4.8 (1.31)	4.9 (1.29)	5.1 (1.23)	5.3 (1.19)	5.4 (1.17)
Future	4.2 (1.48) (-7%)	5.0 (1.26) (-9%)	5.2 (1.22) (-7%)	5.3 (1.20) (-7%)	5.4 (1.16) (-6%)	5.5 (1.14) (-4%)	5.6 (1.12) (-4%)

Table 6.11: Wave parameters at Bushehr port simulated by REGCM wind data

Significant wave height H_{sig} for REGCM at Bushehr (m)							
Return Period	1	5	10	20	50	100	200
Past	0.79	0.86	0.87	0.88	0.89	0.90	0.92
Future	0.71 (-10%)	0.82 (-5%)	0.84 (-3%)	0.86 (-2%)	0.88 (-1%)	0.89 (-1%)	0.90 (-2%)
Peak period T for REGCM at Bushehr (s)							
Return Period	1	5	10	20	50	100	200
Past	7.85	8.95	9.34	9.81	10.33	10.75	11.14
Future	7.36 (-6%)	9.01 (+1%)	9.74 (+4%)	10.50 (+7%)	11.54 (+12%)	12.37 (+15%)	13.24 (+19%)
Wavenumber (Wavelength) $k(L)$ for REGCM at Bushehr ($m^{-1}(m)$)							
Return Period	1	5	10	20	50	100	200
Past	3.8 (1.67)	4.9 (1.27)	5.5 (1.14)	6.1 (1.02)	7.0 (0.90)	7.7 (0.81)	8.5 (0.74)
Future	4.2 (1.48) (-12%)	4.9 (1.15) (-9%)	6.1 (1.04) (-9%)	6.7 (0.94) (-8%)	7.6 (0.83) (-8%)	8.3 (0.76) (-6%)	9.0 (0.70) (-5%)

6.3 Wave load on coastal structures

Because of the random nature of ocean waves, it is not possible to find analytical equations for the wave-induced loads on all types of coastal structures. For any of these structures, we have to use empirical formulae which are extracted from experimental data. Therefore, we have to limit our study to some special structures which are typically used in the target areas, including cylindrical piles, vertical walls, and rubble mound breakwaters.

6.3.1 Wave load on the cylindrical pile

The Morison equation can be used to calculate the inertia force F_I and drag force F_D caused by a wave as follows [103]:

$$F_I = \frac{\pi \rho a C_m D^2}{4} \quad (6.9)$$

$$F_D = \frac{\rho C_d v^2 D}{2} \quad (6.10)$$

Where D is the diameter of the pile, ρ is the water density, and C_d and C_m represent the drag and inertia (or mass) hydrodynamic force coefficients, respectively. a and v are the acceleration and velocity of the water particles in the horizontal direction. Thus, in order to find the changes in these forces, we have to look at the changes in the velocity and acceleration of the water particles caused by a wave. These parameters can be calculated using the following equations [100]:

$$v = \left(\frac{HgT \cosh(F_1)}{2L \cosh(F_2)} \right) \cos(F_3) \quad (6.11)$$

$$a = \left(-\frac{Hg\rho}{L} \frac{\sinh(F_1)}{\cosh(F_2)} \right) \cos(F_3) \quad (6.12)$$

Where H , T , and L are the wave height, period, and wavelength. F_1 , F_2 and F_3 are defined as:

$$F_1 = k(z+d), \quad F_2 = kd, \quad F_3 = kx - \omega t \quad (6.13)$$

Where k and ω are the wavenumber and angular frequency of the wave, and d is the water depth.

As can be seen, the acceleration and velocity of the water particles are determined by the significant wave height, period, and wavelength. Since there is a non-linear relationship between these wave parameters and the velocity and acceleration of the water particles, it would not be possible to find the values of drag and inertia forces for different return periods directly from the numbers calculated and shown in the previous section for the wave parameters. As a further explanation, Eq. 6.11 shows that the velocity of water is proportional to the wave height, while it decreases with increasing wavelength. So, it seems that the maximum velocity is determined by the maximum wave height and the minimum wavelength (i.e. the maximum wave number). Looking at Table 6.2, for example, the wave simulated at Lengeh port using ERA5 past wind data shows that for a 200-year return period, the maximum wave height would be $0.76m$, while the maximum wave number would be $7.4m^{-1}$, corresponding to a wavelength of $0.85m$. Substituting these numbers into Eq. 6.11 leads to completely nonsensical values for the water particle velocity (in the order of $10^4 m/s$). However, it is obvious that this analysis cannot be true because the maximum wave height and minimum wavelength don't occur simultaneously. In other words, a wave with $H_{sig} = 0.76m$ and $L = 0.85m$, which means a wave steepness of ≈ 0.9 , cannot exist. Therefore, we can conclude that the drag and inertia forces for different return periods must be calculated directly from a statistical analysis of these forces for the entire time series. Thus, we have calculated the velocity and acceleration of the water particles from the wave parameters for the entire time series, following the same procedure as explained in section 6.1 to create a statistically independent data set. Finally, we found these parameters for different return periods, which are shown in Tables 6.12 - 6.21 for the five study sites and two wind models. Using Eqs. 6.10 and 6.9, one can easily calculate the predicted change of drag and inertia forces from the past to the future in each case. Such changes are shown in the last rows of the tables. This row shows the ratio of the future force to the force caused by the past data, so a number greater than one means an increase in force.

Fig 6.5 shows a summary of these tables, where the changes in inertia and drag forces are shown for four wind data sets at the study points. In these curves, solid lines show the predictions based on the ERA5 model, while dashed lines represent the results of using REGCM data. It can be seen that for most of the cases, the two models predict the change in the same way. For the points in the north-east part of the Persian Gulf, the REGCM model predicts a larger change than the ERA5 model, while for Asluye and Bushehr, which are located at the north-west of the Persian Gulf, changes predicted by ERA5 wind data are more severe than those of the REGCM model. (Note that both models predict a reduction of the drag force at Bushehr in long-term return periods.)

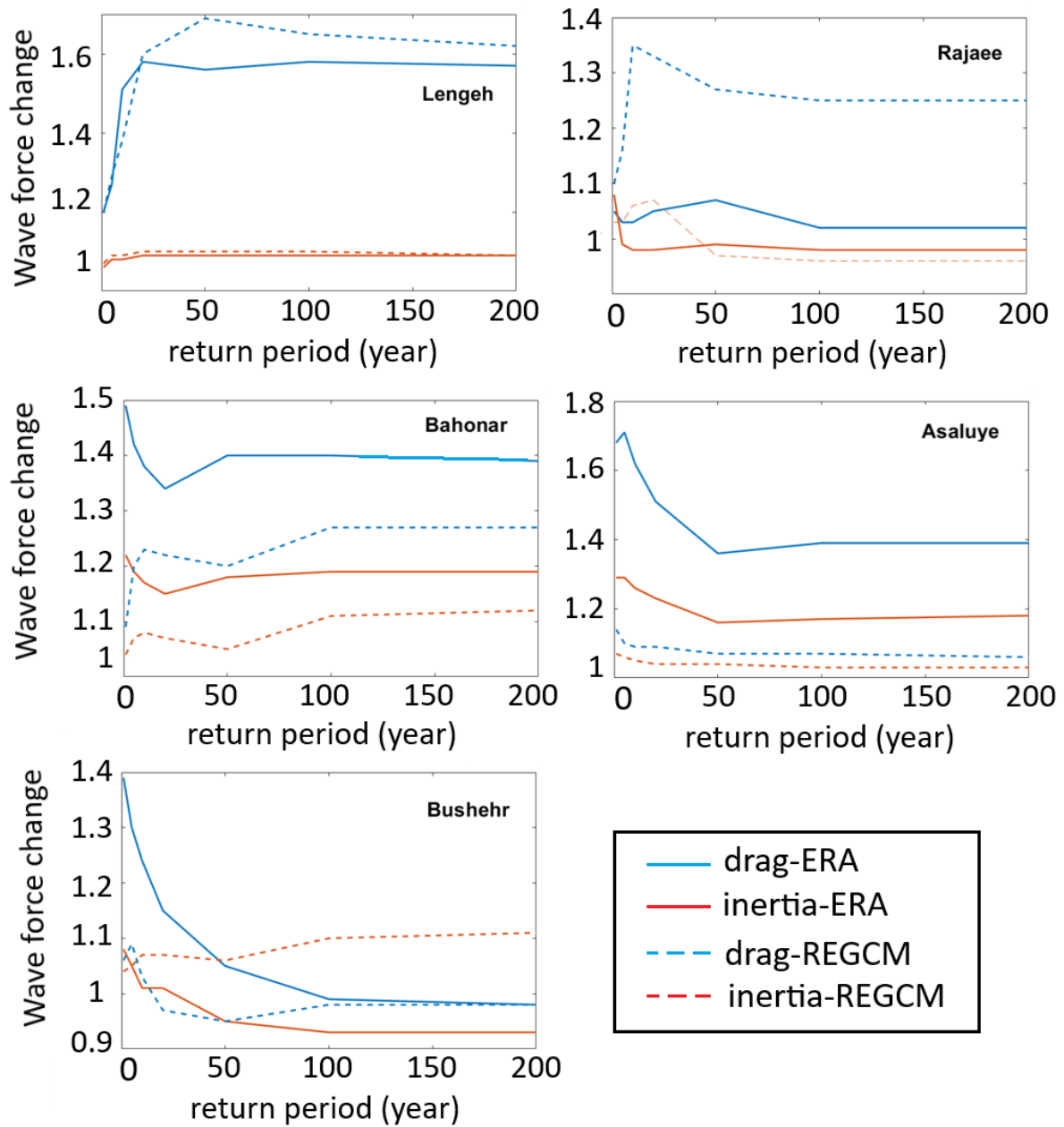


Figure 6.5: Inertia and drag forces change (future/past) predicted by ERA5 and REGCM models

Table 6.12: Water particles velocity and acceleration, as well as inertia and drag force change at Lengeh port simulated by ERA5 wind data

Water particle velocity v for ERA5 at Lengeh (m/s)							
Return Period	1	5	10	20	50	100	200
Past	0.84	0.93	0.96	0.98	1.00	1.01	1.02
Future	0.92	1.05	1.18	1.23	1.25	1.27	1.28
Water particle acceleration a for ERA5 at Lengeh (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	8.28	9.19	9.54	9.73	9.91	9.98	10.03
Future	8.78	9.92	10.30	10.59	10.80	10.88	10.96
Wave load change (future/past) for ERA5 at Lengeh							
Return Period	1	5	10	20	50	100	200
Drag	1.20	1.27	1.51	1.58	1.56	1.58	1.57
Inertia	1.06	1.08	1.08	1.09	1.09	1.09	1.09

Table 6.13: Water particles velocity and acceleration as well as inertia and drag force change at Lengeh port simulated by REGCM wind data

Water particle velocity v for REGCM at Lengeh (m/s)							
Return Period	1	5	10	20	50	100	200
Past	1.14	1.24	1.27	1.29	1.34	1.37	1.39
Future	1.25	1.41	1.49	1.63	1.74	1.76	1.77
Water particle acceleration a for REGCM at Lengeh (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	11.12	12.15	12.46	12.67	13.26	13.59	13.73
Future	11.97	13.19	13.58	13.97	14.61	14.90	15.03
Wave load change (future/past) for REGCM at Lengeh							
Return Period	1	5	10	20	50	100	200
Drag	1.20	1.29	1.38	1.60	1.69	1.65	1.62
Inertia	1.07	1.09	1.09	1.10	1.10	1.10	1.09

Table 6.14: Water particles velocity and acceleration as well as inertia and drag force change at Rajae port simulated by ERA5 wind data

Water particle velocity v for ERA5 at Rajae (m/s)							
Return Period	1	5	10	20	50	100	200
Past	0.72	0.76	0.78	0.80	0.83	0.86	0.87
Future	0.74	0.77	0.79	0.82	0.86	0.87	0.88
Water particle acceleration a for ERA5 at Rajae (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	6.73	7.68	8.01	8.28	8.49	8.81	8.91
Future	7.29	7.65	7.85	8.09	8.42	8.64	8.72
Wave load change (future/past) for ERA5 at Rajae							
Return Period	1	5	10	20	50	100	200
Drag	1.05	1.03	1.03	1.05	1.07	1.02	1.02
Inertia	1.08	0.99	0.98	0.98	0.99	0.98	0.98

Table 6.15: Water particles velocity and acceleration as well as inertia and drag force change at Rajae port simulated by REGCM wind data

Water particle velocity v for REGCM at Rajae (m/s)							
Return Period	1	5	10	20	50	100	200
Past	1.01	1.14	1.16	1.19	1.26	1.28	1.29
Future	1.06	1.23	1.35	1.37	1.42	1.43	1.44
Water particle acceleration a for REGCM at Rajae (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	9.5	10.38	10.58	10.90	12.20	12.39	12.49
Future	9.77	10.68	11.26	11.63	11.85	11.94	12.00
Wave load change (future/past) for REGCM at Rajae							
Return Period	1	5	10	20	50	100	200
Drag	1.10	1.16	1.35	1.33	1.27	1.25	1.25
Inertia	1.03	1.03	1.06	1.07	0.97	0.96	0.96

Table 6.16: Water particles velocity and acceleration as well as inertia and drag force change at Bahonar port simulated by ERA5 wind data

Water particle velocity v for ERA5 at Bahonar (m/s)							
Return Period	1	5	10	20	50	100	200
Past	0.72	0.78	0.80	0.83	0.87	0.88	0.89
Future	0.88	0.93	0.794	0.96	1.03	1.04	1.05
Water particle acceleration a for ERA5 at Bahonar (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	7.11	7.76	7.95	8.24	8.60	8.69	8.74
Future	8.67	9.20	9.33	9.45	10.14	10.31	10.40
Wave load change (future/past) for ERA5 at Bahonar							
Return Period	1	5	10	20	50	100	200
Drag	1.49	1.42	1.38	1.34	1.40	1.40	1.39
Inertia	1.22	1.19	1.17	1.15	1.18	1.19	1.19

Table 6.17: Water particles velocity and acceleration as well as inertia and drag force change at Bahonar port simulated by REGCM wind data

Water particle velocity v for REGCM at Bahonar (m/s)							
Return Period	1	5	10	20	50	100	200
Past	0.95	1.06	1.10	1.14	1.17	1.19	1.20
Future	0.99	1.16	1.22	1.26	1.28	1.34	1.35
Water particle acceleration a for REGCM at Bahonar (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	9.26	10.22	10.69	10.99	11.37	11.57	11.69
Future	9.64	10.98	11.59	11.80	11.96	12.89	13.03
Wave load change (future/past) for REGCM at Bahonar							
Return Period	1	5	10	20	50	100	200
Drag	1.09	1.20	1.23	1.22	1.20	1.27	1.27
Inertia	1.04	1.07	1.08	1.07	1.05	1.11	1.12

Table 6.18: Water particles velocity and acceleration as well as inertia and drag force change at Asaluye port simulated by ERA5 wind data

Water particle velocity v for ERA5 at Asaluye (m/s)							
Return Period	1	5	10	20	50	100	200
Past	0.84	0.94	0.99	1.05	1.15	1.16	1.17
Future	1.09	1.23	1.26	1.29	1.34	1.37	1.38
Water particle acceleration a for ERA5 at Asaluye (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	8.34	9.35	9.82	10.37	11.41	11.53	11.59
Future	10.73	12.09	12.40	12.74	13.22	10.52	13.67
Wave load change (future/past) for ERA5 at Asaluye							
Return Period	1	5	10	20	50	100	200
Drag	1.68	1.71	1.62	1.51	1.36	1.39	1.39
Inertia	1.29	1.29	1.26	1.23	1.16	1.17	1.18

Table 6.19: Water particles velocity and acceleration as well as inertia and drag force change at Asaluye port simulated by REGCM wind data

Water particle velocity v for REGCM at Asaluye (m/s)							
Return Period	1	5	10	20	50	100	200
Past	1.19	1.44	1.54	1.64	1.77	1.87	1.96
Future	1.27	1.51	1.61	1.71	1.83	1.93	2.02
Water particle acceleration a for REGCM at Asaluye (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	11.67	14.07	15.08	16.07	17.37	18.33	19.30
Future	12.49	14.81	15.79	16.76	18.02	18.96	19.90
Wave load change (future/past) for REGCM at Asaluye							
Return Period	1	5	10	20	50	100	200
Drag	1.14	1.10	1.09	1.09	1.07	1.07	1.06
Inertia	1.07	1.06	1.05	1.04	1.04	1.03	1.03

Table 6.20: Water particles velocity and acceleration as well as inertia and drag force change at Bushehr port simulated by ERA5 wind data

Water particle velocity v for ERA5 at Bushehr (m/s)							
Return Period	1	5	10	20	50	100	200
Past	0.94	1.01	1.05	1.10	1.16	1.21	1.23
Future	1.11	1.15	1.17	1.18	1.19	1.20	1.22
Water particle acceleration a for ERA5 at Bushehr (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	8.00	8.55	8.96	9.09	9.82	10.09	10.17
Future	8.65	8.94	9.05	9.16	9.28	9.36	9.42
Wave load change (future/past) for ERA5 at Bushehr							
Return Period	1	5	10	20	50	100	200
Drag	1.39	1.30	1.24	1.15	1.05	0.99	0.98
Inertia	1.08	1.05	1.01	1.01	0.95	0.93	0.93

Table 6.21: Water particles velocity and acceleration as well as inertia and drag force change at Bushehr port simulated by REGCM wind data

Water particle velocity v for REGCM at Bushehr (m/s)							
Return Period	1	5	10	20	50	100	200
Past	1.06	1.12	1.17	1.23	1.27	1.31	1.33
Future	1.09	1.17	1.19	1.21	1.24	1.30	1.32
Water particle acceleration a for REGCM at Bushehr (m/s^2)							
Return Period	1	5	10	20	50	100	200
Past	9.22	10.07	10.28	10.44	10.55	10.61	10.65
Future	9.61	10.59	10.99	11.13	11.28	11.71	11.80
Wave load change (future/past) for REGCM at Bushehr							
Return Period	1	5	10	20	50	100	200
Drag	1.06	1.09	1.03	0.97	0.95	0.98	0.98
Inertia	1.04	1.05	1.07	1.07	1.06	1.10	1.11

6.3.2 Wave load on breakwaters

In this section, we study the effects of wave loading on the breakwaters in the study ports. The typical breakwater used along the northern coast of the Persian Gulf is the rock rubble mound structure. Therefore, we limit our study to this type of breakwater. Due to the random nature of the rubble mound breakwaters, there is no analytical equation to calculate the load caused by water waves on these structures. Instead, the instability of the armor units is usually studied, which can be interpreted as the probability of unit displacement by the waves. The dynamics of the armor units depend on the behavior of the wave as it hits the structure [104, 105]. In other words, the stability formulas are different for overtopping and non-overtopping waves. Here we study the instability of the front slope of a rock rubble mound for both cases because, at the study sites, there are short rubble mound structures where overtopping is very likely. We have also studied the instability of reef rubble mound breakwaters. For the entire analysis, we use empirical equations based on hydraulic model tests.

Rock rubble mound non-overtopped slopes

The stability coefficient of the front slope of a rock rubble mound in the case of non-overtopped waves is proposed in [106, 107, 108] as follows:

$$k_D = \frac{H^3}{(\Delta D)^3 \cot \alpha} \propto H^3, \quad (6.14)$$

Where H is the significant wave height, α is the slope angle, D is the average diameter of the unit, and Δ is defined as follows:

$$\Delta = \frac{\rho_s}{\rho_w} - 1, \quad (6.15)$$

Where ρ_s and ρ_w are the stone and water mass densities, respectively. K_D is the instability coefficient. The higher the K_D value, the higher the probability of the unit displacement caused by the waves. As can be seen from Eq. 6.15, the instability of the front slope of a rock rubble mound in the case of non-overtopped waves depends solely on the significant wave height. Therefore, it is possible to find this instability for different return periods directly from the wave heights calculated in section 6.2. Tables 6.22 to 6.26 show the change of k_D for different return periods at all the study points predicted by the ERA5 and REGCM models.

Rock rubble mound rubble mound overtopped slopes

The stability formula for the front slope of a rock rubble mound caused by overtopped waves is proposed by [106, 108] as follows:

$$\frac{N_{od}}{N_a} = a \cdot \exp \left(b s_p^{-1/3} \frac{H}{\Delta D} \right). \quad (6.16)$$

Where N_{od} and N_a are the number of displaced units and the total number of the units, respectively. s_p is the wave steepness (H/L), and a and b are some constant coefficients which

Table 6.22: Instability of the front slope of a rubble mound structure caused by a non-overtopped wave at Lengeh port

Rock rubble mound instability factor k_D for ERA5 at Lengeh							
Return Period	1	5	10	20	50	100	200
Future/Past	1.77	1.23	1.33	1.57	1.82	2.00	2.30
Rock rubble mound instability factor k_D for REGCM at Lengeh							
Return Period	1	5	10	20	50	100	200
Future/Past	1.44	1.41	1.30	1.33	1.33	1.30	1.30

Table 6.23: Instability of the front slope of a rubble mound structure caused by a non-overtopped wave at Rajaei port

Rock rubble mound instability factor k_D for ERA5 at Rajaei							
Return Period	1	5	10	20	50	100	200
Future/Past	1.30	1.19	1.23	1.26	1.30	1.30	1.30
Rock rubble mound instability factor k_D for REGCM at Rajaei							
Return Period	1	5	10	20	50	100	200
Future/Past	1.56	1.53	1.53	1.48	1.44	1.44	1.44

Table 6.24: Instability of the front slope of a rubble mound structure caused by a non-overtopped wave at Bahonar port

Rock rubble mound instability factor k_D for ERA5 at Bahonar							
Return Period	1	5	10	20	50	100	200
Future/Past	2.30	2.10	2.05	2.05	1.91	1.95	1.86
Rock rubble mound instability factor k_D for REGCM at Bahonar							
Return Period	1	5	10	20	50	100	200
Future/Past	1.86	1.44	1.41	1.41	1.37	1.37	1.37

Table 6.25: Instability of the front slope of a rubble mound structure caused by a non-overtopped wave at Asaluyeh port

Rock rubble mound instability factor k_D for ERA5 at Asaluyeh							
Return Period	1	5	10	20	50	100	200
Future/Past	3.72	3.31	3.87	4.33	4.74	5.18	5.36
Rock rubble mound instability factor k_D for REGCM at Asaluyeh							
Return Period	1	5	10	20	50	100	200
Future/Past	1.91	1.60	1.53	1.48	1.40	1.37	1.33

must be found empirically. Table 6.27 Shows these values where R_c and h are the freeboard and height of the structure respectively.

Similar to the drag and inertia forces, the non-linear dependency of the instability factor on the wave parameters (wave height and wavelength) prevents us from calculating the instability

Table 6.26: Instability of the front slope of a rubble mound structure caused by a non-overtopped wave at Bushehr port

Rock rubble mound instability factor k_D for ERA5 at Bushehr							
Return Period	1	5	10	20	50	100	200
Future/Past	0.94	0.86	0.91	0.88	0.88	0.91	0.91

Rock rubble mound instability factor k_D for REGCM at Bushehr							
Return Period	1	5	10	20	50	100	200
Future/Past	0.73	0.86	0.91	0.94	0.97	0.97	0.94

Table 6.27: a and b parameters found empirically to be used in Eq. 6.16

R_c/h	$a(\times 10^4)$	b	s_p
0.29	0.07	1.66	< 0.03
0.39	0.18	1.58	< 0.03
0.57	0.09	1.92	> 0.03
0.78	0.59	1.07	> 0.03

directly from the wave height and wavelength shown in section 6.1. Therefore, we again calculated the stability factor for all the time samples and found the values of this parameter for different return periods. Tables 6.28 to 6.32 show the changes in the stability factor for different return periods at all the study points predicted by the ERA5 and REGCM models.

Table 6.28: Instability of the front slope of a rubble mound structure caused by an overtopped wave at Lengeh port

Rock rubble mound - displacement probability for ERA5 at Lengeh							
Return Period	1	5	10	20	50	100	200
Future/Past	1.09	1.11	1.10	1.07	1.08	1.10	1.11

Rock rubble mound - displacement probability for REGCM at Lengeh							
Return Period	1	5	10	20	50	100	200
Future/Past	1.29	1.33	1.33	1.38	1.31	1.27	1.22

Table 6.29: Instability of the front slope of a rubble mound structure caused by an overtopped wave at Rajaei port

Rock rubble mound - displacement probability for ERA5 at Rajaei							
Return Period	1	5	10	20	50	100	200
Future/Past	1.22	1.25	1.22	1.21	1.19	1.13	1.10

Rock rubble mound - displacement probability for REGCM at Rajaei							
Return Period	1	5	10	20	50	100	200
Future/Past	1.42	1.36	1.33	1.35	1.29	1.28	1.24

Table 6.30: Instability of the front slope of a rubble mound structure caused by an overtopped wave at Bahonar port

Rock rubble mound - displacement probability for ERA5 at Bahonar							
Return Period	1	5	10	20	50	100	200
Future/Past	1.50	1.58	1.58	1.67	1.67	1.68	1.68

Rock rubble mound - displacement probability for REGCM at Bahonar							
Return Period	1	5	10	20	50	100	200
Future/Past	1.32	1.37	1.70	1.45	1.40	1.41	1.42

Table 6.31: Instability of the front slope of a rubble mound structure caused by an overtopped wave at Asaluye port

Rock rubble mound - displacement probability for ERA5 at Asaluye							
Return Period	1	5	10	20	50	100	200
Future/Past	5.50	6.48	5.96	5.61	5.79	5.85	5.91

Rock rubble mound - displacement probability for REGCM at Asaluye							
Return Period	1	5	10	20	50	100	200
Future/Past	1.88	1.79	1.46	1.38	1.31	1.23	1.22

Table 6.32: Instability of the front slope of a rubble mound structure caused by an overtopped wave at Bushehr port

Rock rubble mound - displacement probability for ERA5 at Bushehr							
Return Period	1	5	10	20	50	100	200
Future/Past	0.65	0.61	0.60	0.61	0.62	0.63	0.64

Rock rubble mound - displacement probability for REGCM at Bushehr							
Return Period	1	5	10	20	50	100	200
Future/Past	0.89	0.89	0.87	0.91	0.91	0.91	0.90

Rock rubble mound - reef breakwater

The stability formula for a rock rubble mound reef breakwater is proposed by [106, 108] as follows:

$$\frac{N_{od}}{N_a} = a \cdot \exp\left(\frac{bH}{\Delta D}\right). \quad (6.17)$$

The values of coefficients a and b are shown in Table 6.33.

Same as previous case, stability factor has to be calculated for the entire time series in order to find its values for different return periods which are show in Tables 6.34 to 6.38.

Fig 6.6 shows a summary of these tables, where the changes in the stability factor are shown for four wind data sets at the study points. In these curves, solid lines show the predictions based on the ERA5 model, while dashed lines represent the results of using REGCM data. It can be seen that for most of the cases, the two models predict the change in the same way. As with the

Table 6.33: a and b parameters found empirically to be used in Eq. 6.17

R_c/h	$a(\times 10^4)$	b
0.0	15	0.31
0.2	17	0.33
0.4	4.8	0.53

Table 6.34: Instability of a rubble mound reef breakwater at Lengeh port

Reef breakwater - displacement probability for ERA5 at Lengeh							
Return Period	1	5	10	20	50	100	200
Future/Past	1.01	1.01	1.00	1.01	1.01	1.01	1.02
Rock rubble mound - displacement probability for REGCM at Lengeh							
Return Period	1	5	10	20	50	100	200
Future/Past	1.02	1.22	1.22	1.36	1.40	1.41	1.41

Table 6.35: Instability of a rubble mound reef breakwater at Rajaee port

Reef breakwater - displacement probability for ERA5 at Rajaee							
Return Period	1	5	10	20	50	100	200
Future/Past	1.02	1.02	1.02	1.01	1.01	1.00	1.01
Rock rubble mound - displacement probability for REGCM at Rajaee							
Return Period	1	5	10	20	50	100	200
Future/Past	1.00	1.06	1.12	1.13	1.13	1.12	1.12

Table 6.36: Instability of a rubble mound reef breakwater at Bahonar port

Reef breakwater - displacement probability for ERA5 at Bahonar							
Return Period	1	5	10	20	50	100	200
Future/Past	1.05	1.05	1.05	1.06	1.06	1.06	1.06
Rock rubble mound - displacement probability for REGCM at Bahonar							
Return Period	1	5	10	20	50	100	200
Future/Past	0.99	1.02	1.05	1.06	1.06	1.06	1.07

Table 6.37: Instability of a rubble mound reef breakwater at Asaluye port

Reef breakwater - displacement probability for ERA5 at Asaluye							
Return Period	1	5	10	20	50	100	200
Future/Past	1.17	1.21	1.21	1.21	1.21	1.22	1.22
Rock rubble mound - displacement probability for REGCM at Asaluye							
Return Period	1	5	10	20	50	100	200
Future/Past	1.01	1.01	1.02	1.02	1.01	1.01	1.01

drag and inertia forces, for the points in the north-east part of the Persian Gulf, the REGCM model predicts a larger change than the ERA5 model, while for Asaluye and Bushehr, which are

Table 6.38: Instability of a rubble mound reef breakwater at Bushehr port

Reef breakwater - displacement probability for ERA5 at Bushehr							
Return Period	1	5	10	20	50	100	200
Future/Past	0.97	0.97	0.98	0.98	0.98	0.98	0.98
Rock rubble mound - displacement probability for REGCM at Bushehr							
Return Period	1	5	10	20	50	100	200
Future/Past	0.99	0.99	1.00	1.00	1.00	1.00	1.00

located at the north-west of the Persian Gulf, changes predicted by ERA5 wind data are more severe than those of the REGCM model. It is worth noting that for all cases at Bushehr port, the instability in the future is predicted to be less than in the past.

6.3.3 Wave load on the vertical walls

In this section, the interaction between the water waves and vertical walls is investigated for three cases:

Wave load on fully reflected vertical wall

In this section, we investigate an impermeable vertical wall which extends all the way down to the seabed (Fig. 6.7). The pressure at different points of the wall generated by the waves can be calculated analytically using the Sainflou formula as follows [109, 108]:

$$\begin{aligned}
 p_1 &= (p_2 + \rho g d) \frac{H + \delta_0}{d + H + \delta_0}, \\
 p_2 &= \frac{\rho g H}{\cosh(kd)}, \\
 p_3 &= \rho g (H - \delta_0),
 \end{aligned} \tag{6.18}$$

where δ_0 can be calculated using the following equation:

$$\delta_0 = \frac{kH^2}{2} \coth(kd), \tag{6.19}$$

Where d is the water depth, g is the gravitational acceleration, and ρ is water density. H and k are the wave height and wavenumber, respectively. It can be seen that P_2 and P_3 are proportional to P_1 . Since we are interested in investigating the changes from the past to the future, it is sufficient to study just one of these pressure values. In this case, we focused on P_1 since it is the maximum pressure that a wave applies to the wall. Again, we have to calculate this pressure for all time steps in order to find its value for different return periods statistically. The results of such calculations are shown in Tables 6.39 to 6.43.

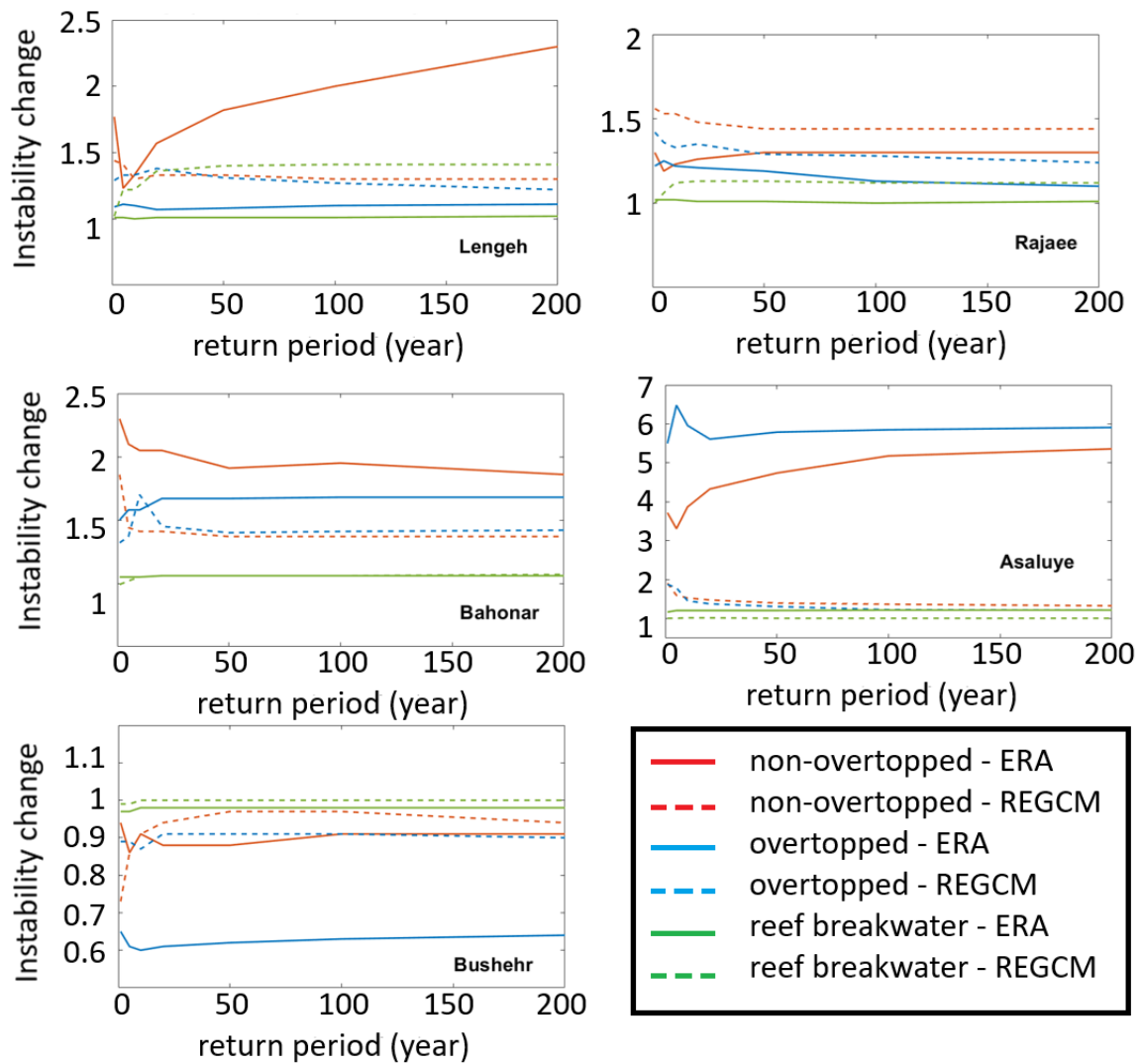


Figure 6.6: Instability of rubble mound structures (future/past) predicted by the ERA5 and REGCM models

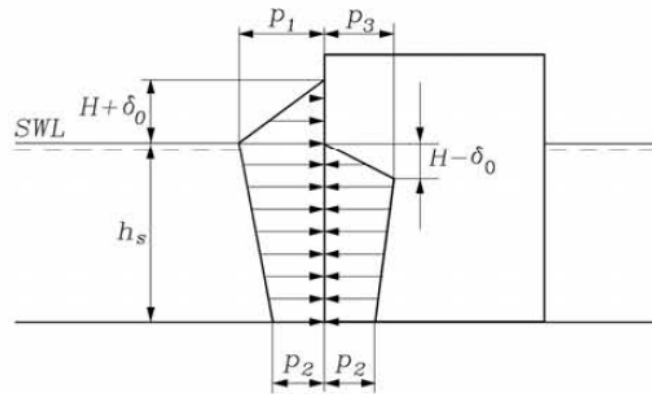


Figure 6.7: Pressure caused by wave on a vertical wall [108].

Table 6.39: Pressure on a vertical wall calculated from Sainflou formula at Lengeh port

Pressure P_1 on vertical wall for ERA5 at Lengeh (kPa)							
Return Period	1	5	10	20	50	100	200
Past	5.83	6.82	7.13	7.68	7.88	7.94	7.97
Future	6.31 (+8%)	7.04 (+3%)	7.25 (+2%)	7.92 (+3%)	8.26 (+5%)	8.31 (+5%)	8.34 (+5%)

Pressure P_1 on vertical wall for REGCM at Lengeh (kPa)							
Return Period	1	5	10	20	50	100	200
Past	14.44	17.19	18.03	18.29	18.58	18.65	18.70
Future	15.12 (+6%)	24.11 (+40%)	25.10 (+39%)	28.96 (+58%)	30.39 (+63%)	30.59 (+64%)	30.68 (+64%)

Table 6.40: Pressure on a vertical wall calculated from Sainflou formula at Rajaei port

Pressure P_1 on vertical wall for ERA5 at Rajaei (kPa)							
Return Period	1	5	10	20	50	100	200
Past	5.13	6.18	6.55	7.12	7.47	7.52	7.54
Future	5.80 (+13%)	6.82 (+10%)	7.13 (+9%)	7.32 (+3%)	7.51 (+1%)	7.60 (+1%)	7.66 (+2%)

Pressure P_1 on vertical wall for REGCM at Rajaei (kPa)							
Return Period	1	5	10	20	50	100	200
Past	12.39	13.79	13.99	14.11	14.33	14.43	14.48
Future	13.24 (+7%)	17.77 (+29%)	18.20 (+30%)	18.54 (+31%)	18.61 (+30%)	18.64 (+29%)	18.67 (+29%)

Wave load on a vertical wall located over a rubble layer

Fig 6.8 shows the study case. Here, we have a vertical impermeable wall located on top of a permeable rubble layer. Goda and Takahashi proposed empirical formulas to estimate the pressure at different points of this wall as follows [110, 111, 108]:

Table 6.41: Pressure on a vertical wall calculated from Sainflou formula at Bahonar port

Pressure P_1 on vertical wall for ERA5 at Bahonar (kPa)							
Return Period	1	5	10	20	50	100	200
Past	5.37	5.72	5.94	6.10	6.70	6.73	6.75
Future	6.86 (+28%)	7.28 (+27%)	7.55 (+27%)	7.93 (+30%)	8.57 (+28%)	8.64 (+28%)	8.68 (+29%)
Pressure P_1 on vertical wall for REGCM at Bahonar (kPa)							
Return Period	1	5	10	20	50	100	200
Past	10.90	12.53	13.00	13.20	13.37	13.42	13.46
Future	10.92 (+0%)	13.31 (+6%)	14.68 (+13%)	15.06 (+14%)	15.29 (+14%)	15.34 (+14%)	15.38 (+14%)

Table 6.42: Pressure on a vertical wall calculated from Sainflou formula at Asaluye port

Pressure P_1 on vertical wall for ERA5 at Asaluye (kPa)							
Return Period	1	5	10	20	50	100	200
Past	9.79	10.15	10.26	10.36	10.77	10.91	10.97
Future	15.76 (+61%)	16.86 (+66%)	17.01 (+66%)	17.13 (+65%)	17.25 (+60%)	17.32 (+59%)	17.38 (+58%)
Pressure P_1 on vertical wall for REGCM at Asaluye (kPa)							
Return Period	1	5	10	20	50	100	200
Past	24.90	27.17	28.01	29.46	30.46	30.71	30.83
Future	25.40 (+2%)	28.80 (+6%)	30.25 (+8%)	32.11 (+9%)	33.20 (+9%)	33.47 (+9%)	33.60 (+9%)

Table 6.43: Pressure on a vertical wall calculated from Sainflou formula at Bushehr port

Pressure P_1 on vertical wall for ERA5 at Bushehr (kPa)							
Return Period	1	5	10	20	50	100	200
Past	8.37	8.75	8.89	8.97	9.04	9.08	9.11
Future	7.21 (-14%)	7.56 (-14%)	7.67 (-14%)	7.78 (-13%)	7.88 (-13%)	7.94 (-12%)	7.98 (-12%)
Pressure P_1 on vertical wall for REGCM at Bushehr (kPa)							
Return Period	1	5	10	20	50	100	200
Past	9.77	9.94	10.01	10.07	10.14	10.19	10.23
Future	9.71 (-1%)	9.86 (-1%)	9.91 (-1%)	9.97 (-1%)	10.03 (-1%)	10.08 (-1%)	10.12 (-1%)

$$P_1 = 0.5(1 + \cos\beta)(\lambda_1\alpha_1 + \lambda_2\alpha_*\cos^2\beta)\rho gH$$

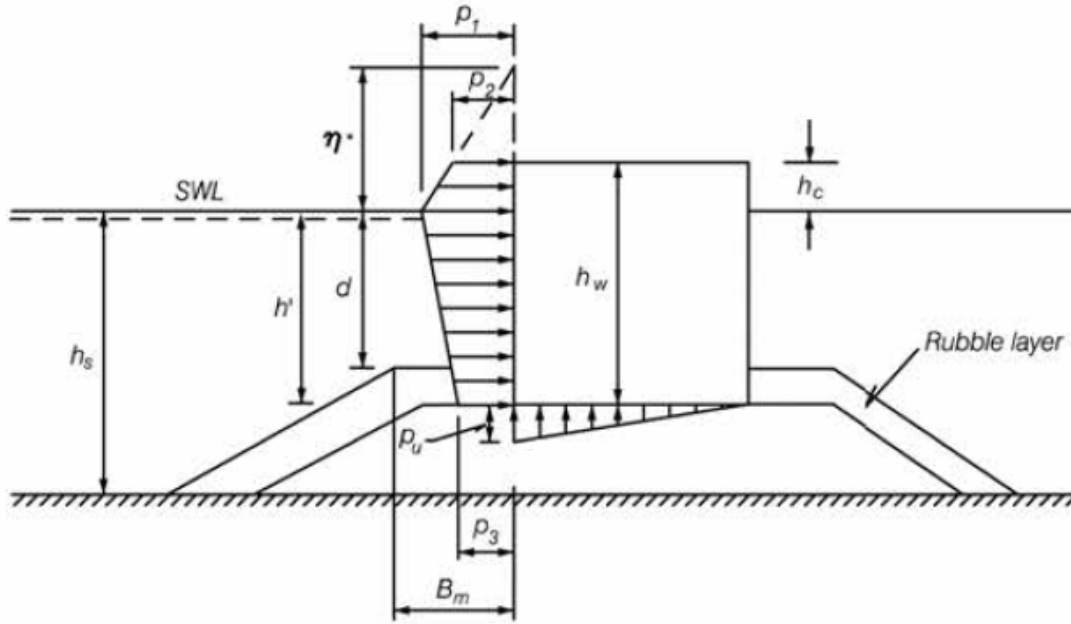


Figure 6.8: Pressure caused by a wave on a vertical wall which is located on a rubble mound structure [108].

$$P_2 = \begin{cases} \left(1 - \frac{h_c}{\eta_*}\right) p_1 & \text{for } \eta_* > h_c \\ 0 & \text{for } \eta_* \leq h_c \end{cases}$$

$$P_3 = \alpha_3 p_1$$

$$P_u = 0.5(1 + \cos\beta) \lambda_3 \alpha_1 \alpha_3 \rho g H \quad (6.20)$$

where β is the angle between the wave crest and the front of the structure, ρ is the water density, g is the gravitational acceleration, and H is the wave height. Other parameters are defined as follows:

$$\alpha_1 = 0.6 + 0.5 \left(\frac{4\pi h_s/L}{\sinh(4\pi h_s/L)} \right)$$

$$\alpha_2 = \min \left[\frac{h_b - d}{3h_b} \left(\frac{H}{d} \right)^2, \frac{2d}{H} \right]$$

$$\alpha_3 = 1 - \frac{h_w - h_c}{h_s} \left(1 - \frac{1}{\cosh(2\pi h_s/L)} \right)$$

$$\lambda_1 = \lambda_2 = \lambda_3 = 1$$

$$\alpha_* = \max[\alpha_2, \alpha_t]$$

$$\eta_* = 0.75(1 + \cos\beta) \lambda_1 H \quad (6.21)$$

where h_b is the water depth at a distance of $5H$ seaward of the breakwater front wall. h_s , h_w and h_c are shown in the Fig 6.8. α_I is an empirical parameter defined as follows:

$$\begin{aligned}\alpha_I &= \alpha_{I0} \cdot \alpha_{I1} \\ \alpha_{I0} &= \begin{cases} \frac{H}{d} & \text{for } H/d \leq 2 \\ 2 & \text{for } H/d > 2 \end{cases} \\ \alpha_{I1} &= \begin{cases} \frac{\cos(\delta_2)}{\cosh(\delta_1)} & \text{for } \delta_2 \leq 0 \\ \frac{1}{\cosh(\delta_1)\sqrt{\cosh(\delta_2)}} & \text{for } \delta_2 > 0 \end{cases} \end{aligned} \quad (6.22)$$

where:

$$\begin{aligned}\delta_1 &= \begin{cases} 20\delta_{11} & \text{for } \delta_{11} \leq 0 \\ 15\delta_{11} & \text{for } \delta_{11} > 0 \end{cases} \\ \delta_{11} &= 0.93 \left(\frac{B_m}{L} - 0.12 \right) + 0.36 \left(\frac{h_s - d}{h_s} - 0.6 \right) \\ \delta_2 &= \begin{cases} 4.9\delta_{22} & \text{for } \delta_{22} \leq 0 \\ 3\delta_{22} & \text{for } \delta_{22} > 0 \end{cases} \\ \delta_{22} &= -0.36 \left(\frac{B_m}{L} - 0.12 \right) + 0.93 \left(\frac{h_s - d}{h_s} - 0.6 \right) \end{aligned} \quad (6.23)$$

where B_m is given in the Fig 6.8. As can be seen from the Eq. 6.20 all different pressures which are shown in Fig6.8 are linearly proportional to each other. Therefore, we focus on P_1 and investigate its variation from the past to the future for different models. Again, we have to calculate this pressure for the entire time period and use statistical methods to find its value for different return periods. In our calculations, we assumed a hypothetical breakwater with the following dimensions:

$$B_m = 1.5m, \quad h_w = 4m, \quad d = 3m, \quad h_c = 1m.$$

For the Bushehr site, the parameters are defined as follows (since the water depth is 2.5 m):

$$B_m = 1m, \quad h_w = 2m, \quad d = 1m, \quad h_c = 0.5m.$$

The results of the calculations are shown in Tables 6.44 to 6.48.

Wave load on a vertical wall protected by a rubble mound

Fig 6.9 shows a vertical wall which is protected by a rubble mound structure [108].

The wave load in this case is similar to the previous one, except that the parameters λ_1 , λ_2 and

Table 6.44: Pressure on a vertical wall calculated from Goda formula at Lengeh port

Pressure P_1 on vertical wall for ERA5 at Lengeh (kPa)							
Return Period	1	5	10	20	50	100	200
Past	5.09	6.28	6.77	7.22	7.31	7.35	7.37
Future	6.31 (+8%)	7.04 (+4%)	7.25 (+2%)	7.92 (+5%)	8.26 (+6%)	8.31 (+6%)	8.34 (+6%)

Pressure P_1 on vertical wall for REGCM at Lengeh (kPa)							
Return Period	1	5	10	20	50	100	200
Past	17.90	24.09	25.49	26.33	26.79	26.88	26.93
Future	19.09 (+7%)	26.32 (+9%)	36.45 (+43%)	41.86 (+59%)	43.39 (+62%)	43.81 (+63%)	43.90 (+63%)

Table 6.45: Pressure on a vertical wall calculated from Goda formula at Rajaee port

Pressure P_1 on vertical wall for ERA5 at Rajaee (kPa)							
Return Period	1	5	10	20	50	100	200
Past	4.29	5.27	5.66	6.22	6.79	6.83	6.85
Future	4.86 (+13%)	6.01 (+14%)	6.35 (+12%)	6.58 (+6%)	6.80 (+0%)	6.94 (+2%)	6.99 (+2%)

Pressure P_1 on vertical wall for REGCM at Rajaee (kPa)							
Return Period	1	5	10	20	50	100	200
Past	13.53	16.07	16.45	16.58	17.10	17.18	17.23
Future	15.54 (+14%)	20.48 (+27%)	20.92 (+27%)	21.86 (+32%)	22.23 (+30%)	22.34 (+30%)	22.36 (+30%)

Table 6.46: Pressure on a vertical wall calculated from Goda formula at Bahonar port

Pressure P_1 on vertical wall for ERA5 at Bahonar (kPa)							
Return Period	1	5	10	20	50	100	200
Past	4.37	4.71	4.91	5.04	5.50	5.53	5.54
Future	5.62 (+28%)	6.10 (+30%)	6.40 (+30%)	6.83 (+36%)	7.57 (+38%)	7.63 (+38%)	7.66 (+38%)

Pressure P_1 on vertical wall for REGCM at Bahonar (kPa)							
Return Period	1	5	10	20	50	100	200
Past	11.47	14.04	14.97	15.25	15.64	15.69	15.73
Future	11.65 (+2%)	15.44 (+10%)	17.94 (+20%)	18.64 (+22%)	19.10 (+22%)	19.17 (+22%)	19.22 (+22%)

λ_3 must be modified as follows [110, 111, 108]:

$$\lambda_1 = \lambda_3 = \begin{cases} 1 & \text{for } \frac{H}{h_s} < 0.3 \\ 1.2 - 0.67 \left(\frac{H}{h_s} \right) & \text{for } 0.3 \leq \frac{H}{h_s} < 0.3 \\ 0.8 & \text{for } \frac{H}{h_s} > 0.3 \end{cases}$$

Table 6.47: Pressure on a vertical wall calculated from Goda formula at Asaluye port

Pressure P_1 on vertical wall for ERA5 at Asaluye (kPa)							
Return Period	1	5	10	20	50	100	200
Past	9.08	9.55	9.77	9.87	9.94	9.97	10.00
Future	13.60 (+50%)	15.57 (+63%)	15.73 (+61%)	15.94 (+61%)	16.12 (+62%)	16.18 (+62%)	16.23 (+62%)

Pressure P_1 on vertical wall for REGCM at Asaluye (kPa)							
Return Period	1	5	10	20	50	100	200
Past	35.12	41.43	42.52	47.03	49.94	50.13	50.22
Future	37.58 (+7%)	45.99 (+11%)	48.90 (+15%)	55.50 (+18%)	60.43 (+21%)	60.66 (+21%)	60.77 (+21%)

Table 6.48: Pressure on a vertical wall calculated from Goda formula at Bushehr port

Pressure P_1 on vertical wall for ERA5 at Bushehr (kPa)							
Return Period	1	5	10	20	50	100	200
Past	7.52	7.95	8.09	8.17	8.23	8.26	8.29
Future	5.95 (-21%)	6.25 (-21%)	6.33 (-22%)	6.40 (-22%)	6.52 (-21%)	6.55 (-21%)	6.57 (-21%)

Pressure P_1 on vertical wall for REGCM at Bushehr (kPa)							
Return Period	1	5	10	20	50	100	200
Past	9.05	9.28	9.36	9.42	9.49	9.53	9.57
Future	8.97 (-1%)	9.17 (-1%)	9.23 (-1%)	9.28 (-1%)	9.35 (-1%)	9.39 (-1%)	9.43 (-1%)

$$\lambda_2 = 0 \quad (6.24)$$

Same as the previous cases, we calculated P_1 for all the time samples and found its values for different return periods, which are shown in Tables 6.49 to 6.53.

Table 6.49: Pressure on a vertical wall protected by a rubble mound structure calculated from modified Goda formula at Lengeh port

Pressure P_1 on vertical wall for ERA5 at Lengeh (kPa)							
Return Period	1	5	10	20	50	100	200
Past	3.65	4.26	4.59	4.66	4.78	4.81	4.83
Future	3.91 (+7%)	4.48 (+5%)	4.71 (+3%)	4.88 (+5%)	4.97 (+4%)	5.04 (+5%)	5.07 (+5%)

Pressure P_1 on vertical wall for REGCM at Lengeh (kPa)							
Return Period	1	5	10	20	50	100	200
Past	9.04	11.87	12.33	12.58	12.88	12.95	12.98
Future	9.93 (+10%)	17.13 (+44%)	18.42 (+49%)	21.03 (+67%)	21.67 (+68%)	21.83 (+68%)	21.88 (+69%)

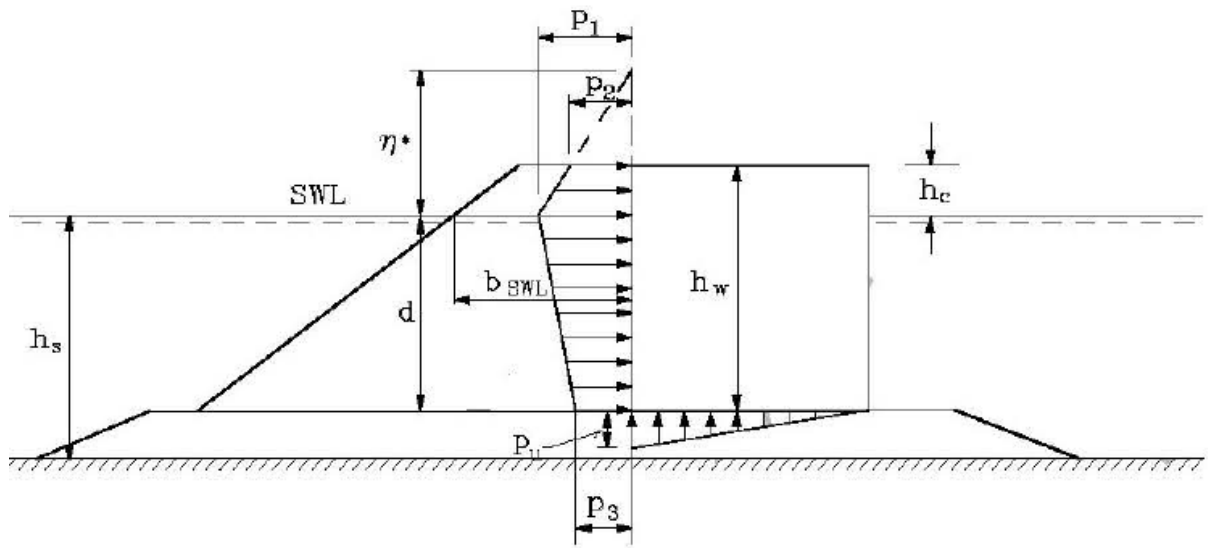


Figure 6.9: Pressure caused by a wave on a vertical wall which is protected by a rubble mound structure [108].

Table 6.50: Pressure on a vertical wall protected by a rubble mound structure calculated from modified Goda formula at Rajaee port

Pressure P_1 on vertical wall for ERA5 at Rajaee (kPa)							
Return Period	1	5	10	20	50	100	200
Past	2.95	3.60	3.80	4.10	4.34	4.37	4.38
Future	3.34 (+13%)	3.97 (+10%)	4.15 (+9%)	4.26 (+4%)	4.36 (+1%)	4.42 (+1%)	4.45 (+2%)
Pressure P_1 on vertical wall for REGCM at Rajaee (kPa)							
Return Period	1	5	10	20	50	100	200
Past	7.24	8.14	8.26	8.32	8.45	8.51	8.54
Future	7.5 (+4%)	9.85 (+21%)	11.30 (+37%)	12.15 (+46%)	12.31 (+46%)	12.34 (+45%)	12.36 (+45%)

Fig 6.10 shows a summary of these tables, where the changes in pressure on the vertical wall are shown for four wind data sets at the study points. In these curves, solid lines show the predictions based on the ERA5 model, while dashed lines represent the results of using REGCM data. It can be seen that for most of the cases, the two models predict the change in the same way. Similar to the other forces studied in the previous sections, for the points in the north-east part of the Persian Gulf, the REGCM model predicts a larger change than the ERA5 model, while for Aslauye and Bushehr, which are located in the north-west of the Persian Gulf, changes predicted by ERA5 wind data are more severe than those of the REGCM model. It is worth noting that for all cases at Bushehr port**, the pressure** in the future is predicted to be less than in the past.

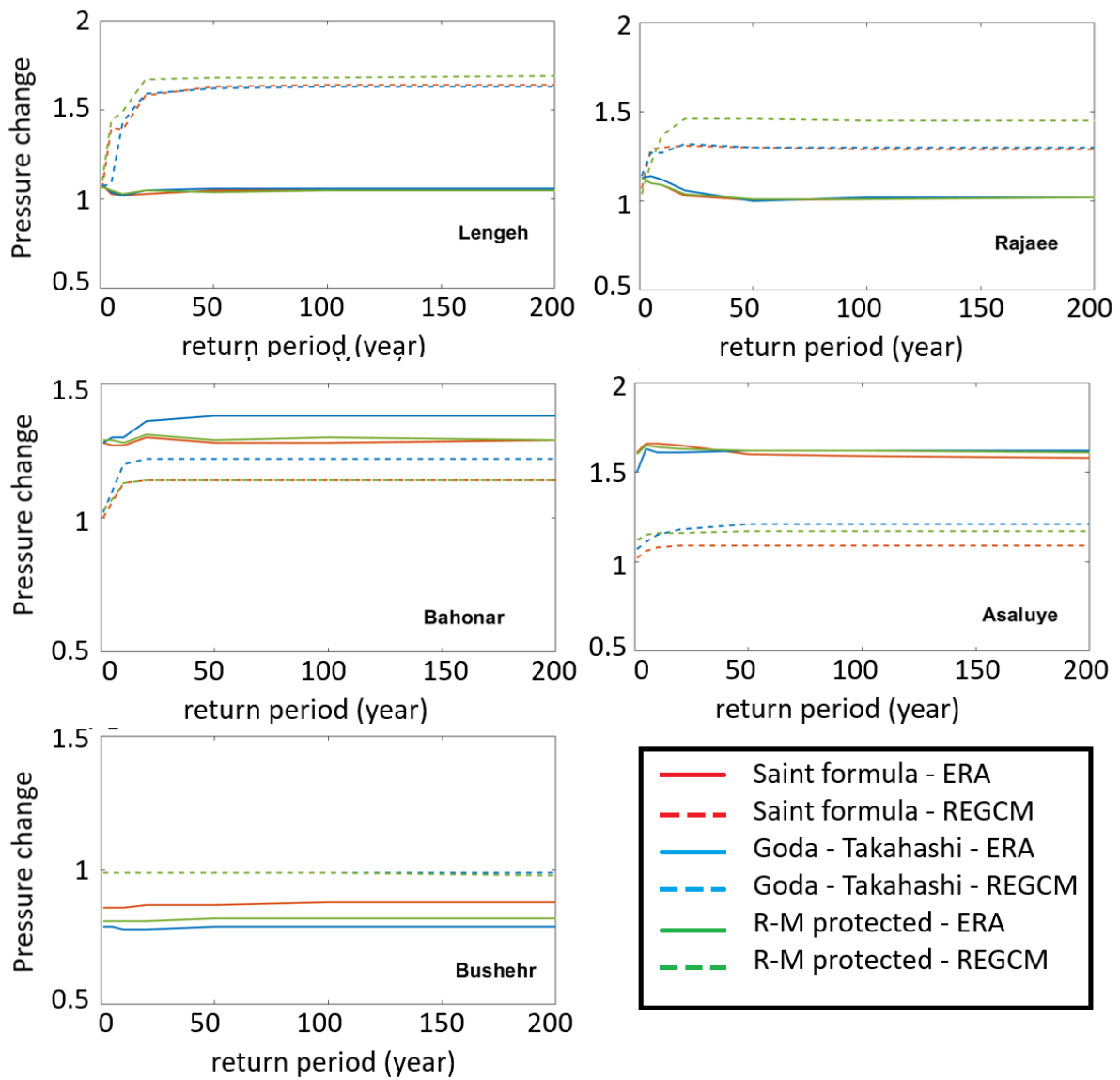


Figure 6.10: Wave load on vertical walls (future/past) predicted by ERA5 and REGCM model

Table 6.51: Pressure on a vertical wall protected by a rubble mound structure calculated from modified Goda formula at Bahonar port

Pressure P_1 on vertical wall for ERA5 at Bahonar (kPa)							
Return Period	1	5	10	20	50	100	200
Past	2.97	3.20	3.33	3.42	3.73	3.75	3.77
Future	3.82 (+29%)	4.12 (+29%)	4.27 (+28%)	4.48 (+31%)	4.82 (+29%)	4.86 (+30%)	4.88 (+29%)
Pressure P_1 on vertical wall for REGCM at Bahonar (kPa)							
Return Period	1	5	10	20	50	100	200
Past	6.40	7.35	7.70	7.87	7.99	8.02	8.04
Future	6.61 (+3%)	7.88 (+7%)	8.96 (+13%)	8.99 (+14%)	9.12 (+14%)	9.15 (+14%)	9.17 (+14%)

Table 6.52: Pressure on a vertical wall protected by a rubble mound structure calculated from modified Goda formula at Asaluye port

Pressure P_1 on vertical wall for ERA5 at Asaluye (kPa)							
Return Period	1	5	10	20	50	100	200
Past	5.77	5.99	6.08	6.14	6.21	6.26	6.30
Future	9.21 (+60%)	9.86 (+65%)	9.95 (+64%)	10.01 (+63%)	10.08 (+62%)	10.12 (+62%)	10.16 (+61%)
Pressure P_1 on vertical wall for REGCM at Asaluye (kPa)							
Return Period	1	5	10	20	50	100	200
Past	14.42	15.93	16.28	17.21	17.78	17.92	17.99
Future	16.15 (+12%)	18.32 (+15%)	18.88 (+16%)	19.96 (+16%)	20.80 (+17%)	20.97 (+17%)	21.05 (+17%)

Table 6.53: Pressure on a vertical wall protected by a rubble mound structure calculated from modified Goda formula at Bushehr port

Pressure P_1 on vertical wall for ERA5 at Bushehr (kPa)							
Return Period	1	5	10	20	50	100	200
Past	7.30	7.64	7.75	7.82	7.87	7.90	7.92
Future	5.89 (-19%)	6.18 (-19%)	6.26 (-19%)	6.32 (-19%)	6.43 (-18%)	6.47 (-18%)	6.50 (-18%)
Pressure P_1 on vertical wall for REGCM at Bushehr (kPa)							
Return Period	1	5	10	20	50	100	200
Past	8.51	8.68	8.75	8.80	8.86	8.90	8.94
Future	8.44 (-1%)	8.60 (-1%)	8.65 (-1%)	8.69 (-1%)	8.74 (-1%)	8.77 (-1%)	8.80 (-2%)

6.4 Conclusion

In this section, we present an analysis of the results obtained from studying different wave loads on coastal structures.

To achieve a better understanding of the results, we must first consider the characteristics of the study sites. As shown in Fig 5.1, the first three ports, including Lengeh, Rajaei, and Bahonar, are located in the eastern part of the north coast of the Persian Gulf, close to the Strait of Hormuz. Specifically, Rajaei and Bahonar ports are situated between the Iranian coast and Qeshm Island, which leads to a much shorter fetch length for them compared to the other ports. The depth of water in these ports varies from 10 to 13 meters, which is considered intermediate depth. Asaluyeh and Bushehr, on the other hand, are located in the northern and northwestern parts of the Persian Gulf, respectively, where the fetch is longer and the wind dynamics differ. The water depth in Asaluyeh port is 49 m, which places it in the deep-water regime. However, Bushehr is categorized as shallow water with a depth of 2.4 m. Therefore, it can be concluded that the investigated ports cover a wide range of environmental parameters.

The analysis shows that the trend of wave loading variation from the past to the future in each port is independent of the type of coastal structure. Only in Bushehr Port do both ERA5 and REGCM predict a decrease in wave loading for all coastal structures. However, this decrease for most of the structures is so minimal (less than 5%) that we can assume that the wave loading in the future will remain relatively consistent with the past period.

In contrast to Bushehr, the most significant increase in wave loading is observed at Asaluyeh port. A similarity between wave loading in Bushehr and Asaluyeh is that in both ports, the ERA5 model predicts a more severe change from the past to the future. For Lengeh port, the changes predicted by REGCM are higher than those predicted by ERA5, while in Rajaei and Bahonar, both models predict changes in wave loading in the same range. However, we must take into account that the results predicted by the ERA5 model are likely closer to reality for two reasons: first, this model has a finer temporal resolution (one hour) and inaccuracies due to SWAN interpolation are much smaller than those of the REGCM model (as discussed in detail in section 5.5). Second, the wind data provided by the ERA5 model align much more closely with observational data than the REGCM wind predictions. Therefore, we can interpret the discrepancy between the ERA5 and REGCM models at different locations as the difference in wind dynamics along the Persian Gulf. In other words, different wind dynamics (e.g., frequency of direction or velocity changes) lead to different probabilities of missing extreme events between sampling times. The faster the changes, the higher the probability of losing extreme events in the data. Overall, it could be concluded that, at least for ports in medium and deep water, wave loads could increase by up to 50% in the future due to the effects of climate change.

Chapter 7

Summary and Outlook

In the present work, we have investigated the impact of climate change on wave loading on coastal structures in the Persian Gulf by simulating wave conditions for the past (1979-2020) and future periods (2021-2100).

We limited our study to five major ports along the entire Iranian coast of the Persian Gulf. These ports include Lengeh, Rajaee, Bahonar, Asaluyeh, and Bushehr, all of which play a significant role in the region's energy production and transit economy. The selected ports are located in different parts of the Persian Gulf, and their depths vary from 2 to 50 metres. Thus, our investigation covers a wide range of input parameters in terms of the geographical characteristics of the study points. For the climate change reference, we used the latest version of the REGCM model, REGCM4.7. This model is a regional climate model which uses a Cartesian coordinate system with a 25-km mesh (approximately 0.23 degrees). REGCM4.7 provides wind data with 3-hour temporal resolution, which is a significant improvement over previous versions, but still insufficient for detailed wave studies. Therefore, we also utilized the ERA5 wind model, which provides hindcast wind data with 1-hour temporal resolution. ERA5 wind data is in spherical coordinates with a 0.25-degree mesh.

A novel downscaling method is proposed to generate so-called *future ERA5* wind data. In this method, we viewed climate change as a linear time-invariant (LTI) system and applied systems theory, which posits that the output of an LTI system to any input can be determined from the frequency response of the system. The frequency response is, in turn, the response of the system to a Dirac delta function input. This response can also be calculated by dividing the Fourier transform of the output by the Fourier transform of the corresponding input to the system. In our downscaling process, we used the available REGCM hindcast and forecast data to find the frequency response of climate change. We calculated the Fourier transform of these two data sets separately for all grid points and determined the frequency response of each point. In fact, these frequency responses contain the trend of changes in the wind data from past to future, as derived from the REGCM model. This trend is then applied to the ERA5 model hindcast data to generate a high-resolution future data set. However, as the two wind models use different coordinate systems and grid points, several interpolations were required to calculate the frequency responses at the ERA5 model grid points. The advantage of the proposed downscaling method is that, unlike statistical methods, it preserves the information of the original data. Even the order of individual data points is maintained. This ensures that extreme events are not ignored and that

even hidden extreme events can be reconstructed from the original data.

After generating the future ERA5 wind data, we analyzed the hindcast and forecast wind of the ERA5 and REGCM models and performed statistical comparisons, which show good agreement between the two models. The wave conditions at the study points were simulated using both ERA5 and REGCM wind data for past and future periods. The SWAN model was employed to perform these simulations. We carried out a sensitivity analysis to determine the mesh resolution required to obtain reliable results. Such analysis showed that a computational grid size of 550 metres is necessary. We also validated our model by comparing its results with available observational data at the Asaluyeh and Bushehr stations for the period April to June 2008. The simulation results indicated a discrepancy in the wave direction for some of the study points at the eastern part of the Persian Gulf. However, further investigations showed that the source of this discrepancy lies in the low temporal resolution of the REGCM data and the interpolation performed by the SWAN model. It was also verified that wave dynamics in some parts of the Persian Gulf are such that a 1-hour temporal resolution is required to obtain accurate results. We used statistical analysis of extreme conditions to determine wave parameters, including significant wave height, peak period, and wavelength at different return periods from 1 to 200 years. In the final part of the thesis, the wave-structure interaction was investigated by calculating the wave load for different return periods. Since the wave-structure interaction depends on the type of coastal structure, we limited our study to the typical structures mainly used in the study points, including rubble mound breakwaters and different types of vertical walls. We also calculated the drag and inertia forces caused by the waves on cylindrical piles. Our calculations show that, particularly in regions with deep or intermediate water levels, an increase in wave loading of up to 50% could be expected. It is therefore worth considering the impact of climate change in order to adopt a more conservative approach to the design and maintenance of coastal structures. This is particularly critical when we consider the vital role of the Persian Gulf in supplying the world's energy.

However, further studies are needed to gain a more comprehensive insight into the influence of climate change on the wave climate in the Persian Gulf and to propose comprehensive guidelines for port planning and climate change adaptation. In the current work, we limited our studies to the RCP8.5 scenario, which is the most extreme case. It is, of course, worthwhile to examine other scenarios. A new set of climate scenarios, called SSP (Shared Socioeconomic Pathways), was introduced by the IPCC in their sixth assessment report (AR6) [112]. Since this set of scenarios is intended to be improved compared to the RCP scenarios, it would also be useful to investigate the wave climate using climate models based on the SSPs. Furthermore, as mentioned above, we limited our study to five major Iranian ports. We have already seen that climate change can have different effects in different parts of the Persian Gulf and at different water depths; therefore, studying wave conditions at more locations across the entire Persian Gulf will help to better describe the effects of climate change as a function of geographical characteristics.

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