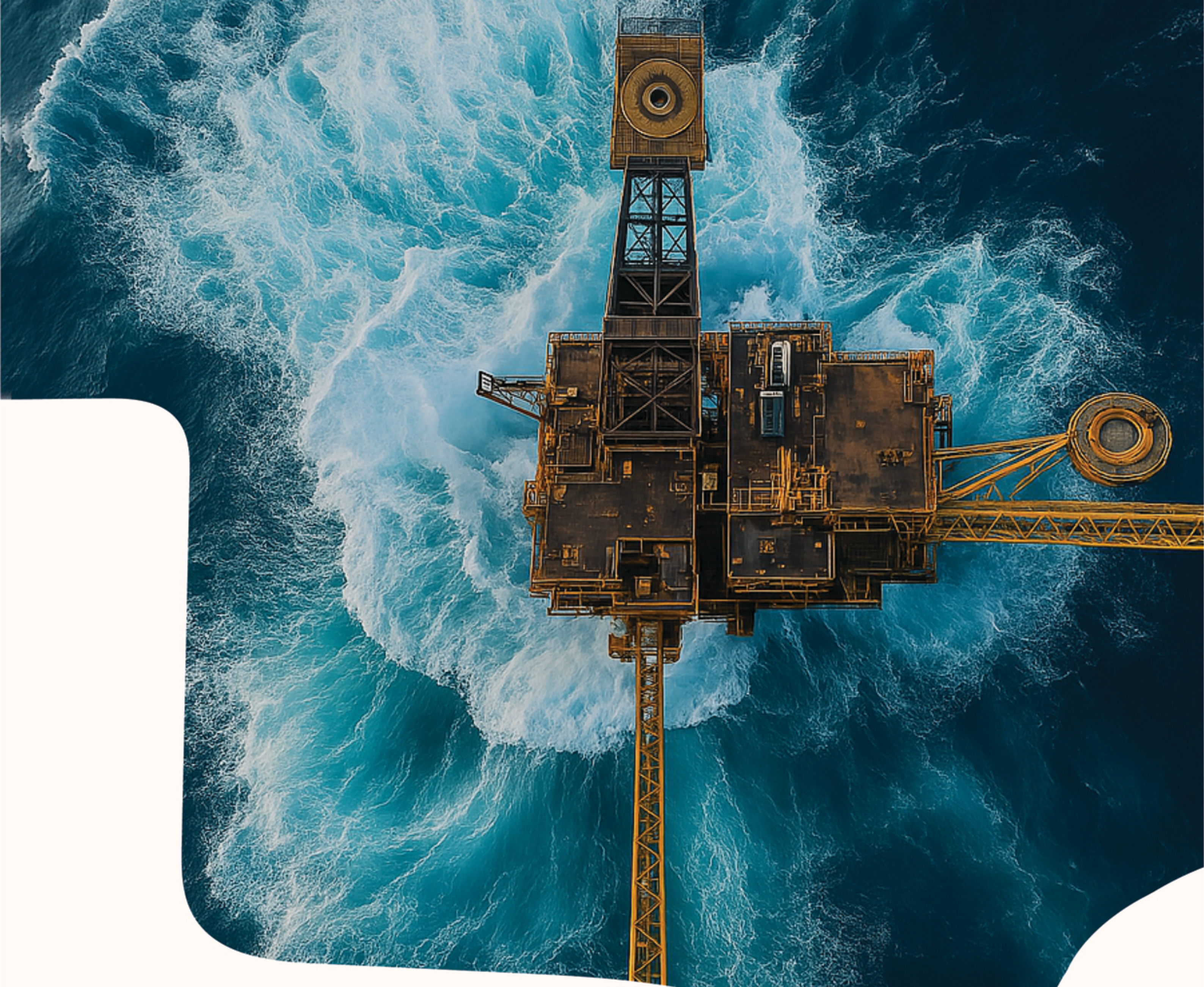


IMPACT OF EXTREME EVENTS AND CLIMATE CHANGE ON OIL & GAS ACTIVITIES IN THE OFFSHORE AREA

National Institute of Oceanography

DGH

Directorate General of Hydrocarbons

June 2025

DISTRIBUTION RESTRICTED

PROJECT REPORT

Impact of Extreme Events and Climate Change on Oil & Gas Activities in the Offshore Area

A joint initiative of

CSIR-National Institute of Oceanography Dona Paula, Goa	Directorate General of Hydrocarbons Noida, Uttar Pradesh
Oil Industry Safety Directorate Noida, Uttar Pradesh	Advanced Trailing Institute, ONGC Goa

MESSAGE FROM DG, DGH

The Government of India continues to accord the highest priority to energy security, recognizing the nation's dependence on hydrocarbons as a fundamental pillar of its economic growth. As the global energy landscape undergoes a transformative shift, oil and gas will remain integral to India's energy mix, ensuring stability and sustainability in meeting the country's rising energy demands.

However, the Indian petroleum sector faces growing climate-related risks, particularly in coastal and offshore Oil and Gas installations. The increasing frequency of extreme weather events, such as cyclones and floods, poses significant threats to critical infrastructure, underscoring the need for robust resilience strategies and proactive risk mitigation.

In response to these emerging threats, the Directorate General of Hydrocarbons (DGH), in collaboration with the CSIR-National Institute of Oceanography (NIO), conducted a study titled "*Impact of Extreme Events and Climate Change on Oil and Gas Activities in Offshore Areas*''. This study provides a systematic evaluation of the risks confronting vital E&P assets and introduces a meticulously structured Standard Operating Procedure (SOP) designed to facilitate comprehensive risk assessment, establish timely early-warning mechanisms, and implement adaptive response strategies.

The resulting report will serve as a vital resource for industry stakeholders, offering strategic frameworks to strengthen operational resilience and promote sustainable practices. DGH extends its commendations to the entire team at CSIR-NIO, as well as the distinguished experts from the Oil Industry Safety Directorate (OISD), Advanced Training Institute (ATI), ONGC, whose expertise and dedication were instrumental in the development of this report and SOP. DGH is confident that this initiative will provide invaluable guidance for mitigating the effects of climate change and extreme events on offshore Oil and Gas operations to both new entrants and seasoned professionals engaged in offshore exploration and production drilling.

As India advances its energy security agenda, safeguarding E&P infrastructure against climate change is paramount. By adopting innovative risk management strategies and integrating sustainability into operations, the sector can achieve a balance between economic growth and environmental responsibility, ensuring long-term resilience and prosperity.

(Dr. Pallavi Jain Govil, IAS)
Director General
Directorate General of Hydrocarbons

MESSAGE FROM ED, OISD

The oil and gas sector in India remain a cornerstone of national development, significantly contributing to economic growth, energy security, and industrial advancement. As the nation strives to meet the escalating energy demands of its expanding population and dynamic economy, it must address the critical challenge of ensuring energy reliability while mitigating the effects of climate change.

The sector is highly susceptible to climate-related vulnerabilities, as major E&P installations are in the Indian coastal and offshore area. Extreme weather events such as cyclones and floods present severe risks to infrastructure, highlighting the urgent need for robust resilience strategies and proactive risk management.

In response to these challenges, the Directorate General of Hydrocarbons (DGH), in collaboration with the CSIR-National Institute of Oceanography (NIO), conducted a study titled "*Impact of Extreme Events and Climate Change on Oil & Gas Activities in Offshore Areas.*" This study examines the risks faced by critical E&P infrastructure and introduces a comprehensive Standard Operating Procedure (SOP) to enable effective risk assessment, provide timely early warnings, and implement adaptive measures.

The handbook resulting from this initiative serves as a valuable resource for industry stakeholders, offering practical strategies and deep insights for navigating climate-related risks. It aims to enhance operational resilience, promote sustainable practices, and equip the sector to operate securely and sustainably amid evolving environmental challenges.

As India progresses toward its energy security aspirations, safeguarding E&P assets against the growing impacts of climate change has become a pressing priority. By adopting innovative risk management approaches and integrating environmentally sustainable practices, the oil and gas sector can achieve a harmonious balance between economic growth and ecological preservation, ensuring a resilient and sustainable future for generations to come.

(Arun Mittal)
Executive Director
Oil Industry Safety Directorate

MESSAGE FROM HEAD, ATI

India's Oil and Gas sector remains an indispensable pillar of the nation's economic trajectory, energy security, and industrial advancement. As the country seeks to fulfill the surging energy demands of its burgeoning population and rapidly expanding economy, it must adeptly navigate the dual imperative of ensuring energy availability while addressing the multifaceted challenges posed by climate change.

Fossil fuels, while integral to India’s developmental ambitions, render the sector particularly susceptible to the escalating risks of climate-induced phenomena. Extreme weather events, including cyclones and floods, present significant threats to critical offshore and coastal infrastructure, necessitating the development of robust frameworks for risk assessment, mitigation, and resilience-building.

In recognition of these pressing challenges, the Directorate General of Hydrocarbons (DGH), in collaboration with the CSIR-National Institute of Oceanography (NIO) and Advanced Training Institute (ATI), ONGC, undertook a pivotal study titled "*Impact of Extreme Events and Climate Change on Oil & Gas Activities in Offshore Areas*". This comprehensive analysis delineates vulnerabilities within vital Oil and Gas infrastructure and introduces a meticulously designed Standard Operating Procedure (SOP) encompassing risk evaluation, early warning mechanisms, and adaptive strategies.

The resulting handbook will serve as a guide for stakeholders across industry, offering pragmatic solutions and strategic insights to address the implications of climate change. By equipping the sector with the necessary tools to fortify its operations, it ensures both the continuity of essential activities and the advancement of long-term sustainability amid the uncertainties of a changing environment.

As India charts its course toward enhanced energy security, it is imperative to reaffirm our commitment to safeguarding Exploration and Production (E&P) infrastructure against the pervasive impacts of climate change. By embracing proactive risk management approaches and fostering sustainable practices, the Oil and Gas sector can achieve a resilient and innovative future—one that harmonizes economic progress with environmental stewardship, securing prosperity for generations to come.

(Sanjeev Singhal)
Chief, Advanced Training Institute (ATI)
ONGC

Acknowledgements

The report entitled "*Impact of Extreme Events and Climate Change on Oil & Gas Activities in the Offshore Area*" has been developed based on a series of meetings and discussions involving an interdisciplinary team of professionals from the Oil and Gas sector and experts in oceanography. These collaborative efforts took place between March 2024 and October 2024. The project was facilitated by the Directorate General of Hydrocarbons (DGH), under the Ministry of Petroleum and Natural Gas.

We sincerely thank Dr. Kaustav Nag, ADG (E), DGH, for his unwavering support, which was instrumental in successfully completing this project.

We would also like to express our special thanks to Mr. Gada Lal Das, Head of Department (E&C), DGH, for his invaluable guidance and encouragement throughout the project period.

Our appreciation extends to Ms. Neha Singh, Senior Chemist, for her significant contributions in editing, drafting, revising, collating, and proofreading the report at every stage.

We thank the Director, CSIR-National Institute of Oceanography, and the Scientist in Charge, Regional Centre-Kochi, for the facilities and support.

We would like to acknowledge and commend the collaborative efforts of various individuals who contributed to the successful completion of this report, which we hope will serve as a meaningful and impactful resource for promoting a healthy and sustainable oceanic environment. Special recognition is given to the professionals from the following organisations:

- Advanced Training Institute (ATI), Oil and Natural Gas Corporation (ONGC)
- Oil Industry Safety Directorate (OISD)

Finally, we express our deep gratitude to the Directorate General of Hydrocarbons (DGH), Ministry of Petroleum and Natural Gas, for funding this project and providing continuous support in finalising this report.

(Dr Muraleedharan K.R.)
Project leader-NIO

CONTENTS

LIST OF FIGURES

List Of Tables

LIST OF ABBREVIATIONS

American Petroleum Institute	-	API
Arabian Sea	-	AS
Bay of Bengal	-	BoB
Carbon Capture and Storage	-	CCS
Carbon dioxide	-	CO_2
Central Pollution Control Board	-	CPCB
Clean Ballast Tanks	-	CBTs
Clean Oil Washing Systems	-	COW
Coastal Zone Management Authority	-	CZMA
Conference of the Parties	-	COP
Coupled Model Intercomparison Project	-	CMIP6
Cyclonic Storm	-	CS
Deep Depressions	-	DD
Depressions	-	D
Emergency Response Plan	-	ERP
Emergency Shutdown Systems	-	ESD
Environmental Impact Assessment	-	EIA
Exclusive Economic Zone	-	EEZ
Geographic Information Systems	-	GIS
Greenhouse Gases	-	GHGs
Intergovernmental Panel on Climate Change	-	IPCC
Island Coastal Regulation Zone	-	ICRZ
Man And the Biosphere	-	MAB
Methane	-	CH_4
Ministry of Environment and Forests	-	MoEF
National Green Tribunal	-	NGT

National Oil Spill Disaster Contingency Plan	-	NOSDCP
Nationally Determined Contributions	-	NDCs
Nitrous Oxide	-	N_2O
Northern India Ocean	-	NIO
Oil Industry Safety Directorate	-	OISD
Personal Protective Equipment	-	PPE
Sea Surface Temperatures	-	SST
Severe Cyclonic Storms	-	SCS
Shared Socio-Economic Pathways	-	SSPs
Standard Operating Procedures	-	SOPs
State Pollution Control Board	-	SPCB
United Nations Convention On The Law Of The Sea	-	UNCLOS
United Nations Environment Programme	-	UNEP
United Nations Framework Convention On Climate Change	-	UNFCCC
Very Severe Cyclonic Storms	-	VSCS
World Climate Research Programme	-	WCRP
World Meteorological Organization	-	WMO

Project Team

Dr. Sunil Kumar Singh	Director	
Dr. Jyothibabu R.	Scientist-In-Charge	
Dr. Muraleedharan K.R.	Principal Scientist	Project Leader
Dr. Gireeshkumar T.R.	Senior Scientist	Co-Project Leader
Dr. Abdul Jaleel	Senior Scientist	Co-Project Leader

Physical Oceanography

Dr. Muraleedharan K.R.	Principal Scientist	Member

Chemical Oceanography

Dr. Gireeshkumar T.R.	Senior Scientist	Member
Dr. Ramzi A.	Technical Officer	Member

Biological Oceanography

Phytoplankton

Dr. Madhu N.V.	Senior Scientist	Member

Zooplankton

Dr. R Jyothibabu	Senior Scientist	Member

Benthos

Dr. Abdul Jaleel K.U.	Scientist	Member

Microbiology

Dr. Anas Abdulaziz	Principal Scientist	Member

Research Scholars

Ms. Angela Sabu.	Project Associate -I	Member
Mr. Rahul Dev	Project Associate -I	Member
Ms. Anjana Jayaprakash	Project Associate -I	Member
Mrs. Arya K S	Research Scholar	Member
Ms. Ann Varna K. X.	Project Associate -I	Member

EXECUTIVE SUMMARY

The global average surface temperature increased by approximately 1.1°C (range: 0.95-1.20°C) during the period 2011–2020 compared to 1850–1900, with land areas warming more significantly (1.34-1.83°C) than oceans (0.68-1.1°C). Notably, coal contributed 41% of global CO_2 emissions, oil 32%, natural gas 21%, and cement production 4%. Efforts to regulate and enforce compliance have demonstrated potential reductions in atmospheric carbon levels, as evidenced by decreases associated with the dissolution of the Soviet Union, the global financial crisis, and the COVID-19 pandemic. India is currently the third largest CO_2 emitter (3.1 Gt), following China (11.9 Gt) and the United States (4.9 Gt).

The oil and gas sector has been responsible for approximately 40% of global energy-related CO_2 emissions in recent years, primarily due to gas flaring, methane emissions, and the energy-intensive processes of extraction and processing. As per India's 2022 National Inventory Report submitted to the UNFCCC, the energy sector accounts for about 75-80% of India's total greenhouse gas (GHG) emissions, with the oil and gas industry contributing approximately 20-25% of the total GHG emissions.

Since the early 2000s, offshore production has constituted roughly 30% of global oil and 27% of natural gas output. The coastal and offshore installations in India are particularly susceptible to sea-level rise due to climate change, with historical data indicating a 40 cm increase over the past century and projections estimating an additional 60 cm rise over the next 100 years. The anticipated rate of sea-level rise, between 1.5 to 10 mm/year, could lead to water inundation of up to 0.5 m/year towards offshore areas. Climate change exacerbates risks through rising air and water temperatures, shifting precipitation patterns, shoreline erosion, severe storms, ocean acidification, and heightened cyclone intensity. The other impacts of increasing GHG emissions are changes in air and water temperature, changes in precipitation patterns, shoreline erosion, heightened storm intensity, oil spills, ocean acidification, severe cyclones, heat waves, droughts, localized heavy rainfalls, changes in crops, and other large socio-economic impacts. Furthermore, human activities such as urbanisation, sand mining, and offshore construction disrupt natural sediment transport and compound the impact of natural phenomena like monsoon waves, tides, and currents.

Internationally, significant measures such as the 2015 Paris Agreement have been adopted to curb GHG emissions, limiting global warming to well below 2°C, with an aspirational goal of 1.5°C. Achieving these targets necessitates a global shift to low-carbon energy sources and a significant reduction in the use of fossil fuels.

The Working Group I (WGI) of the Intergovernmental Panel on Climate Change (IPCC) assessed the climate response to various future scenarios based on Shared Socio-economic

High and very high emissions scenarios (SSP3-7.0 and SSP5-8.5) projected CO_2 emissions are predicted to double by 2100 and 2050, respectively. An intermediate emissions scenario (SSP2-4.5) shows emissions stabilizing mid-century. Low and very low emissions pathways (SSP1-1.9 and SSP1-2.6) predicted net-zero CO_2 emissions by 2070 and 2050, followed by net-negative levels.

This study was conducted by collecting comprehensive data on the current environmental status of India's major sedimentary basins (e.g., Gulf of Kutch, Saurashtra basin, Mumbai offshore, Kerala Lakshadweep, Konkan, Cauvery basin, Krishna Godavari, Mahanadi basin, Andaman basin) within the Exclusive Economic Zone (EEZ). The data were analysed using the Coupled Model Intercomparison Project (CMIP6) to forecast future environmental parameters under various SSPs, assessing temperature, precipitation, wind patterns, and other critical factors in the northern Indian Ocean. Cyclone characteristics, wave regimes, and related environmental impacts were also studied and documented for each basin.

Model predictions indicate a continued linear warming trend through 2050, with temperatures in the northern Indian Ocean potentially rising by 3 to 6°C by 2100. This suggests that current nationally determined contributions (NDCs) under the Paris Agreement are inadequate for mitigating significant warming. A low-carbon scenario forecasts a 1.2°C increase in air temperature, while a high-carbon scenario anticipates a 3.8°C rise. Historical sea surface temperature (SST) data show an increase of 1.6°C in the Arabian Sea and 1.1°C in the Bay of Bengal. Between 1982 and 2019, there has been a marked increase in the frequency, intensity, and duration of cyclonic storms, with projections indicating that 30% of storms in the northern Indian Ocean could reach Category 5 status on the Saffir-Simpson scale. These powerful storms can generate waves exceeding 10 meters, posing substantial risks to offshore infrastructure.

As climate change accelerates, the oil and gas industry faces increasing challenges. Infrastructure such as extraction sites, pipelines, refineries, and storage facilities, designed for historical environmental conditions, must now endure more severe weather events, including hurricanes, typhoons, floods, and storm surges. Rising temperatures contribute to operational issues, equipment strain, and higher maintenance demands. In particular, rising sea levels heighten the risk of damage and spills, threatening offshore installations' safety and operational integrity.

CHAPTER 1

INTRODUCTION

1.1 Global warming and climate change

Global warming is the long-term heating of the Earth's climate system observed since the pre-industrial period (between 1850 and 1900) due to human activities, primarily burning fossil fuels, which increases heat-trapping greenhouse gas levels in the Earth's atmosphere. Climate change, on the other hand, is the long-term shift in the average temperature of the Earth and associated weather patterns. To study the climate aspects of the atmosphere, at least 30 years of data is required, whereas 19 years of data is considered sufficient for studying the oceanic aspect.

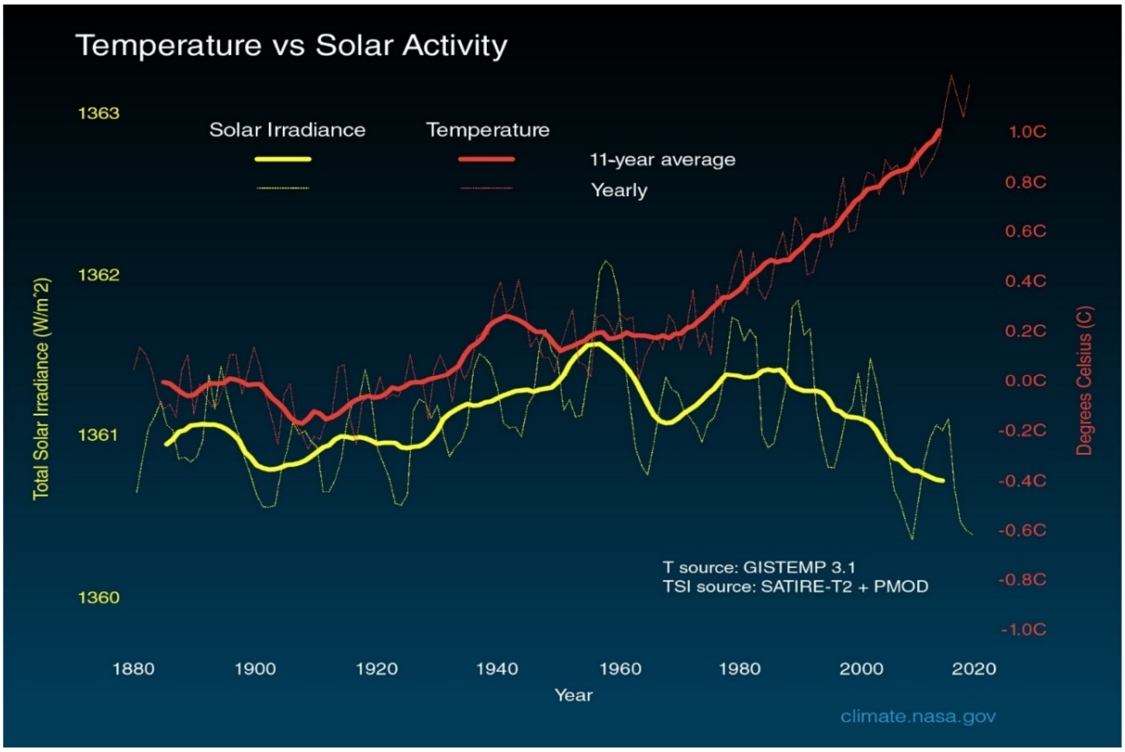


Figure 1.1 Shows the long-term variation of temperature (red line) and total solar irradiance (Yellow line).

Figure 1.1 clearly illustrates the elevation in solar irradiance and temperature till 1945; after that, solar irradiance showed a decreasing trend. But the temperature showed a drastic increase from 1950 to the present. Human activities could have predominantly driven this increase in temperature since the Industrial Revolution's emissions in the mid-1900s. The widespread burning of fossil fuels such as coal, oil, and natural gas has released massive amounts of greenhouse gases (GHGs), particularly carbon dioxide

(CO_2), methane (CH_4), and nitrous oxide (N_2O), into the atmosphere. These gases function like an insulating layer around the planet, trapping heat and causing global temperatures to rise (Arias, 2021). Although the climate has naturally fluctuated over millions of years, the current pace of warming is unprecedented and primarily linked to human activity. The Earth's climate is interlinked with 5 compartments: Atmosphere, Ocean, Glaciers, Land and Forest (Figure 1.2), and the balance of CO_2 is linked with these compartments, or any change in these compartments has feedback on the carbon cycle.

Figure 1.2 Shows changes and feedback mechanisms between various compartments in the earth system in the budgeting of CO_2.

1.2 Global warming and greenhouse gases

Globally, the increase in average surface temperature in 2011–2020 was approximately 1.1°C (0.95-1.20°C) compared to 1850–1900, characterized by a relatively higher warming over the land (1.34-1.83 °C) than the Ocean (0.68-1.1 °C) (IPCC Report, 2021). The observed warming is contributed to by greenhouse gases such as carbon dioxide, methane, nitrous oxide, and water vapour, which are responsible for warming 0.8 to 1.3°C. The present-day CO_2 concentrations are higher than ever over at least the past two million years, reaching up to 420 ppm (Figure 1.3b) (*Source: NOAA-GML; Scripps Institution of Oceanography; Friedlingstein et al, 2023; Global Carbon Project, 2023)*. Similarly, the concentrations of CH_4 and N_2O have increased, reaching up to 1866 ppb and 332 ppb, respectively, to levels unprecedented in at least 800,000 years.

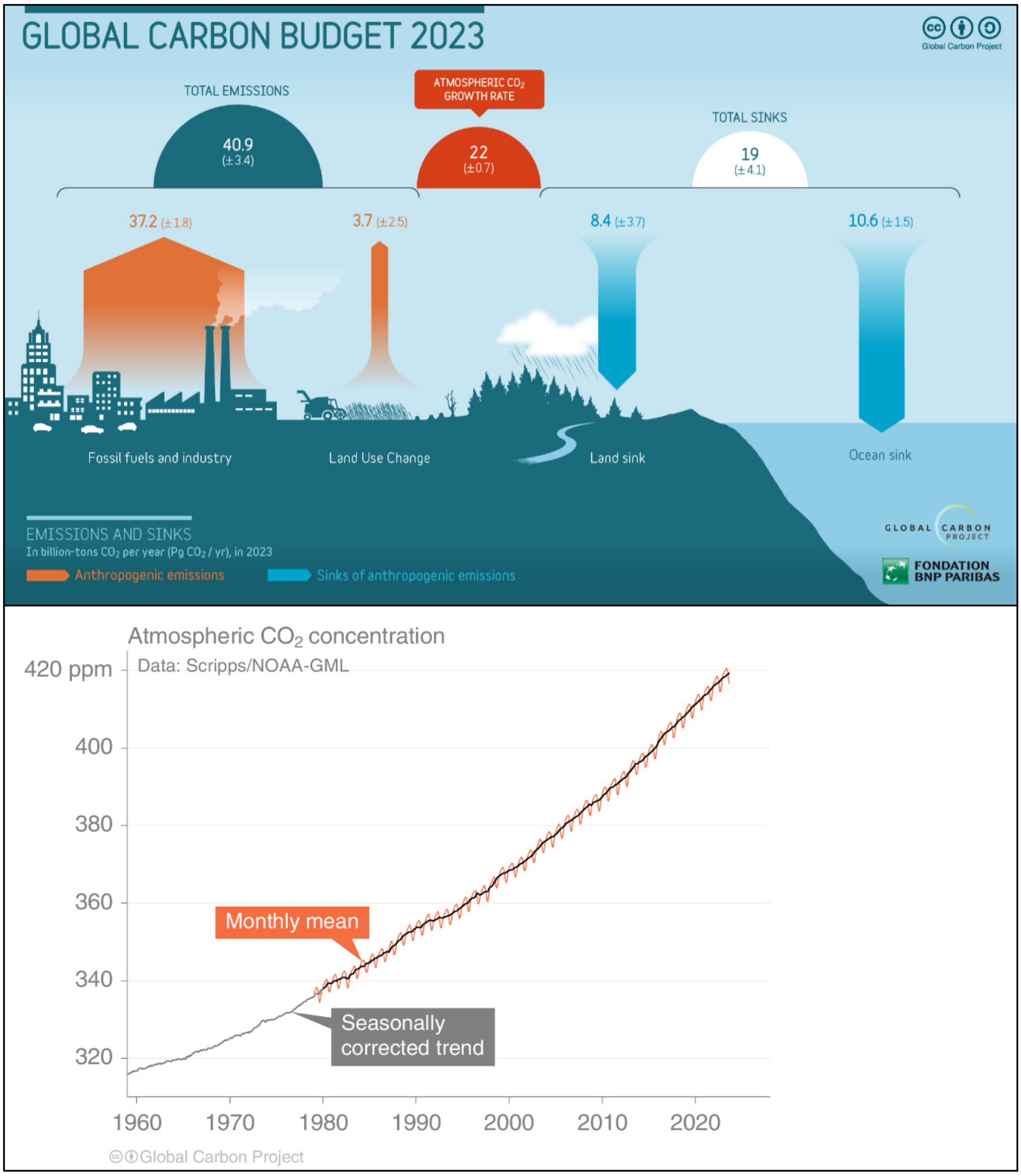


Figure 1.3a and b. **a)** Source sink budgeting of CO_2, b) Globally averaged surface atmospheric CO_2 concentration (ppm). Data from: NOAA-GML after 1980; the Scripps Institution of Oceanography before 1980.

The combustion of fossil fuels, including coal, oil, and gas, as well as cement production, contributes to what is known as fossil CO_2. These emissions account for about 90 per cent of all CO_2 emissions from anthropogenic activities. Emissions from all fossil sources increased in 2023 compared to 2022. Although fossil CO_2 emissions continue to rise, net emissions from land-use changes such as deforestation, which act as a CO2 source, remain essential when offset by CO_2 removals like reforestation (CO_2 sink) (Figure 1.3a). Net emissions from land-use change were 4.1 billion tonnes of CO_2 in 2023. Terrestrial vegetation and oceans absorb about half of all CO_2 emissions. This fraction has remained stable for six decades.

Figures 1.4 and 1.5 clearly show the annual increase in CO_2 emissions to the atmosphere. Still, we could see a dip in the curve with the dissolution of the Soviet Union in the 1990s, the Global financial crisis and the COVID-19 pandemic period. This reveals that imposing regulations or decreasing fossil fuels in a phased manner could reduce the release of CO_2 into the atmosphere, and thereby, we can decrease global warming trends and, hence, climate change. After the COVID pandemic, natural gas consumption declined in 2022, but oil recovered most of its pandemic-period losses.

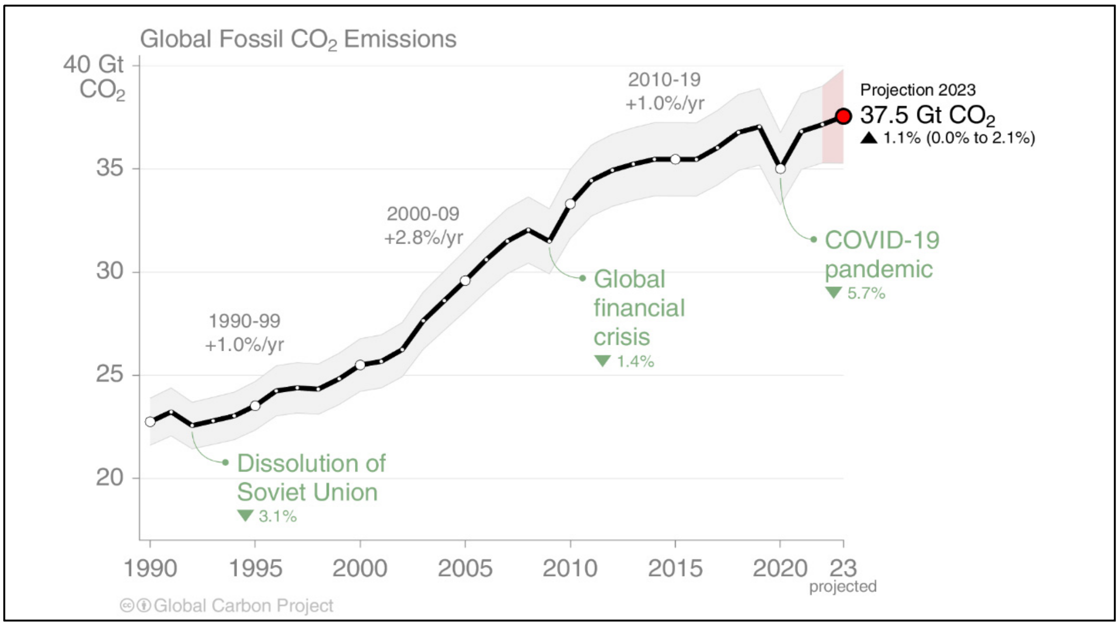


Figure 1.4 Yearly increase of global fossil CO_2 emissions.

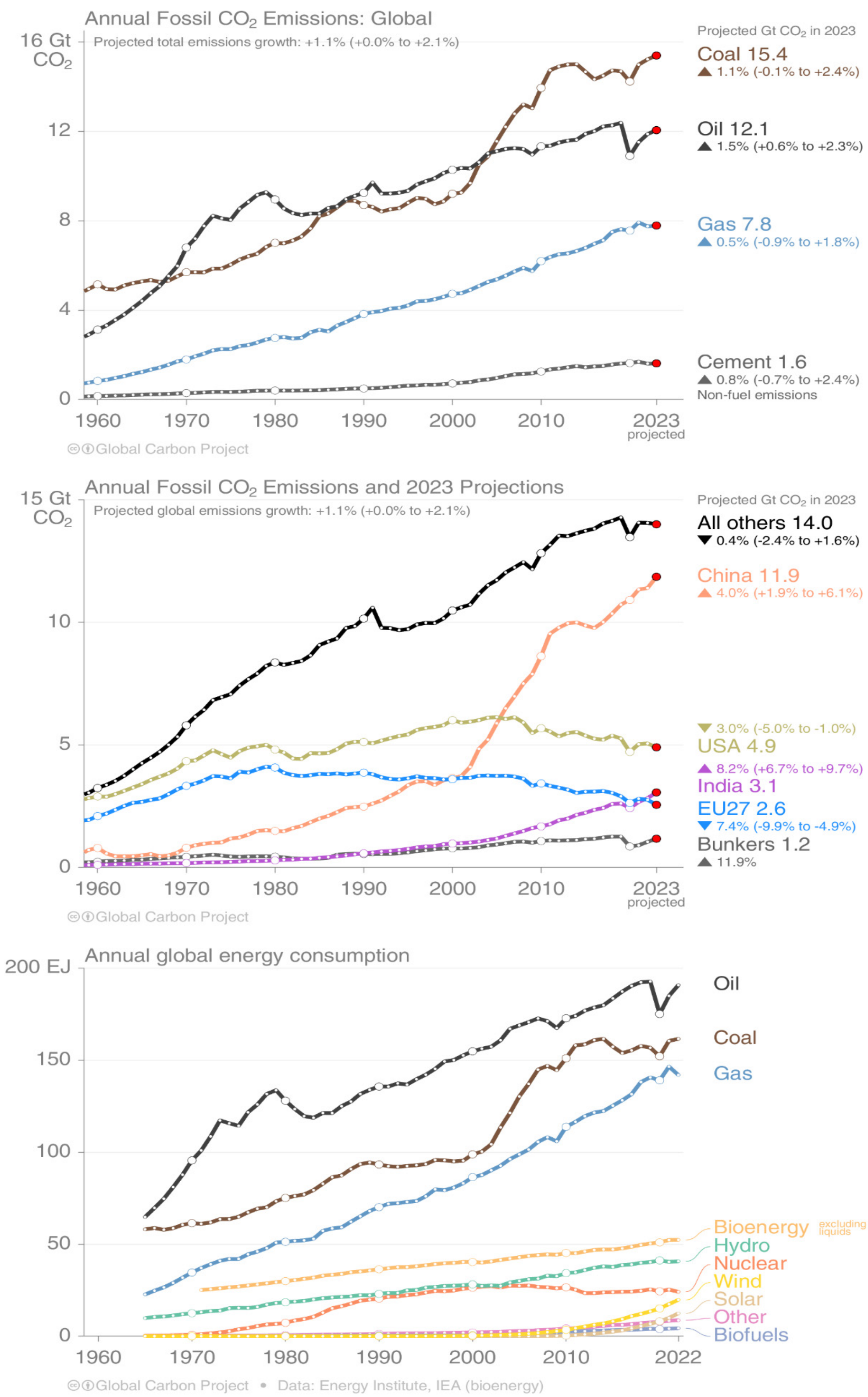


Figure 1.5 Yearly increase of global fossil CO_2 emissions a) sectors that emit CO_2, b) Major countries that contribute CO_2 and c) Comparison of annual consumption of fossil fuel and other renewable sources of energy.

1.3 GHG emission from India

1.3.1 CO_2 contribution to GHG

India is the third leading CO_2 contributor (3.1 Gt) behind China (11.9 Gt) and the USA(4.9 Gt). According to India's National Inventory Report (2022) submitted to the UNFCCC, the energy sector contributes approximately 75-80% of India's total GHG. The emissions from fossil fuels (coal, oil, and gas) and other sources are shown in Figure 1.6. India mainly depends on coal for energy generation compared to other sources such as oil and gas or other renewable energy resources. India's emissions continue to grow sharply in 2023. Increases in solar and wind capacity were insufficient to meet a significant increase in power demand as the economy grew strongly. The oil and gas sector contributes ~20-25% of total GHG emissions from India. 3 Gt of annual CO_2 emissions of India only amounts to about two and a half tons per person annually, less than the world average due to high population density (Pearson, T. R, 2017).

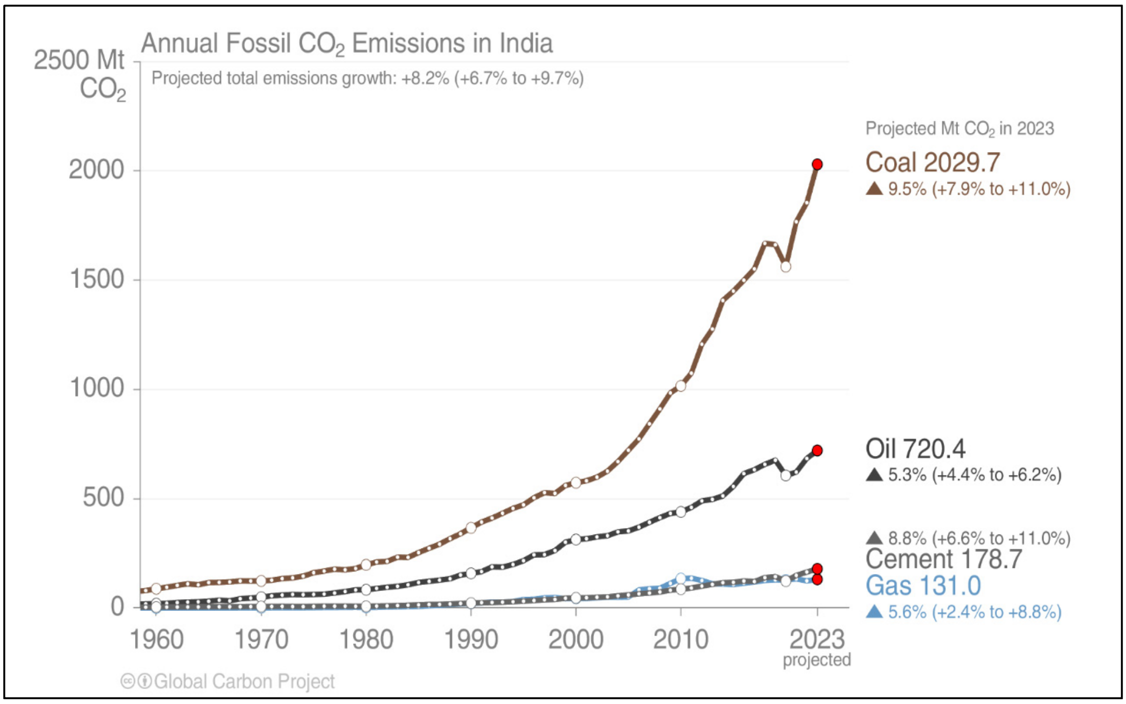


Figure 1.6 Shows the contribution of GHG emissions from various sectors in India.

1.3.2 Methane contribution to GHG

The methane concentration in the atmosphere is currently around two-and-a-half times greater than its pre-industrial levels. The increase has accelerated in recent years, and preliminary analysis indicates that 2021's rise will likely be the largest ever recorded. Estimates of methane emissions are subject to a high degree of uncertainty. However, the most recent comprehensive assessment provided in the Global Methane Budget (Figure 1.7) suggests that annual global methane emissions are around 580 Mt. These include emissions from natural sources, around 40% of emissions, and the remaining 60% which originate from human activity, known as anthropogenic emissions such as agriculture (25 % of total emission) and energy sector (Figure 1.8), which includes emissions from coal, oil, natural gas and biofuels.

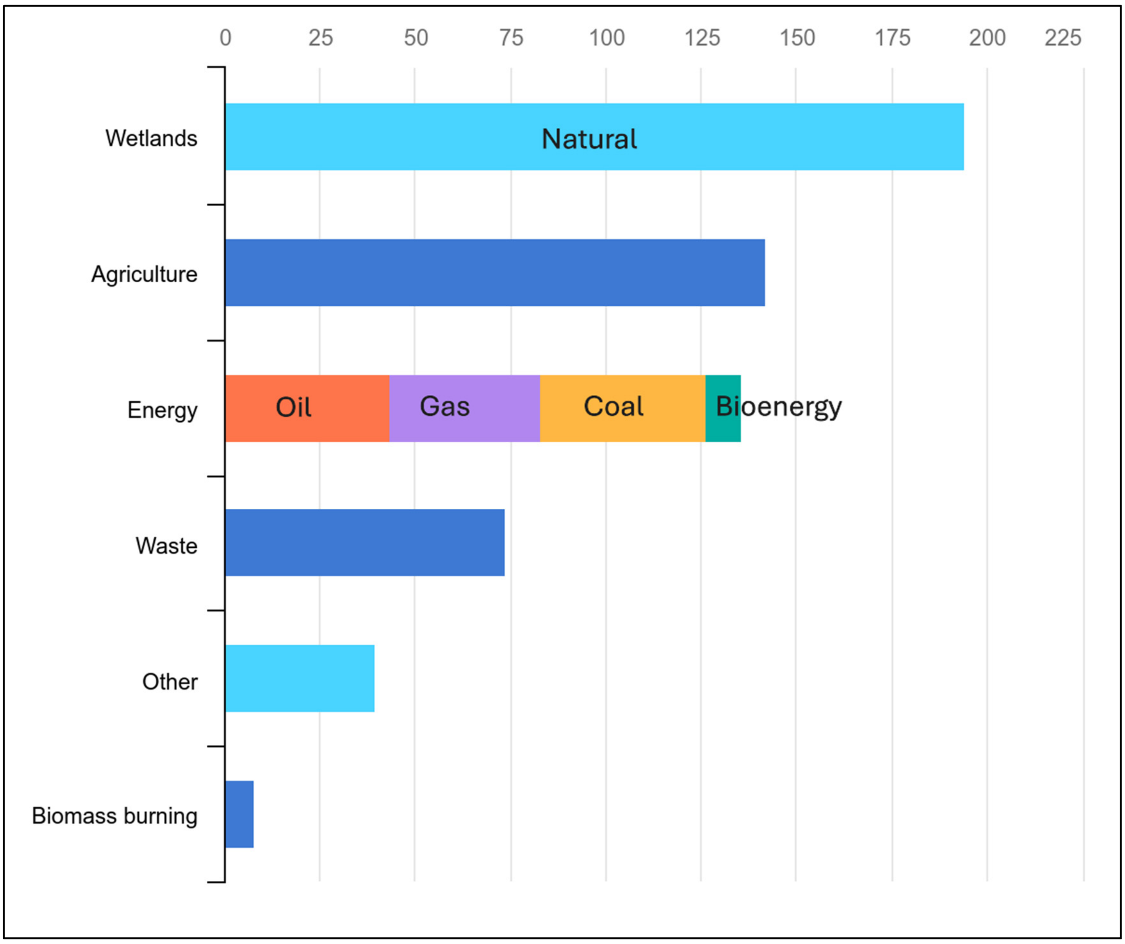


Figure 1.7 Global annual methane emissions 2021 IEA (2022), sources of methane emissions, 2021, IEA, Paris.

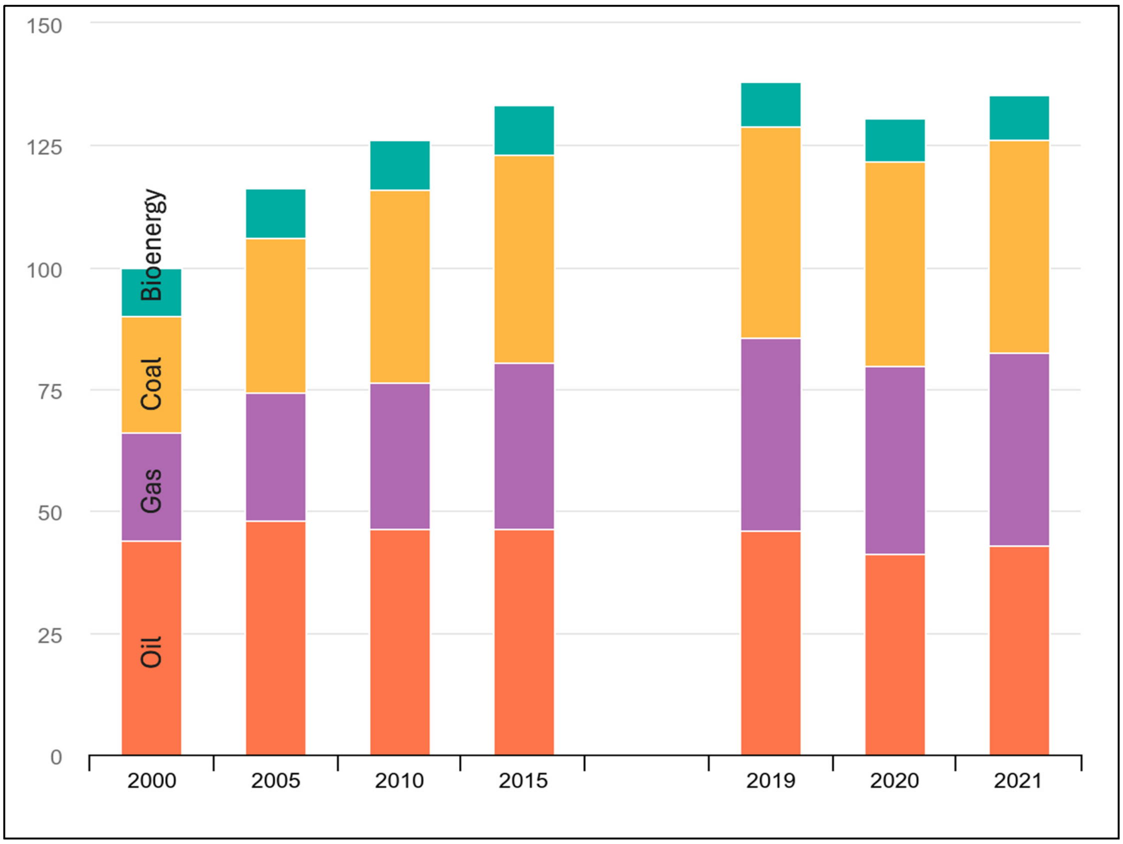


Figure 1.8 Global methane emissions from the energy sector over time, 2000-2021, IEA, Paris.

1.4 How oil and gas industry contribute to GHG?

The oil and gas industry significantly contributes to global GHG emissions throughout its lifecycle, from extraction and production to utilization. According to the International Energy Agency (IEA), the major contributors to GHG emissions are CO_2, Methane and N_2O.

- **CO_2 Contribution:** The oil and gas sector accounted for approximately 40% of global energy-related CO_2 emissions in recent years.
- **Methane contribution:** Methane emissions from oil and gas operations contribute significantly to global warming due to methane's high global warming potential compared to CO_2. (Methane 27-30 times greater than CO_2)
- **Nitrous Oxide (N_2O):** Global warming potential of N_2O is 273 times that of CO_2

a) Emissions from exploration and production

- Methane can leak from oil and gas extraction sites, pipelines, and storage facilities.
- Excess natural gas flares during oil extraction, releasing CO_2 and other pollutants during gas flaring.

b) Emissions from transportation and processing

- Pipelines transport oil and gas over long distances, consuming energy. Pipelines may also experience leaks, releasing methane and other gases into the atmosphere.
- Marine transport tankers are used to transport oil and gas, which emit CO_2 and other pollutants.

c) Emissions from refining:

- The refining process, e.g., gasoline, diesel, which is highly energy-intensive
- Refining can also produce other GHGs, including methane and nitrous oxide.

d) Emissions from end-use consumption

- The combustion of gasoline, diesel, and jet fuel in vehicles and aircraft is a major source of CO_2 emissions.
- Heating and Power Generation: Natural gas is widely used for heating and electricity generation, contributing to CO_2 emissions.

1.5 The effects of climate change on global economies and industries

Climate change is not just an environmental issue. It poses significant risks to global economies and industries, particularly agriculture, forestry, fisheries, and energy sectors. These industries are closely linked to natural resources and are highly sensitive to changing weather patterns. In offshore regions, rising sea levels and stronger storm surges damage infrastructure, displace communities, and strain economic resources needed for disaster recovery.

In the energy sector, climate change poses a dual threat. On the one hand, fossil fuel-based energy production is a primary driver of climate change due to the vast amounts of CO_2 released during coal, oil, and gas combustion. On the other hand, energy systems are vulnerable to the impacts of a changing climate. Extreme weather events, such as heat waves, can strain energy grids by increasing demand for cooling, while hurricanes and floods can disrupt energy infrastructure, causing blackouts and operational disruptions. Additionally, energy systems that rely on water, such as hydroelectric power plants and cooling systems for thermal power plants, are particularly vulnerable to changes in water availability due to droughts and altered precipitation patterns.

This rapid warming has far-reaching consequences for the Earth's ecosystems, weather systems, and human societies. One of the most visible signs of climate change is the increase in the frequency and intensity of extreme weather events. For example, tropical storms, hurricanes, floods, droughts, heat waves, and wildfires have become more common and destructive. Melting glaciers, rising sea levels, ocean acidification, and changes in precipitation patterns are also clear indicators of a changing climate. These events not only disrupt natural ecosystems but also threaten food and water security, threaten offshore communities, and place immense strain on economic systems worldwide.

The industrial and energy sectors are among the most significant contributors to greenhouse gas emissions. As global energy demand continues to rise, driven by population growth and economic development, the burning of fossil fuels has increased alarmingly. This has created a feedback loop where increased energy consumption leads to more emissions, accelerating climate change. The transportation sector, power generation, and heavy industries such as steel and cement production heavily rely on fossil fuels, making them significant sources of carbon emissions.

1.6 Impact of climate change on the oil and gas industry

The oil and gas sector is deeply intertwined with the climate change narrative, as it remains one of the largest sources of greenhouse gas emissions. Oil and gas extraction, production, refinement, transportation, and consumption have historically powered global economic growth, but at a significant environmental cost. Using petroleum products for electricity generation, transportation, and industrial processes releases large quantities of CO_2 into the atmosphere, contributing to the greenhouse effect and global warming. Despite the push for cleaner and more sustainable energy sources, oil and gas still account for a significant portion of the world's energy supply.

The oil and gas sector is one of India's eight core industries, pivotal in shaping decisions across other key economic sectors. As India's economic growth drives energy demand, the need for oil and gas is expected to rise, making the industry highly attractive for investment. In 2023, India remained the world's third-largest oil consumer.

The less-discussed aspect of the climate change debate highlights the escalating threats posed by unmitigated climate change, including the increasing frequency and intensity of extreme weather events such as heavy rainfall, heat waves, cyclones, storm surges, and droughts. Additional risks include reduced water availability, diminished agricultural productivity, land loss, heightened heat stress, and the spread of vector-borne diseases. Historical evidence indicates that the oil and gas sector is particularly vulnerable to extreme climatic events like cyclones, storm surges, floods, and slow-onset changes such as rising ambient temperatures, water scarcity, and declining soil moisture. The sector's physical infrastructure and operational efficiency are susceptible to changing climatic conditions, potentially resulting in financial losses, infrastructure damage, and disruptions in supply chains. Such disruptions could significantly impact other economic sectors, given that India's oil and gas infrastructure supports over a third of the country's primary energy supply, which is projected to grow in absolute terms for at least the next two decades.

The sector's extensive infrastructure, spanning land-locked areas, coastal regions, and deep-sea locations, faces varying degrees of vulnerability to extreme events, including cyclones, storm surges, floods, and heatwaves. Past incidents have shown how extreme climatic events can cause significant infrastructure damage and operational disruptions, leading to substantial financial and economic losses.

Climate change presents three critical challenges for the oil and gas sector. The first is the existential challenge of mitigating greenhouse gas emissions, which threatens the industry's long-term viability. The second is the risk to infrastructure and operations, particularly from extreme weather events. The third challenge arises from the Paris Agreement, which demands enhanced transparency in reporting greenhouse gas emissions. This issue brief explores these challenges in the context of India's oil and gas sector. It emphasizes the need for a comprehensive understanding of climate impacts to enhance resilience against these threats.

However, the oil and gas industry is a major contributor to climate change and is highly susceptible to its effects. As climate change accelerates, the risks to oil and gas E&P infrastructure become more pronounced. The industry's infrastructure extraction sites, pipelines, refineries, and storage facilities are built to withstand certain environmental conditions, but climate change is introducing new and more severe challenges. Extreme weather events such as hurricanes, typhoons, flooding, and storm surges are becoming more frequent and intense, threatening the integrity of oil rigs, refineries, and pipelines. Rising temperatures can also cause operational challenges, including equipment failures, increased wear and tear, and higher maintenance costs. In some regions, rising sea levels pose an existential threat to offshore oil and gas infrastructure, increasing the risk of spills and accidents.

The Working Group I (WGI) of the Intergovernmental Panel on Climate Change (IPCC) assessed the climate response to various future scenarios based on Shared Socio-economic Pathways (SSPs). Model predictions indicate a continued linear warming trend through 2050, with temperatures in the northern Indian Ocean potentially rising by 3-6°C by 2100. Internationally, significant measures such as the 2015 Paris Agreement have been adopted to curb GHG emissions, limiting global warming to below 2°C, with an aspirational goal of 1.5°C. Achieving these targets necessitates a global shift to low-carbon energy sources and a significant reduction in the use of fossil fuels. This suggests that current nationally determined contributions (NDCs) under the Paris Agreement are inadequate for mitigating significant warming. Between 1982 and 2019, there has been a marked increase in the frequency, intensity, and duration of cyclonic storms, with projections indicating that 30% of storms in the northern Indian Ocean could reach Category 5 status on the Saffir-Simpson scale. These powerful storms can generate waves exceeding 10 meters, posing substantial risks to offshore infrastructure.

The project has emphasized that climate change will accelerate the ageing of oil infrastructure, shortening its lifecycle and increasing the likelihood of failures. This can lead to disastrous events such as oil spills, fires, or explosions, which pose environmental risks and economic and reputational damage to the companies involved. Managing these risks is becoming a central concern for oil and gas companies. As the frequency of Natech (Natural Hazard Triggering Technological Disasters) events increases, companies must invest in climate-resilient infrastructure and adopt new technologies to mitigate the impact of climate-related disasters.

Six key climate change drivers in offshore and marine regions of the oil and gas industries are:

- Air and water temperature
- Precipitation patterns
- Rate of sea level rise and Shoreline erosions
- Storm intensity and Wave regime
- Damage to infrastructure can lead to oil spills and the release of hazardous contaminants.
- Changes in carbon dioxide levels and Ocean Acidification

Increases in temperatures, changing precipitation patterns, more frequent and intense storms, and rising sea levels increase the risk of operational disruptions, structural damage, oil spills, etc., which will result in

- Material integrity and corrosion risk.
- Decreased efficiency of cooling systems.
- Increased operational and maintenance challenges

Thus, a proper understanding and a detailed study are required, which suggests adaptation and mitigation strategies to minimise the impact of climate-induced phenomena on the offshore oil and gas industries. The industry must invest in climate-resilient infrastructure design, implement comprehensive risk assessment and management strategies, and adopt best practices to minimise environmental impacts and enhance operational safety.

1.7 Objectives of the project

1) How do global warming and climate change affect offshore and offshore oil and gas industries?
2) Compendium of relevant national/ international legal and statutory laws related to climate change and oil E&P activities.
3) Literature review depicting present environmental conditions prevailing over the marine sedimentary basins in the Indian EEZ.
4) Long-term effects of climate change and associated extreme weather events on oil E&P installations and associated activities.
5) Mitigation and avoidance measures are to be taken to reduce the impacts of climate change on oil E&P activities.
6) SOP for adoption by operators to overcome the impacts of climate change.

CHAPTER 2

LAWS AND REGULATIONS RELATED TO COASTAL AND OFFSHORE WATERS

Activities in the maritime zones of India are managed by various governmental ministries, such as the Ministry of Shipping, Road Transport and Highways, External Affairs, Defence, Earth Sciences, Petroleum & Natural Gas Law and Justice, etc., with differing rights, interests, mandates and responsibilities. This has led to the drafting and enactment of very general worded statutes in the maritime sector, subsequently leading to frail enforcement provisions, which are a bit of a stumbling block of this chapter.

2.1 International maritime laws

2.1.1 United Nations Convention on the Law of the Sea

The year 1982 marked the emergence of the United Nations Convention on the Law of the Sea. The law is a comprehensive regime that deals with the regulations about the world's oceans and seas, thereby establishing law and order. It further lays down rules regulating the usage of ocean resources. The Law of the Sea is a compilation of traditional laws that deal with the uses of oceans and several new legal notions and regimes that talk about current issues and maritime matters. Also, the law provides a legal framework further to develop several areas of the Law of the Sea. It is an international agreement in which several countries are signatories, which enumerates several guidelines for conducting business via sea, the marine environment framework, and the management of marine natural resources.

2.1.2 MARPOL (Applicable to oil and gas platforms and rigs)

The main objective of MARPOL is to reduce the discharge of oil products by maritime traffic during usual operations. Certain tankers are allowed to discharge a limited amount of oil contained in ballast water and tank washings into the sea. Regulation 9 of MARPOL 73/78 limits the amount of oil discharge into the sea to 1/30,000 of the total volume of the crude oil cargo. The additional requirement is that the oil content of the discharged effluent cannot exceed 15 ppm (1 mg/l is approximately 1 ppm) and, in effect, limits the operational discharge to amounts much less than the specified maximum value. In addition, the release of oil-bearing wastewater within 50 nautical miles of the shoreline is strictly prohibited.

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the leading international convention covering the prevention of marine environment pollution by ships from operational or accidental causes. The MARPOL Convention was adopted on 2nd November 1973 at the IMO. The Protocol of 1978 was adopted in response to tanker accidents in the 1976–1977. In 1997, a Protocol was adopted to amend the convention, and a new Annex VI was added, which entered into force on 19th May 2005. The convention includes regulations to prevent and minimise pollution from ships, both accidental pollution and routine operations, with several technical Annexes.

Under regulation 13 of MARPOL 73/78, oil tankers of 20,000 tonnes deadweight and above are required to have segregated ballast tanks (SBTs), dedicated clean ballast tanks (CBTs), and/or clean oil washing systems (COW), depending on the vessels type, when they were built, and their size. These ballast tanks are entirely separated from the cargo and fuel oil systems and are exclusively allocated to carry ballast water. This system greatly reduces the likelihood of oil-containing ballast water discharge, and tankers with a CBT system have a pipe system connected with the crude oil cargo pump and piping system. Discharge of fuel oil sludge from the machinery room is strictly forbidden anywhere in the world by MARPOL, and the sludge oil should be discharged at reception facilities in ports.

The Convention includes regulations mainly aimed at preventing and minimising pollution from ships, including accidental pollution and routine operations. It currently has six technical Annexes. Particular areas with strict controls on operational discharges are included in most Annexes.

Annex I *Regulations for the Prevention of Pollution by Oil (2nd October 1983):* Covers prevention of pollution by oil from operational measures as well as from accidental discharges; the 1992 amendments to Annex I made it mandatory for new oil tankers to have double hulls and brought in a phase-in schedule for existing tankers to fit double hulls, which was subsequently revised in 2001 and 2003.

Annex II *Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk (2nd October 1983):* Details the discharge criteria and measures for the control of pollution by noxious liquid substances carried in bulk; some 250 substances were evaluated and included in the list appended to the Convention; the discharge of their residues is allowed only to reception facilities until specific concentrations and conditions (which vary with the category of substances) are complied with. No discharge of residues containing noxious substances is permitted within 12 miles of the nearest land.

Annex III *Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form (1st July 1992):* It contains general requirements for issuing detailed standards on packing, marking, labelling, documentation, stowage, quantity limitations, exceptions, and notifications. For this Annex, "harmful substances" are those identified as marine pollutants in the International Maritime Dangerous Goods Code (IMDG Code) or those that meet the criteria.

Annex IV *Prevention of Pollution by Sewage from Ships (27th September 2003):* Contains requirements to control pollution of the sea by sewage; the discharge of sewage into the sea is prohibited, except when the ship has in operation an approved sewage treatment plant or when the ship is discharging and disinfecting sewage using an approved system at a distance of more than three nautical miles from the nearest land;

sewage which is not disinfected has to be discharged at a distance of more than 12 nautical miles from the nearest land.

Annex V *Prevention of Pollution by Garbage from Ships (31st December 1988):* Dealing with different types of garbage specifies the distances from land and how they may be disposed of; the most important feature of the Annex is the complete ban imposed on the disposal into the sea of all forms of plastics.

Annex VI *Prevention of Air Pollution from Ships (19th May 2005):* Sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone-depleting substances; designated emission control areas set more stringent standards for SOx, NOx and particulate matter. A chapter adopted in 2011 covers mandatory technical and operational energy efficiency measures aimed at reducing greenhouse gas emissions from ships.

2.1.3 Safety of Life at Sea (SOLAS) Convention

The 'Safety of Life at Sea' Convention is considered to be one of the most important conventions in the field of Maritime. In the marine industry, the most crucial concern is the safety of crew members and passengers on the vessel. In light of this, the above-mentioned convention was enacted. The convention lays down minimum safety requirements that need to be met in relation to the construction, equipment, and maintenance of the ship. The code consists of 14 chapters which lay down various safety standards to be followed. However, the convention does not apply to all ships. The convention applies only to vessels travelling in international waters, provided it does not include warships, cargo ships of less than 500 GT, non-propelled ships, wooden ships, non-commercial pleasure yachts, and fishing vessels. Hence, the above-mentioned list of vessels will not be held accountable for not following the rules and regulations enumerated in the SOLAS convention.

SOLAS Protocol 1978 covers the important amendments pertaining to tanker safety and pollution prevention, particularly the requirement and acceptable exemption for inert gas systems and the requirement for radar and steering gear control systems. SOLAS Protocol 1988 covers the changes to SOLAS Chapter V, such as the details of the navigational systems and equipment referred to in the records of equipment attached to the certificates and also introduces a new Harmonized System of Survey and Certification (HSSC) to harmonise two (2) Conventions, namely: the International Convention on Load Lines and the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL 73/78).

2.1.4 International Maritime Organisation - GHG strategy (2018):

IMO aims to reduce total GHG emissions from the shipping sector by at least 50% by 2050 compared to 2018 levels and to pursue efforts to phase them out entirely as soon as possible in this century.

2.2 Maritime laws in India

2.2.1 The Oilfields Regulation and Development Act, 1948

The Oilfields (Regulation and Development) Act of 1948 is an important legislation in India regulating the exploration, development, and production of petroleum resources.

- Protection of the environment: The act includes provisions for protecting the environment during the exploration and production activities.
- It mandates compliance with environmental regulations and may impose penalties for violations.

2.2.2 The Wildlife (Protection) Act, 1972, relevant to waterbodies

The act was enacted to effectively protect this country's wildlife and control poaching, smuggling, and illegal trade in wildlife and its derivatives. The act was amended in January 2003, and the punishment and penalty for offences under the act have been made more stringent. The Ministry has proposed further amendments to the law by introducing more rigid measures to strengthen the act. The objective is to provide protection to the listed endangered flora and fauna and ecologically important protected areas.

- Declaration of the sanctuary: The State Government may, by notification, declare its intention to constitute any area other than an area comprised within any reserve forest or the territorial waters as a sanctuary if it considers that such area is of adequate ecological, faunal, floral, geomorphological, natural or zoological significance, to protect, propagate or to develop wildlife or its environment.
- Declaration of National Parks: Whenever it appears to the State Government that an area, whether within a sanctuary or not, is, because of its ecological, faunal, floral, geomorphological or zoological association of importance, needs to be constituted as a National Park to protect, propagate or developing wildlife therein or its environment, it may, by notification, declare its intention to constitute such area as a National Park.

2.2.3 The Water (Prevention and Control of Pollution) Act, 1974

The "Water Act" has been enacted to prevent and control water pollution and maintain or restore the wholesomeness of water in the country. It further provides for the establishment of Boards for the prevention and control of water pollution with a view to carrying out the aforesaid purposes. The Water Act prohibits the discharge of pollutants into water bodies beyond a given standard and lays down penalties for non-compliance. At the Centre, the Water Act has set up the CPCB, which lays down standards for preventing and controlling water pollution. At the State level, SPCBs function under the direction of the CPCB and the State Government.

2.2.4 Maritime Zones Act, 1976 (The Territorial Waters, Continental Shelf, Exclusive Economic Zones)

The United Nations Convention for the Law of the Sea ("UNCLOS"), also identified as the Law of the Sea, is an international treaty structuring and establishing rules and regulations safeguarding the usage of oceans and seas worldwide. This convention introduced maritime zones: the territorial sea, contiguous zone, exclusive economic zone, and continental shelf. This convention articulates state jurisdiction in maritime areas.

Section of the Territorial Waters, Continental Shelf, Exclusive Economic Zone and other Maritime Zones Act 1976 notifies the sovereignty of the Indian states over the respective territorial waters. Foreign ships, submarines, warships, and so on can utilise the territorial waters but only with the approval of the Central Government. Further, the distance of 24 nautical miles towards the sea, measured from the baseline, is considered to be the Contiguous zone. It lies between the territorial seas and the high seas. The contiguous zone provides the state with control and jurisdiction over the surface and floor of the ocean, but it does not include air space rights. According to Article 33 of the convention, the coastal states can take steps to punish infringement of customs, immigration protocols, etc., whose commission took place within the territory or territorial sea concerning the contiguous zone.

The exclusive economic zone beside the territorial sea is 200 nautical miles away from the baseline. The exclusive economic zone is crucial in trade-offs related to UNCLOS. Protection of the exclusive economic zones retains the Indian maritime interests. India has an almost 2.172 million km^2 exclusive economic zone along the nation's 7500 km long coastline. Coastal states have the right to carry out procedures for producing energy from water and wind. They can also explore, manage, maintain, utilise, and conserve natural resources.

Several environmental protection legislations existed even before the Independence of India. However, the true thrust for putting in force a well-developed framework came only after the UN Conference on the Human Environment (Stockholm, 1972). After the Stockholm Conference, the National Council for Environmental Policy and Planning was set up in 1972 within the Department of Science and Technology to establish a regulatory body for environmental issues. This Council became a full-fledged Ministry of Environment and Forests (MoEF). MoEF was established in 1985, and today is the apex administrative body in the country for regulating and ensuring environmental protection and lays down the legal and regulatory framework for the same. Since the 1970s, several environmental legislations have been put in place. The MoEF and the pollution control boards ("CPCB", i.e., the Central Pollution Control Board and "SPCBs", i.e., State Pollution Control Boards) together form the regulatory and administrative core of the sector.

2.2.5 The Coast Guard Act, 1978

The Coast Guard Act 1978 states that preserving and protecting the marine environment and controlling marine pollution is the function of the Indian Coast Guard. The ICG was accordingly nominated in 1986 as the Central Coordinating Authority for oil-spill response in the Maritime Zones of India. Coast Guard officers have been empowered under the Merchant Shipping Act 1958 to take necessary actions against polluters. The comprehensively revised National Oil Spill Disaster Contingency Plan (NOSDCP) has been prepared for the offshore oil and gas field, which reflects current international norms and best practices, key relevant practices, and key relevant national regulations.

2.2.6 The Air (Prevention and Control of Pollution) Act, 1981

The "Air Act" is an act to provide for the prevention, control and abatement of air pollution and the establishment of Boards at the Central and State levels to carry out the aforesaid purposes. To counter the problems associated with air pollution, ambient air quality standards were established under the Air Act. The Air Act seeks to combat air pollution by prohibiting the use of polluting fuels and substances and regulating appliances that give rise to air pollution. The Air Act empowers the State Government, after consultation with the SPCBs, to declare any area or areas within the State as air pollution control areas or areas. Under the Act, establishing or operating any industrial plant in the pollution control area requires consent from SPCBs. SPCBs are also expected to test air pollution control areas and inspect pollution control equipment and manufacture.

2.2.7 The Environment Protection Act, 1986

The “Environment Act” provides for the protection and improvement of the environment. The Environment Protection Act establishes the framework for studying, planning and implementing long-term requirements of environmental safety and laying down a system of speedy and adequate response to situations threatening the environment. It is an umbrella legislation designed to provide a framework for coordinating central and state authorities established under the Water Act and the Air Act. The term “environment” is understood widely under s 2(a) of the Environment Act. It includes water, air and land, and the interrelationship between water, air and land, and human beings, other living creatures, plants, micro-organisms, and property. Under the Environment Act, the Central Government is empowered to take measures necessary to protect and improve the quality of the environment by setting standards for emissions and discharges of pollution in the atmosphere by any person carrying on an industry or activity; regulating the location of industries; management of hazardous wastes, and protection of public health and welfare. From time to time, the Central Government issues notifications under the Environment Act for the protection of ecologically sensitive areas or issues guidelines for matters under the Environment Act.

2.2.8 The Biological Diversity Act, 2002

Biodiversity Act, 2002, also does not contain any specific provision that can be used against climate change or marine conservation. Technically, though, the understanding emanating from the Act can be extended to protect and conserve any biodiversity found in India's coastal areas. Besides, the regulatory framework related to biosphere reserves, established under UNESCO's Man and the Biosphere (MAB) Programme, can also be read within the general framework of biodiversity protection in India. The Act aims to conserve biological resources and associated knowledge and facilitate access to them in a sustainable manner. The National Biodiversity Authority in Chennai has been established to implement the objectives of the Act.

2.2.9 Environmental Impact Assessment - EIA 2006

The Ministry of Environment and Forests (MoEF) uses Environmental Impact Assessment Notification 2006 as a major tool for minimising the adverse impact of rapid industrialisation on the environment and reversing those trends that may lead to climate change in the long run. EIA 2006 was issued on 14th September 2006, in supersession of EIA 1994, except with respect to things done or omitted to be done before such supersession. The notification is issued under relevant provisions of the Environment (Protection) Act, 1986.

2.2.10 Hazardous Wastes Management Regulations, 2008

Hazardous waste means any waste that, because of its physical, chemical, reactive, toxic, flammable, explosive or corrosive characteristics, causes danger or is likely to cause a threat to health or the environment, whether alone or when in contact with other wastes or substances. There are several legislations that directly or indirectly deal with hazardous waste management. The relevant legislations are the Factories Act, 1948, the Public Liability Insurance Act, 1991, the National Environment Tribunal Act, 1995 and rules and notifications under the Environmental Act.

2.2.11 The Petroleum and Natural Gas Rules, 2008

In India, PNG rules (2008) were enacted to regulate the exploration, production, storage, distribution, and marketing of petroleum and natural gas resources in the country. These rules are designed to ensure the efficient, safe, and environmentally responsible management of India's energy resources. Key points in the view of environment aspects of the Petroleum and Natural Gas Rules 2008 are as follows: *Regulation of Exploration and Production*: The rules govern the procedures for granting exploration licenses for petroleum and natural gas, including the terms for carrying out exploration activities, production, and the proper assessment of resources. *Safety and Environmental Compliance*: Strict safety standards are outlined for the operations in the petroleum and natural gas sectors. The rules ensure that operators must comply with environmental regulations to prevent spills, accidents, and pollution.

Based on the Petroleum and Natural Gas rules (2008), the Oil Industry Safety Directorate prepared “Guidance Notes” in November 2009, which have been revised and amended in 2012 based on industry feedback, new standards, changes in the International standards and OIDS’s audit observations. The major key safety rules and guidelines for offshore installations, as per OISD standards, point out that Offshore installations must be designed and constructed to withstand extreme environmental conditions, including high winds, waves, and seismic activity. All equipment and structures must comply with international standards and codes, such as API (American Petroleum Institute) and ISO (International Organisation for Standardisation). Safety-critical systems, such as blowout preventers (BOPs) and emergency shutdown systems (ESD), must be installed and regularly tested. Fire detection and suppression systems, including smoke detectors, fire alarms, and firefighting equipment, must be installed throughout the installation. Hazardous areas must be classified according to the risk of fire or explosion, and appropriate equipment (e.g., explosion-proof lighting) must be used. Offshore installations must have a well-defined emergency response plan (ERP) that includes evacuation, rescue, and medical assistance procedures. Life-saving appliances, such as lifeboats, life rafts, and personal flotation devices, must be readily available and regularly inspected. Offshore installations must have measures in place to prevent oil spills and other environmental hazards. Oil spill response equipment, such as booms and skimmers, must be available on-site. Regular environmental monitoring must be conducted to ensure compliance with regulations. All equipment and systems must undergo regular inspection, testing, and maintenance to ensure safe operation. Records of inspections and maintenance activities must be maintained and audited. Offshore installations must comply with all relevant OISD standards, national regulations, and international conventions. Regular safety audits and inspections must be conducted to ensure compliance and identify areas for improvement. Non-compliance issues must be addressed promptly, and corrective actions must be documented. These rules and guidelines are part of OISD's commitment to ensuring the highest standards of safety in the oil and gas industry. Compliance with these standards is mandatory for all offshore installations operating under OISD's jurisdiction. Regular updates and revisions to these standards are made to incorporate new technologies and lessons learned from incidents.

2.2.12 Merchant Shipping (Prevention of Oil Pollution) Regulations 2010

Merchant Shipping (Prevention of Oil Pollution) Regulations (2010) were established to prevent and minimize the pollution of the marine environment caused by oil discharges from ships. These regulations are aligned with international conventions, specifically the International Convention for the Prevention of Pollution from Ships (MARPOL), and are aimed at ensuring that Indian waters remain free from harmful oil pollution caused by shipping activities.

Key points of the Merchant Shipping (Prevention of Oil Pollution) Regulations 2010 are:*Oil Pollution Prevention Requirements*: The regulations stipulate that ships must have onboard facilities, including oil filtration and storage systems, to prevent oil discharge into the sea. Ships are required to follow strict operational procedures for handling oil waste and ensuring that oil pollution does not occur. *Oil Record Book*: Ships are required to maintain an Oil Record Book in which all oil-related activities, such as discharges, transfers, and disposal, are recorded. This book must be readily available for inspection by port authorities. *Oil Pollution Prevention Equipment:* The regulations specify the equipment that ships must carry, such as oil-water separators, and their maintenance. These devices help to separate oil from wastewater to prevent contamination of the ocean. *Compliance with MARPOL Standards*: Ships are required to comply with the provisions set out in the MARPOL convention, including maintaining specific operational standards to prevent accidental discharges of oil, including during ballast water operations, tank cleaning, and fuel handling. *Reporting and Notification*: In case of an oil pollution incident, the regulations mandate that the ship's operator must immediately report the spill to relevant maritime authorities and provide details about the situation to ensure prompt action is taken to mitigate the environmental damage. *Inspection and Enforcement*: Port and government authorities are empowered to inspect ships to ensure compliance with these regulations. Non-compliance may lead to penalties, fines, or even detention of the ship until corrective actions are taken. *Pollution Response Plans*: Ships are required to have an oil pollution emergency plan in place that outlines procedures for responding to oil spills, including containment and cleanup measures to minimize environmental damage.

2.2.13 The National Green Tribunal Act, 2010 (No. 19 of 2010)

(NGT Act) has been enacted with the objectives of providing for the establishment of a National Green Tribunal (NGT) for the effective and expeditious disposal of cases relating to environmental protection and conservation of forests and other natural resources, including enforcement of any legal right relating to the environment and giving relief and compensation for damages to persons and property and matters connected therewith or incidental thereto. The Act envisages the establishment of NGT in order to deal with all environmental laws relating to air and water pollution, the Environment Protection Act, the Forest Conservation Act and the Biodiversity Act as having been set out in Schedule I of the NGT Act.

2.2.14 Island Coastal Regulation Zone (ICRZ) Notification, 2019

The notification of the Government of India in the Ministry of Environment, Forest and Climate Change number S.O. 1242(E), dated the 8th March, 2019 [hereinafter referred to as the Island Coastal Regulation Zone (ICRZ) Notification, 2019], the Central Government declared certain coastal stretches as Coastal Regulation Zone and restrictions were imposed on the setting up and expansion of industries, operations and processes in the said zone.

i) All permitted or regulated project activities attracting the provisions of this notification shall be required to obtain ICRZ clearance prior to their commencement.

ii) All development activities or projects in ICRZ-I and ICRZ-IV areas, which are regulated and permissible as per this notification, shall be dealt with by the Ministry of Environment, Forest and Climate Change for clearance based on the recommendation of the concerned CZMA.

iii) For all other permissible and regulated activities as per this Notification, which fall purely in ICRZ–II and ICRZ-III areas, the ICRZ clearance shall be considered by the concerned CZMAs. Such projects in ICRZ –II and III, which also happen to be traversing through ICRZ–I and/or ICRZ-IV areas, ICRZ clearance shall, however, be considered only by the Ministry of Environment, Forest and Climate Change, based on recommendations of the CZMA.

iv) Projects or activities which attract the provisions of this Notification as also the provisions of EIA Notification 2006, shall be dealt with for a composite Environmental and ICRZ clearance under EIA Notification 2006 by the concerned approving Authority, based on recommendations of concerned CZMA, as per delegations i.e., State Environmental Impact Assessment Authority (hereinafter referred to as the SEIAA) for category 'B' projects and by the Ministry of Environment, Forest and Climate Change for category 'A' projects respectively.

v) In the case of building and construction projects with a built-up area less than the threshold limit stipulated for attracting the provisions of the EIA Notification, these shall be approved by the concerned local Union Territory Planning Authorities in accordance with this notification after obtaining recommendations of the CZMA.

vi) Only for self-dwelling units up to a total built-up area of 300 sq. meters approval shall be accorded by the concerned local authority without the requirement of recommendations of the CZMA. However, such authorities shall examine the proposal from the perspective of this Notification before approval.

2.3 Laws and regulations related to GHG emissions and climate change

2.3.1 United Nations Framework Convention on Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty negotiated at the Earth Summit in Rio de Janeiro from 3rd to 14th June 1992, then entered into force on 21st March 1994.

Objective: The main objective of the UNFCCC is to stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. To achieve this, the Convention emphasises the importance of reducing emissions of greenhouse gases and enhancing the resilience of ecosystems and societies to the impacts of climate change.

The **Conference of the Parties (COP)** to the **UNFCCC** serves as the primary international platform for negotiating and regulating climate change policies. Over the years, the COP has focused on a variety of action themes to mitigate and adapt to climate change. These themes provide the framework for global cooperation and climate governance, aiming for a sustainable, low-carbon future. Below are the key COP action themes in regulating climate change:

I. Mitigation of greenhouse gas emissions

Paris Agreement (2015): One of the central aims is to limit global temperature rise to well below 2°C, preferably 1.5°C, by reducing global greenhouse gas emissions.

Nationally Determined Contributions (NDCs): Countries must submit their own emissions reduction targets (NDCs) and update them every five years. This bottom-up approach encourages each nation to take responsibility for its own climate action.

Decarbonisation: Transitioning from fossil fuel dependence to renewable energy sources (solar, wind, geothermal, etc.) and energy-efficient technologies. Countries are increasingly setting **net-zero emissions** goals by mid-century (e.g., 2050).

II. Adaptation to climate impacts

Adaptation plans and strategies: COP decisions emphasise the need for countries, especially those vulnerable to climate impacts (e.g., small island nations, and developing countries), to create and implement national adaptation plans (NAPs) to reduce vulnerability and enhance resilience.

Local adaptation initiatives: The focus is on enhancing community-based adaptation, ensuring that local stakeholders have the capacity and resources to address climate risks (e.g., droughts, floods, rising sea levels).

Adaptation finance: Developed countries are called to support adaptation efforts in developing countries, particularly those most affected by climate change, through financial mechanisms like the **Green Climate Fund (GCF)**.

III. Climate finance

$100 Billion Commitment: Developed countries committed to providing $100 billion annually to support developing countries' mitigation and adaptation efforts, a goal to be met by 2020 and sustained thereafter.

Funding mechanisms: Key financial instruments like the Green Climate Fund (GCF), the Adaptation Fund, and the Global Environment Facility (GEF) support climate action in developing countries by financing projects that help reduce emissions and enhance climate resilience.

Private sector mobilisation: Encouraging private investment in green technologies, renewable energy, and sustainable development projects through public-private partnerships and carbon markets.

IV. Loss and damage

Compensation for climate impacts: COP discussions on loss and damage focus on the costs of irreparable losses due to climate change, particularly in vulnerable nations. This includes funding for disasters that go beyond adaptation capabilities.

COP27 (2022) Agreement: A major outcome of COP27 was the agreement to establish a dedicated loss and damage fund, which aims to compensate countries that face severe climate impacts, such as extreme weather events, which are beyond their ability to adapt.

V. Carbon markets and climate finance mechanisms

Article 6 of the Paris Agreement: Establishes carbon market mechanisms to facilitate international cooperation on emissions reduction. Countries can trade carbon credits or implement joint mitigation activities to meet their targets (e.g., carbon trading and carbon offsetting).

International carbon markets: These mechanisms aim to create incentives for reducing emissions where it is most cost-effective. This also includes voluntary carbon markets and corporate commitments to offset emissions.

Pricing carbon: Many countries implement carbon pricing mechanisms (such as carbon taxes or cap-and-trade systems) to incentivise emissions reductions by putting a price on carbon emissions.

VI. Technological innovation and knowledge sharing

Clean energy technologies: The COP fosters international collaboration to develop and deploy low-carbon technologies like solar, wind, green hydrogen, and electric vehicles.

Climate technology transfer: COP discussions emphasise facilitating the transfer of climate-friendly technologies and know-how to developing countries.

Climate innovation hubs: Establishing platforms and centers for sharing knowledge, research, and innovations in climate science, clean technologies, and sustainable practices.

VII. Loss of biodiversity and ecosystem protection

Nature-based solutions: Recognising the role of ecosystems (forests, wetlands, oceans) in both mitigating climate change (by absorbing CO_2) and adapting to its impacts (e.g., flood protection, agricultural resilience).

Biodiversity protection: COP actions are aligned with the global biodiversity goals (e.g., the Convention on biological diversity) to protect natural ecosystems and species threatened by climate change.

Deforestation: There is growing attention on halting deforestation and encouraging reforestation to store carbon and protect biodiversity, particularly through initiatives like the New York declaration on forests.

VIII. Just transition

Social and economic equity: A just transition focuses on ensuring that climate actions are equitable, taking into account social justice concerns. It emphasises fair treatment of workers, communities, and sectors most affected by the transition to a low-carbon economy.

Green jobs: Encouraging the creation of new green jobs in sectors like renewable energy, energy efficiency, and sustainable agriculture.

Climate justice: Ensuring that the most vulnerable populations, including indigenous people, women, and low-income communities, are included in decision-making processes and benefit from climate solutions.

IX. International cooperation and governance

Global Climate Governance: COP provides a platform for countries to cooperate and set the global climate agenda. The Paris Agreement established a legally binding international framework for tackling climate change.

Enhanced transparency: Strengthening the transparency framework to ensure that all countries report their climate actions, financial contributions, and progress toward meeting their targets.

Capacity building: Providing support to developing countries to strengthen their institutional capacity to address climate change through training, resources, and technology sharing.

X. Public engagement and civil society

Inclusion of non-state actors: COP increasingly involves non-governmental actors (e.g., businesses, NGOs, local governments) in climate action discussions, recognising their role in achieving climate goals.

Youth and indigenous leadership: Empowering youth movements and Indigenous communities to be at the forefront of climate action and decision-making.

Raising public awareness: COP negotiations also aim to raise global awareness about the urgency of climate action and the importance of collective responsibility to address climate change.

2.3.2 Kyoto Protocol

The Kyoto Protocol is a landmark international treaty adopted in 1997 as part of the United Nations Framework Convention on Climate Change (UNFCCC). The Kyoto Protocol was adopted on 11th December 1997. Owing to a complex ratification process, it entered into force on 16th February 2005. Currently, there are 192 Parties to the Kyoto Protocol. Its main objective is to reduce GHG emissions, based on the scientific consensus that global warming is occurring and that human-made CO_2 emissions are driving it. To commit that industrialised countries and their economies are in transition to limit and reduce GHG emissions in accordance with agreed individual targets. The Convention itself only asks those countries to adopt policies and measures on mitigation and to report periodically.

2.3.3 The Intergovernmental Panel on Climate Change (IPCC) 1988

IPCC is a key international body of the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO). Its primary purpose is to assess scientific information related to climate change, its impacts, and potential adaptation and mitigation strategies. IPCC releases major assessment reports every six to seven years. There is a clear and unequivocal link between human activities and climate change, primarily due to fossil fuel combustion and deforestation.

- Temperature Rise: Global surface temperature has risen by about 1.1°C since the late 19th century. Immediate and significant action is needed to limit warming to 1.5°C or 2°C.
- Impacts on Ecosystems: Climate change is causing widespread changes in ecosystems, leading to species extinctions and disruptions in biodiversity.
- Extreme Weather Events: Increased frequency and intensity of extreme weather events, including heatwaves, floods, and hurricanes, are directly linked to climate change.
- Social and Economic Consequences: Vulnerable populations are disproportionately affected, highlighting the need for equitable adaptation and resilience strategies.

2.3.4 Paris Agreement

The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on ^{12th} December 2015. It entered into force on 4^{th} November 2016. Its overarching goal is to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursue efforts “to limit the temperature increase to 1.5°C above pre-industrial levels.”

The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations together to combat climate change and adapt to its effects. Since 2020, countries have been submitting their national climate action plans, known as nationally determined contributions (NDCs). Each successive NDC is meant to reflect an increasingly higher degree of ambition compared to the previous version. In their NDCs, countries communicate actions they will take to reduce their greenhouse gas emissions in order to reach the goals of the Paris Agreement. Countries also communicate in their NDCs actions they will take to build resilience to adapt to the impacts of climate change. To better frame the efforts towards the long-term goal, the Paris Agreement invites countries to formulate and submit long-term low greenhouse gas emission development strategies (LT-LEDS).

At the Conference of the Parties (COP) 21 in Paris, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low-carbon future. The Paris Agreement builds upon the Convention and – for the first time – brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so. As such, it charts a new course in the global climate effort.

The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change. Appropriate financial flows, a new technology framework, and an enhanced capacity-building framework will be put in place to reach these ambitious goals, thus supporting action by developing countries and the most vulnerable countries in line with their national objectives. The Agreement also provides for enhanced transparency of action and support through a more robust transparency framework.

The Paris Agreement adopted crucial areas necessary to combat climate change. Some of the key aspects of the agreement are set out below:

- Long-term temperature goal (Art. 2): The Paris Agreement, in seeking to strengthen the global response to climate change, reaffirms the goal of limiting global temperature increase to well below 2°C while pursuing efforts to limit the increase to 1.5°C.

- Global peaking (Art. 4): To achieve this temperature goal, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognising peaking will take longer for developing country Parties so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century.

- Mitigation (Art. 4): The Paris Agreement establishes binding commitments by all Parties to prepare, communicate and maintain a nationally determined contribution (NDC) and to pursue domestic measures to achieve them. It also prescribes that Parties shall communicate their NDCs every 5 years and provide information necessary for clarity and transparency. Each successive NDC will represent a progression beyond the previous one and reflect the highest possible ambition to set a firm foundation for higher ambition. Developed countries should continue to take the lead by undertaking absolute economy-wide reduction targets, while developing countries should continue enhancing their mitigation efforts and are encouraged to move toward economy-wide targets over time in light of different national circumstances.

- Sinks and reservoirs (Art.5): The Paris Agreement also encourages Parties to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases as referred to in Article 4, paragraph 1(d) of the Convention, including forests.

- Market and non-market (Art. 6): The Paris Agreement establishes a mechanism to mitigate greenhouse gas emissions, support sustainable development, and define a framework for non-market approaches to sustainable development.

- Adaptation (Art. 7): The Paris Agreement establishes a global goal to significantly strengthen national adaptation efforts – enhancing adaptive capacity, strengthening resilience and reduction of vulnerability to climate change – through support and international cooperation. It also recognises that adaptation is a global challenge faced by all. All Parties should submit and update an adaptation communication periodically on their priorities, implementation and support needs, plans and actions. Developing country Parties will receive enhanced support for adaptation actions.

- Loss and damage (Art. 8): The Paris Agreement significantly enhances the Warsaw International Mechanism on Loss and Damage, which will develop approaches to help vulnerable countries cope with the adverse effects of climate change, including extreme weather events slow-onset events such as sea-level rise. The Agreement now provides a framework for Parties to enhance understanding, action, and support regarding loss and damage.

- Support (Art. 9, 10 and 11): The Paris Agreement reaffirms the obligations of developed countries to support the efforts of developing country Parties to build clean, climate-resilient futures, while for the first time encouraging voluntary contributions by other Parties. The provision of resources should also aim to achieve a balance between adaptation and mitigation. In addition to reporting on finance already provided, developed country Parties commit to submit indicative information on future support every two years, including projected levels of public finance. The agreement also provides that the Financial Mechanism of the Convention, including the Green Climate Fund (GCF), shall serve the Agreement. International cooperation on climate-safe technology development and transfer and building capacity in the developing world are also strengthened: a technology framework is established under the agreement, and capacity building activities will be enhanced through, inter alia, enhanced support for capacity building actions in developing country parties and appropriate institutional arrangements.

- Transparency (Art. 13): The Paris Agreement relies on a robust transparency and accounting system to provide clarity on action and support by Parties, with flexibility for their differing capabilities. In addition to reporting information on mitigation, adaptation and support, the agreement requires that the information submitted by each Party undergoes international review. The Agreement also includes a mechanism that will facilitate implementation and promote compliance in a non-adversarial and nonpunitive manner and report annually to the COP.

- Global Stocktake (Art. 14): A “global stocktake” to take place in 2023 and every five years thereafter will assess collective progress toward meeting the purpose of the Agreement in a comprehensive and facilitative manner. Its outcomes will inform Parties in updating and enhancing their actions and support and enhancing international cooperation.

2.4 Indian initiative towards the Paris Agreement

India communicated an update to its first NDC submitted earlier on 2nd October, 2015, for the period up to 2030, as follows:

1) To put forward and further propagate a healthy and sustainable way of living based on traditions and values of conservation and moderation, including through a mass movement for 'LIFE'– 'Lifestyle for Environment' as a key to combating climate change.
2) To adopt a climate-friendly and cleaner path than the one followed hitherto by others at corresponding levels of economic development.
3) To reduce the Emissions Intensity of its GDP by 45 per cent by 2030, from the 2005 level.
4) To achieve about 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030, with the help of the transfer of technology and low-cost international finance, including from the Green Climate Fund (GCF).
5) To create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030.
6) To better adapt to climate change by enhancing investments in development programmes in sectors vulnerable to climate change, particularly agriculture, water resources, Himalayan rfegion, coastal regions, health and disaster management.
7) To mobilise domestic and new & additional funds from developed countries to implement the above mitigation and adaptation actions in view of the resource required and the resource gap.
8) To build capacities, create domestic framework and international architecture for quick diffusion of cutting-edge climate technology in India and for joint collaborative R&D for such future technologies.

India has undertaken several significant initiatives to reduce carbon emissions as part of its commitments under the Paris Agreement. Key initiatives include:

1) Enhanced NDCs: India updated its Nationally Determined Contributions (NDCs) in 2021, committing to reduce the emissions intensity of its GDP by 33-35% by 2030 compared to 2005 levels.
2) Renewable energy expansion: Honourable Prime Minister Shri Narendra Modi announced ambitious plans to increase India's renewable energy capacity to 500 GW by 2030, with a strong focus on solar and wind energy.
3) International solar alliance: Honourable Prime Minister Shri Narendra Modi launched the International Solar Alliance to promote solar energy globally and enhance collaboration on renewable technologies.
4) Afforestation and reforestation: The government aims to create additional carbon sinks through initiatives to enhance forest and tree cover.
5) Electric mobility: The Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme was introduced to promote electric vehicles, aiming for a significant reduction in emissions from the transportation sector.
6) Sustainable development goals: The government emphasises sustainable development, integrating climate action into economic policies and encouraging energy efficiency measures across industries.
7) Panchamrit commitment: In 2021, during the COP26 summit, the Prime Minister announced the "Panchamrit" framework, which includes targets for reaching net-zero emissions by 2070, reducing total projected carbon emissions by 1 billion tonnes by 2030, and increasing the non-fossil fuel energy capacity to 50% by 2030.

These initiatives illustrate India's proactive stance on climate action while balancing developmental needs.

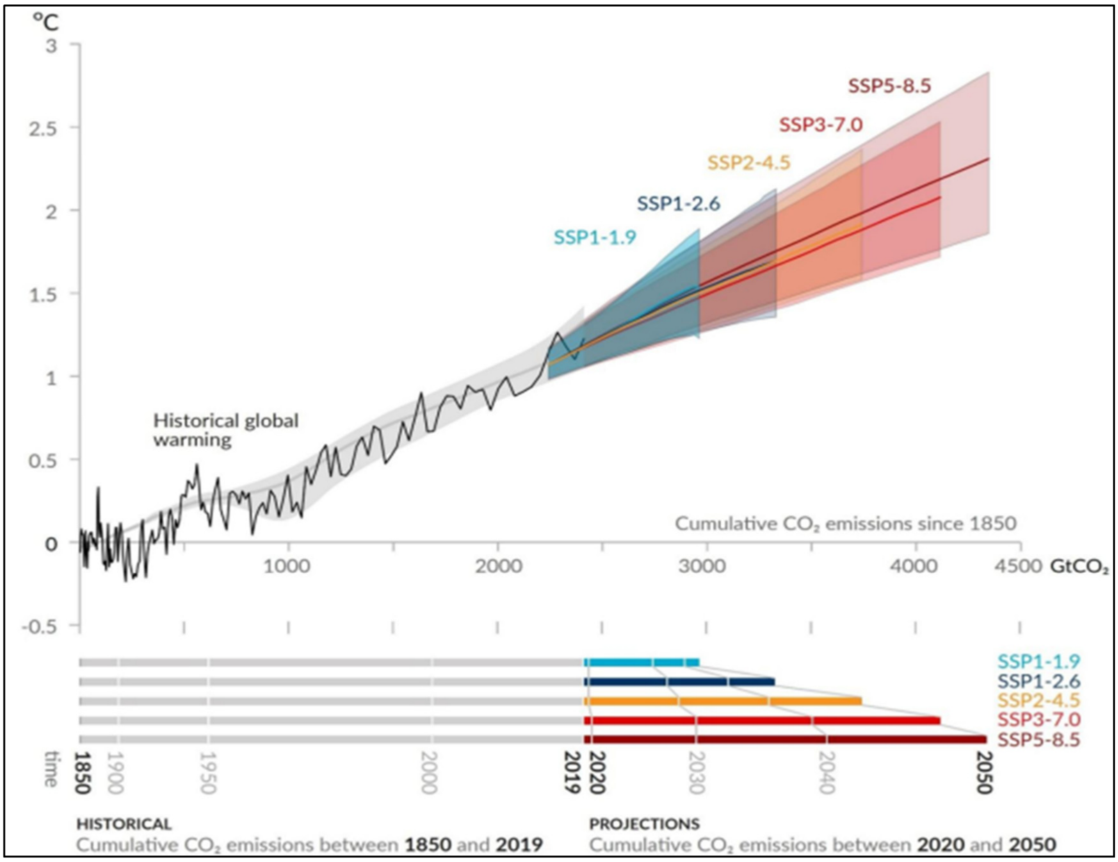


Figure 2.1 Shows that the global mean temperature has risen by 1.1°C, and the climate projection shows that it may further increase to 2°C by 2040 to 2060 (Source: IPCC).

Historical data on cumulative CO_2 emissions from 1850 to 2019 and model predictions on average temperature clearly show the warming trend. The projected CO_2 emission under various SSPs has been estimated and the model prediction indicated a linear warming trend until year 2050 (Figure 2.1). This indicates that nationally determined contributions through the Paris Agreement is insufficient to flatten the temperature curve.

Chapter 3

IPCC, CLIMATE CHANGE AND NORTHERN INDIAN OCEAN

3.1 IPCC and CMIP

The Intergovernmental Panel on Climate Change (IPCC) has warned that global temperatures could rise by more than 1.5°C above pre-industrial levels within the next few decades without significant and immediate reductions in greenhouse gas emissions. Such an increase would have catastrophic consequences, including more frequent heatwaves, severe droughts, loss of biodiversity, and widespread displacement of populations due to rising sea levels.

Coupled Model Intercomparison Project (CMIP6): The Coupled Model Intercomparison Project (CMIP) is a coordinated international effort to compare and evaluate climate models for simulating and projecting climate change. Initiated by the World Climate Research Programme (WCRP), CMIP facilitates the systematic intercomparison of various climate models from different research institutions worldwide. The results from CMIP contribute significantly to the assessments conducted by the Intergovernmental Panel on Climate Change (IPCC), shaping global climate policies and adaptation strategies.

The Paris Agreement, a landmark international accord adopted in 2015, seeks to limit global warming to well below 2°C, with efforts to limit the increase to 1.5°C. To achieve this, countries must transition toward low-carbon energy systems and drastically reduce their reliance on fossil fuels.

3.1.1 Shared Socio-economic Pathways

1. **SSP1-2.6 (Sustainability - Taking the green road)**

   In this scenario, the world gradually moves towards a more sustainable and inclusive path, focusing on protecting the environment. Global cooperation improves, and there are greater investments in education and health, leading to slower population growth. The focus shifts from purely economic growth to improving overall well-being. With a strong commitment to development goals, inequality decreases both within and between countries. Consumption is oriented towards low material growth and lower resource and energy intensity.

Climate impacts: Low levels of greenhouse gas emissions, leading to a peak and decline in radiative forcing at around 2.6 W/m² by the year 2100. This pathway is consistent with keeping global warming below 2°C compared to pre-industrial levels.

2. **SSP2-4.5 (Middle of the road)**

In this scenario, the world continues along a familiar path, with social, economic, and technological trends consistent with historical patterns. Some countries make good progress in development and income growth, while others struggle. Efforts to achieve sustainable development goals are slow and uneven. Environmental degradation persists despite some improvements, and resource and energy use intensity decreases. Global population growth is moderate and stabilizes in the second half of the century. Income inequality remains or improves only slightly, and reducing vulnerability to social and environmental changes remains a significant challenge.

Climate impacts: Intermediate levels of greenhouse gas emissions, leading to a stabilisation of radiative forcing at 4.5 W/m² by 2100. This scenario leads to moderate climate change impacts, with global warming likely to exceed 2°C but remain below 3°C by the end of the century.

3. **SSP3-7.0 (Regional rivalry - A rocky road)**

In this scenario, nationalism is rising, and concerns about competitiveness, security, and regional conflicts lead countries to focus more on their own issues. Over time, policies increasingly prioritize national and regional security. Countries aim for energy and food security within their regions, often neglecting broader development goals and decreasing investments in education and technology. Economic growth is slow, consumption is resource-heavy, and inequalities either persist or worsen. Population growth is low in industrialized countries but high in developing ones. Since environmental issues are given low priority internationally, some regions suffer severe environmental damage.

Climate impacts: High levels of greenhouse gas emissions, resulting in radiative forcing of 7.0 W/m² by 2100. This pathway results in severe climate impacts, with global warming potentially exceeding 3°C by the end of the century.

4. **SSP5-8.5 (Fossil-fuelled development - Taking the highway)**

In this scenario, there's a strong belief in competitive markets, innovation, and active societies as the key to sustainable development. Global markets have become more connected. Significant investments are made in health, education, and institutions to boost human and social capital. However, economic and social progress also relies on using abundant fossil fuels and adopting resource-heavy lifestyles. Significant economic growth and technological development exist, but with high inequality and environmental degradation. Local environmental issues like air pollution are managed successfully. There is confidence in handling social and ecological systems, even considering geo-engineering if needed.

Climate impacts: Very high levels of greenhouse gas emissions, leading to a radiative forcing of 8.5 W/m² by 2100. This pathway leads to extreme climate impacts, with global warming likely exceeding 4°C by the end of the century, posing severe risks to ecosystems and human societies.

The table provides an overview of the Shared Socio-economic Pathways outlined in the IPCC Sixth Assessment Report, detailing future scenarios based on socio-economic trends and policy choices.

Table 3.1: Projected global temperature increases under various Shared Socio-economic Pathways (SSPs) based on greenhouse gas (GHG) emission scenarios, as outlined in the IPCC Sixth Assessment Report.

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely range in °C (2081–2100)
SSP1-2.6	Low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7°C	1.8°C	1.3 – 2.4
SSP2-4.5	Intermediate GHG emissions: CO_2 emissions will be around current levels until 2050, then falling but not reaching net zero by 2100	2.0°C	2.7°C	2.1 – 3.5
SSP3-7.0	High GHG emissions: CO_2 emissions double by 2100	2.1°C	3.6°C	2.8 – 4.6
SSP5-8.5	Very high GHG emissions: CO_2 emissions triple by 2075	2.4°C	4.4°C	3.3 – 5.7

3.2 Climate change and the northern Indian Ocean

3.2.1 Near-surface air temperature

The historical near-surface air temperature in the Arabian Sea and Bay of Bengal has been relatively stable, with slight fluctuations from 25°C to 26°C in the North Arabian Sea, 26°C to 27°C in the South Arabian Sea, 26°C to 27°C in the North Bay of Bengal and 26°C to 27.5°C in the South Bay of Bengal, all showing an upward trend toward 2015. Future projections under different SSP scenarios indicate a significant increase in temperatures.

In the North Arabian Sea, under the SSP1-2.6 scenario, temperatures are projected to stay below 27°C by 2100, while SSP2-4.5 shows a rise to around 28°C, SSP3-7.0 projects an increase to approximately 29°C, and SSP5-8.5 sees temperatures potentially exceeding 29°C (Fig 3.1a). Similarly, in the South Arabian Sea, SSP1-2.6 keeps temperatures below 28°C, SSP2-4.5 reaches around 29°C, SSP3-7.0 pushes temperatures to about 30°C, and SSP5-8.5 shows a rise to 30°C by 2100 (Fig 3.1b). In the North Bay of Bengal, SSP1-2.6 projects temperatures below 28°C, SSP2-4.5 sees an increase to around 28.5°C, SSP3-7.0 suggests temperatures reaching 30°C, and SSP5-8.5 shows the most significant rise, with temperatures potentially exceeding 31°C by 2100 (Fig 3.1c). In the South Bay of Bengal, under the SSP1-2.6 scenario, temperatures are projected to stay below 28°C by 2100, while SSP2-4.5 shows a rise to around 29°C, SSP3-7.0 projects an increase to approximately 30°C, and SSP5-8.5 sees temperatures potentially exceeding 30.5°C (Fig 3.1d). The shaded areas in the projections represent the uncertainty range (^{10th} to ^{90th} quantiles), indicating variability in the potential outcomes in Figure (3.1).

\

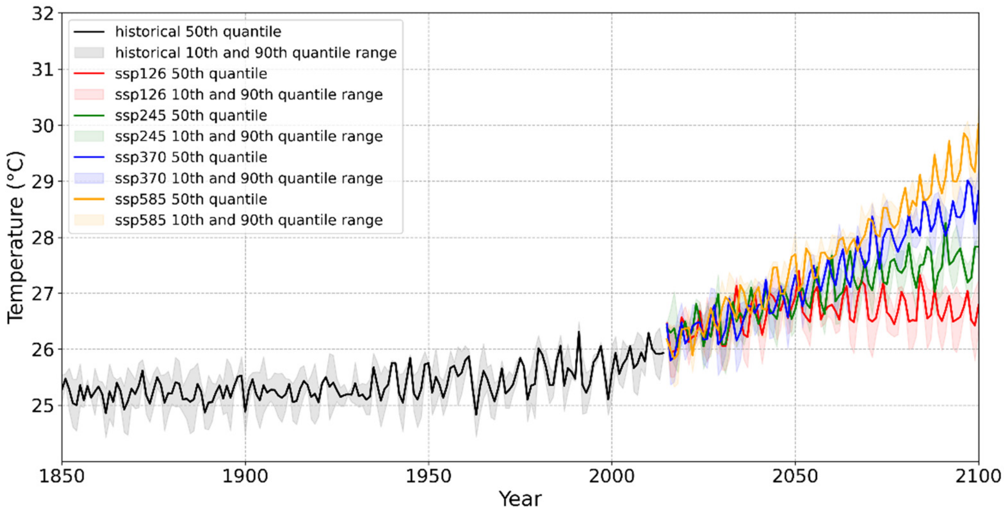


Figure 3.1a Near-surface air temperature - northern Arabian Sea

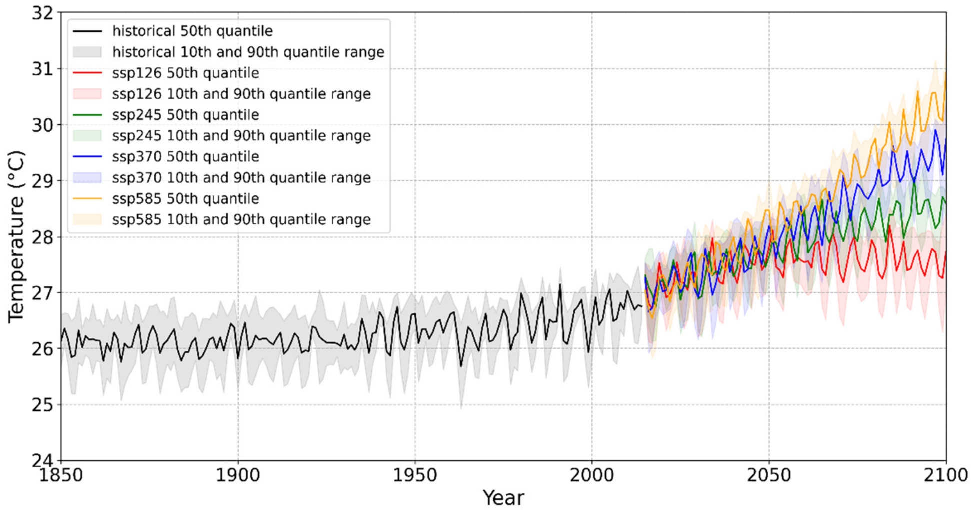


Figure 3.1b Near-surface air temperature- southern Arabian Sea

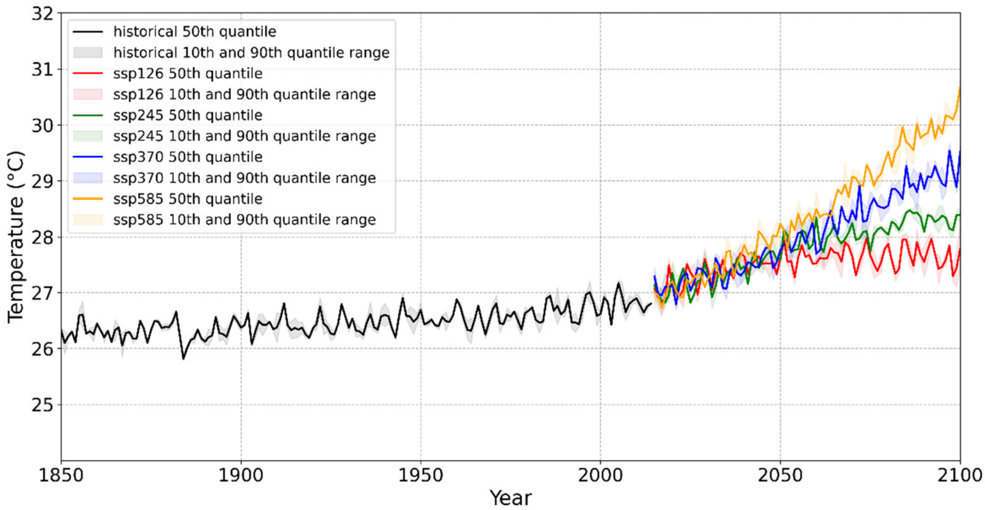


Figure 3.1c Near-surface air temperature- northern Bay of Bengal

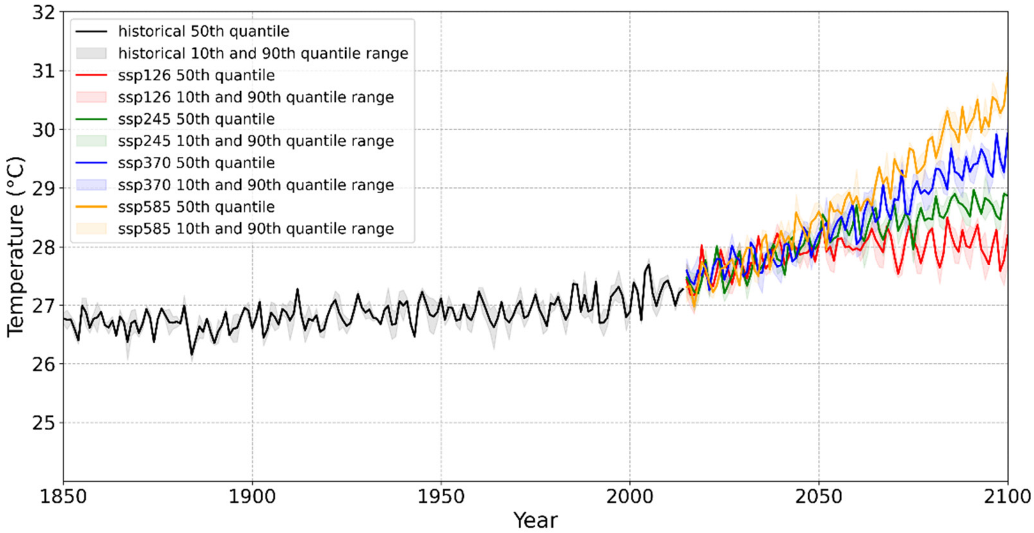


Figure 3.1d Near-surface air temperature- southern Bay of Bengal

3.2.2 Relative humidity

The historical relative humidity in the Arabian Sea and Bay of Bengal, from 1850 to 2014, remained relatively stable, fluctuating around 0.025 and showing a slight increase toward 2015. Future projections under different SSP scenarios from 2015 to 2100 indicate a noticeable rise in relative humidity, especially under the SSP3-7.0 and SSP5-8.5 scenarios, which show the highest increases.

In the North Arabian Sea, SSP1-2.6 projects a gradual rise to approximately 0.050% by 2100, SSP2-4.5 indicates a more pronounced increase to around 0.070%, SSP3-7.0 shows a significant rise to 0.120%, and SSP5-8.5 projects the highest increase, reaching 0.130% (Figure 3.2a). Similar trends are observed in the South Arabian Sea, where relative humidity under SSP1-2.6 increases to around 0.050%, SSP2-4.5 rises to 0.070%, SSP3-7.0 reaches 0.120%, and SSP5-8.5 approaches 0.125% (Figure 3.2b). In the North Bay of Bengal, SSP1-2.6 projects a rise to 0.050%, SSP2-4.5 to 0.070%, SSP3-7.0 to 0.120%, and SSP5-8.5 to 0.140% (Figure 3.2c). Likewise, in the South Bay of Bengal, SSP1-2.6 projects a rise to 0.050%, SSP2-4.5 to 0.070%, SSP3-7.0 to 0.120%, and SSP5-8.5 sees the highest increase to 0.135% (Figure 3.2d). The shaded areas around the projection lines represent uncertainty ranges (10^{th} to ^{90th} quantiles), reflecting the potential variability in these projections (Figure 3.2).

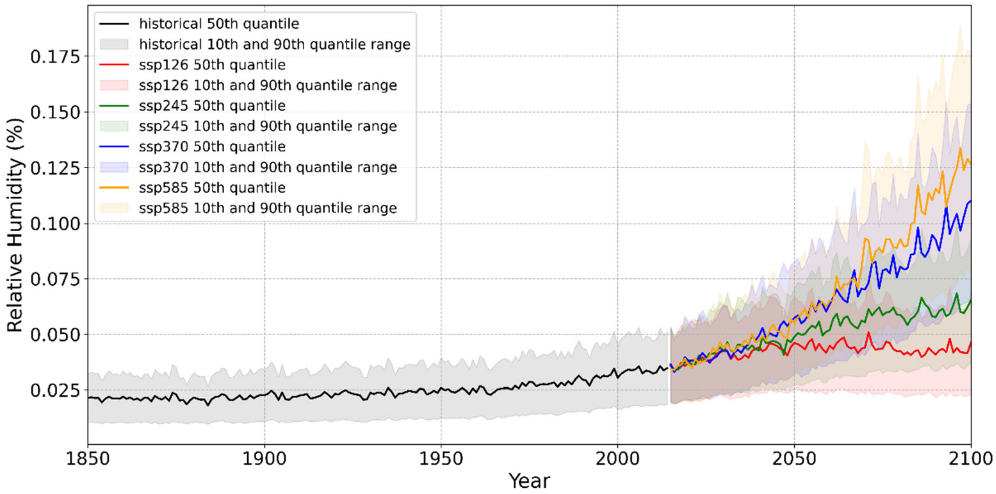


Figure 3.2a Relative humidity - northern Arabian Sea

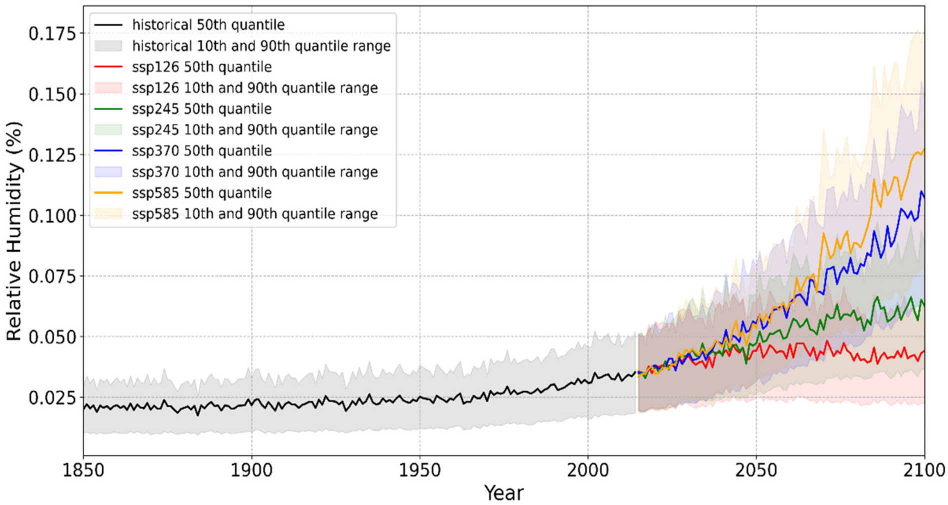


Figure 3.2b Relative humidity - southern Arabian Sea

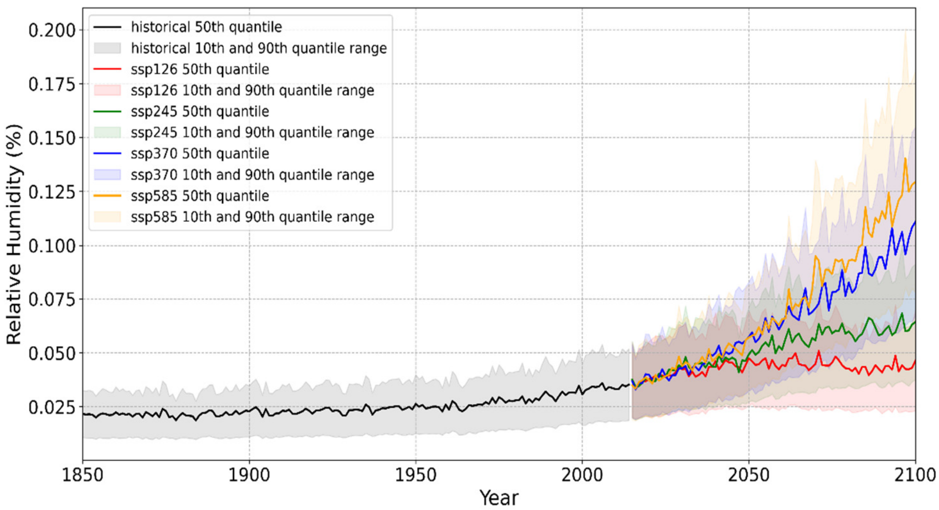


Figure 3.2c Relative humidity – northern Bay of Bengal

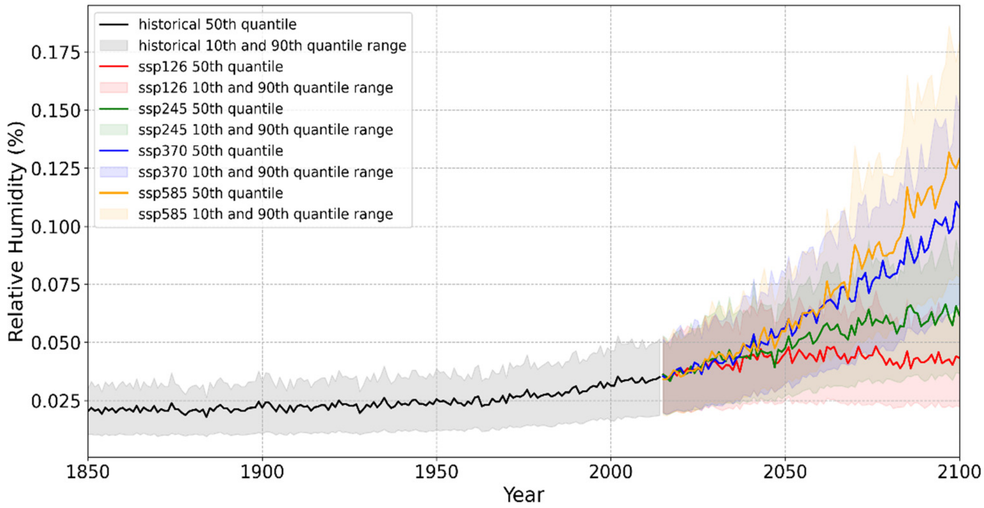


Figure 3.2d Relative humidity – southern Bay of Bengal

3.2.3 Sea surface temperature

The historical sea surface temperature in the Arabian Sea and Bay of Bengal from 1850 to 2014 remained relatively stable at around 25°C. Future projections from 2015 to 2100 under various SSP scenarios indicate a significant increase in sea surface temperature, particularly under SSP3-7.0 and SSP5-8.5, which show the highest increases.

In the North Arabian Sea, SSP1-2.6 projects a gradual rise to about 26°C by 2100, SSP2-4.5 shows a more pronounced increase to around 28°C, SSP3-7.0 projects temperatures reaching 28.5°C, and SSP5-8.5 indicates the highest rise, approaching 29°C by 2100 (Figure 3.3a). In the South Arabian Sea, SSP1-2.6 projects an increase to 28°C, SSP2-4.5 to 29°C, and SSP3-7.0 to 30°C. SSP5-8.5 indicates an error with sea surface temperatures incorrectly stated as 210°C, which likely meant a rise approaching 31°C by 2100 (Figure 3.3b). In the North Bay of Bengal, SSP1-2.6 shows temperatures reaching about 28°C, SSP2-4.5 projects an increase to around 28.5°C, SSP3-7.0 to 29.5°C, and SSP5-8.5 to 30.5°C by 2100 (Figure 3.3c). Similarly, in the South Bay of Bengal, SSP1-2.6 projects temperatures to rise to about 28°C, SSP2-4.5 shows a rise to 28.5°C, SSP3-7.0 projects an increase to around 30°C, and SSP5-8.5 indicates the highest rise, approaching 31°C by 2100 (Figure 3.3d). These projections are accompanied by uncertainty ranges, indicating the variability in future outcomes across different emissions pathways (Figure 3.3).

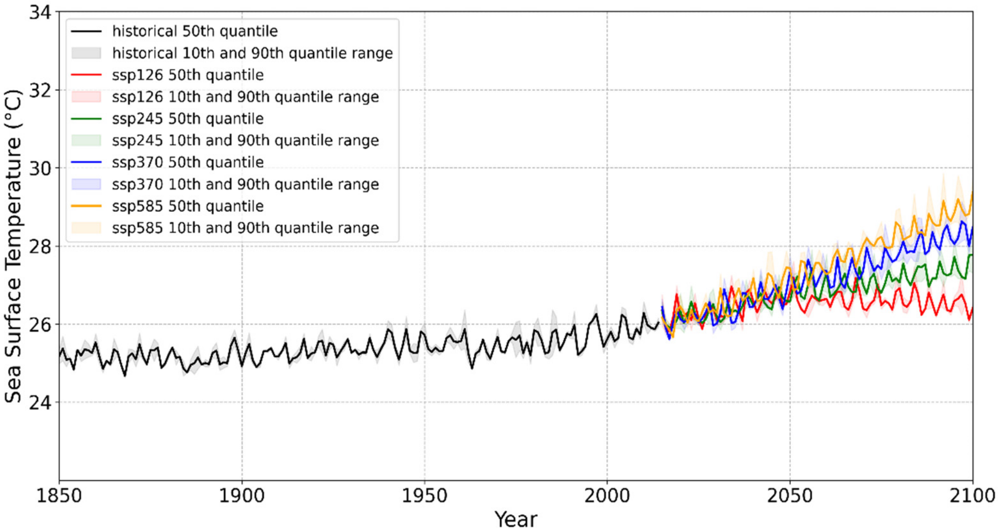


Figure 3.3a Sea Surface Temperature - northern Arabian Sea

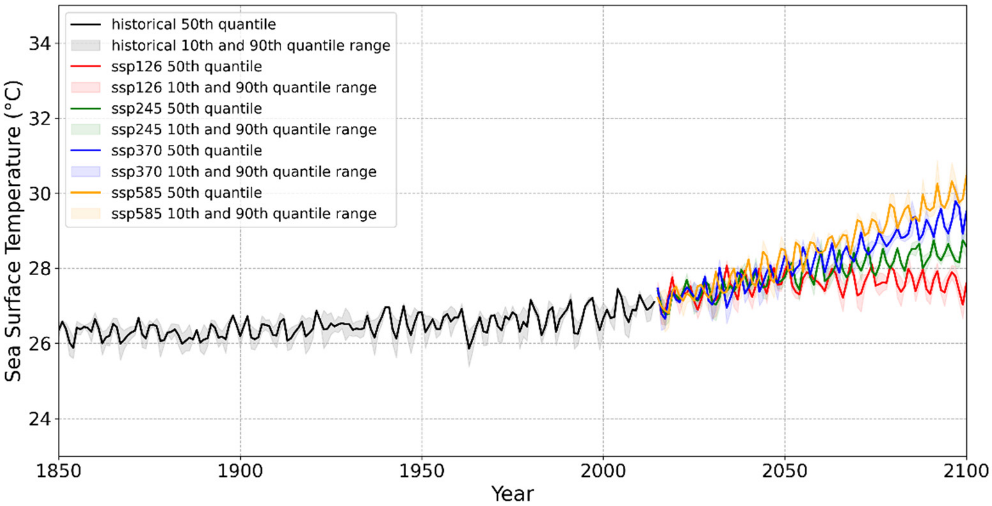


Figure 3.3b Sea Surface Temperature - southern Arabian Sea

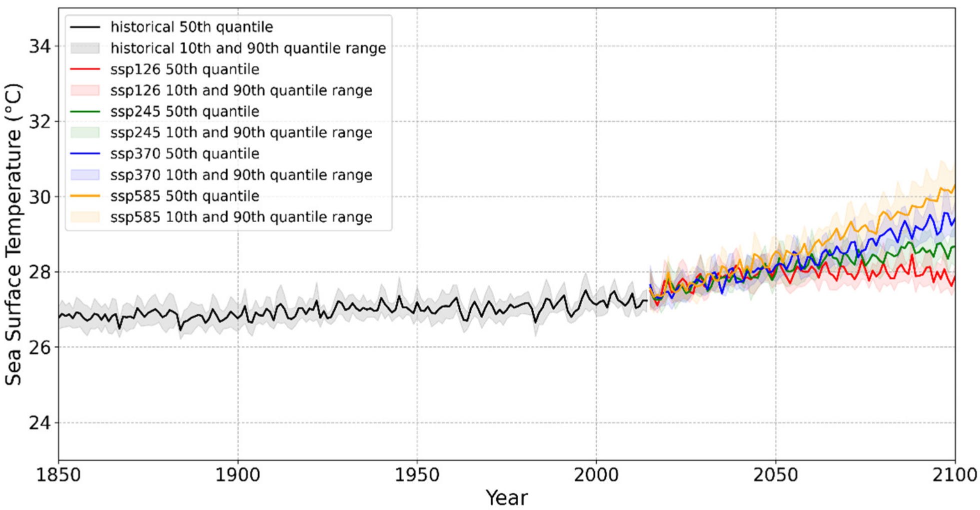


Figure 3.3c Sea Surface Temperature – northern Bay of Bengal

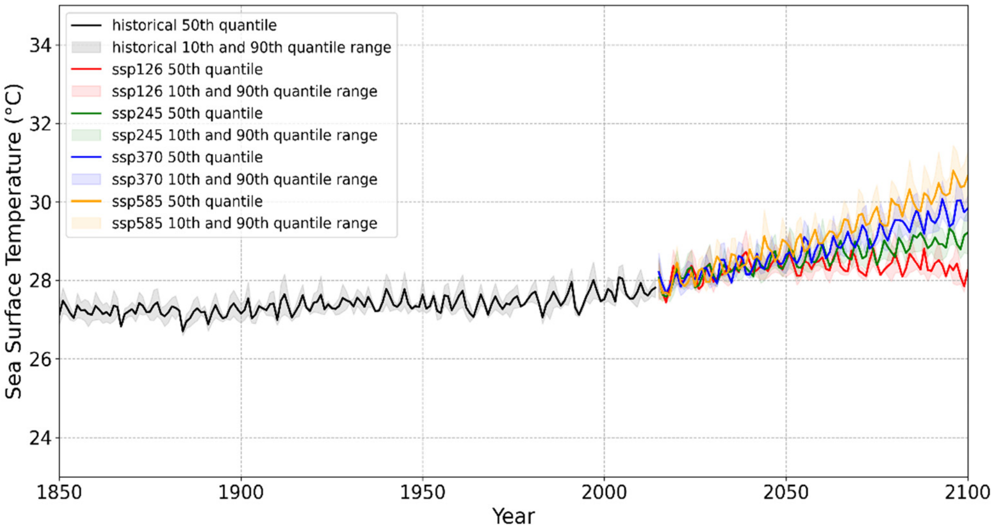


Figure 3.3d Sea Surface Temperature – southern Bay of Bengal

3.2.4 Sea level pressure

Historical data on sea level pressure from 1850 to 2014, along with future projections under various SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) from 2015 to 2100, indicate that sea level pressure remains relatively stable, with minor fluctuations.

In the North and South Arabian Sea regions, sea level pressure is projected to stay within the range of 1.007×10^5 Pa to 1.009×10^5 Pa across all scenarios (Figure 3.4a & 3.4b). Similarly, in the North and South Bay of Bengal regions, sea level pressure remains stable, ranging from 1.008×10^5 Pa to 1.010×10^5 Pa (Figure 3.4c & 3.4d). The uncertainty range (^{10th} to ^{90th} quantiles), represented by the shaded areas around the projection lines, reflects the potential variability in these projections, but the overall trend remains consistent and stable across both historical and future periods (Figure 3.4).

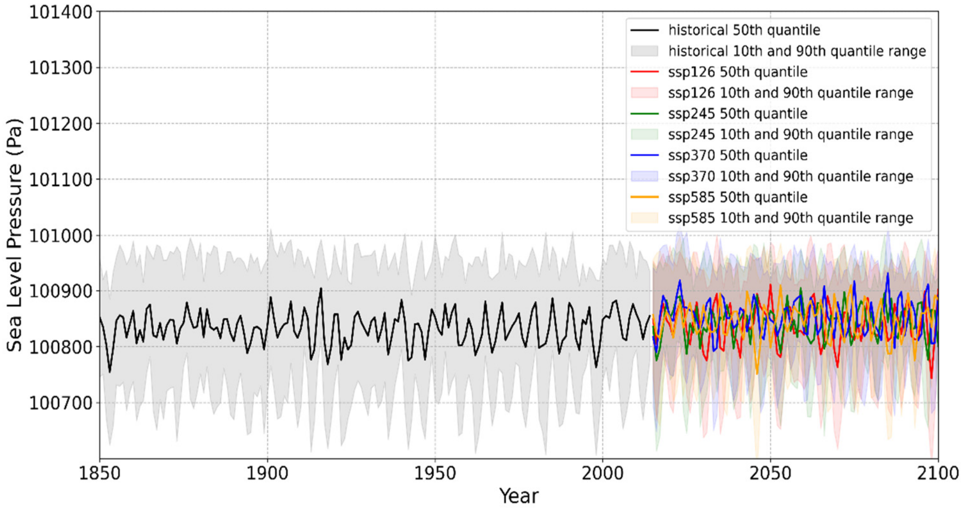


Figure 3.4a Sea level pressure – northern Arabian Sea

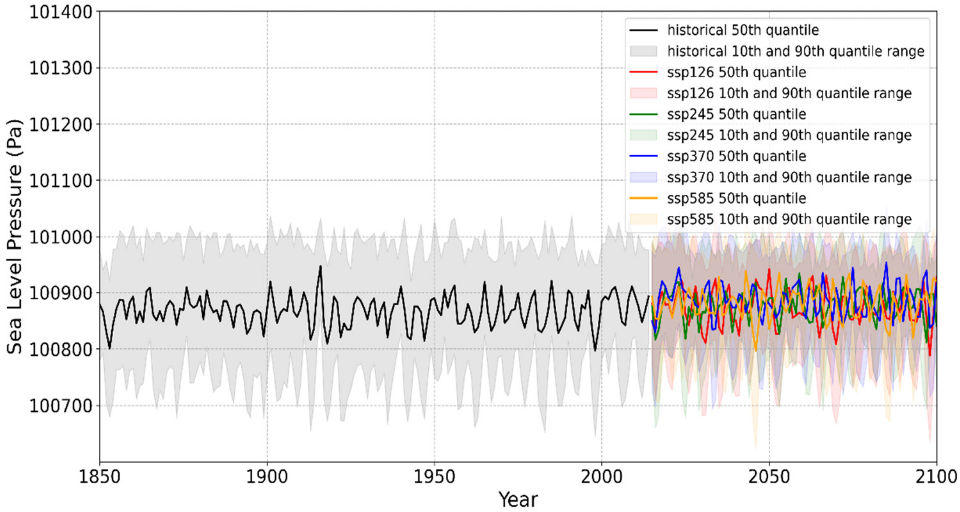


Figure 3.4b Sea level pressure – southern Arabian Sea

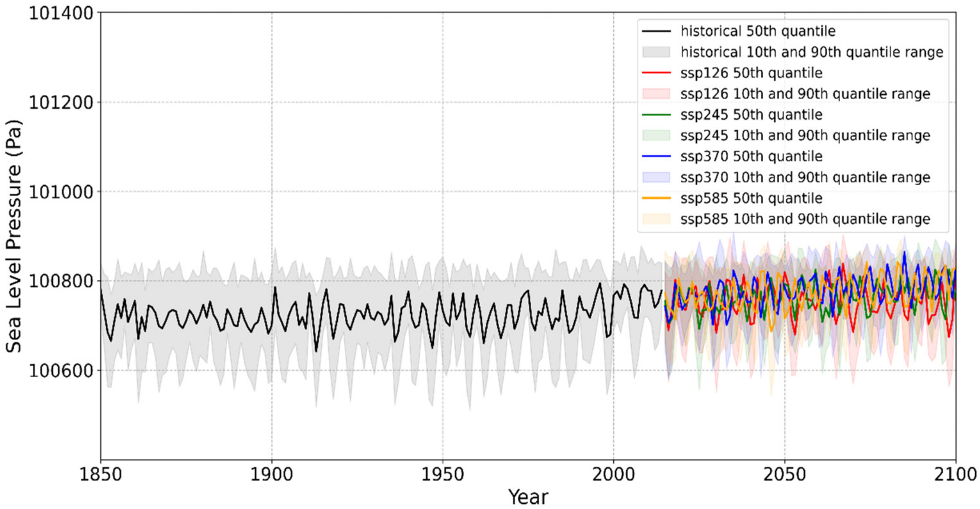


Figure 3.4c Sea level pressure – northern Bay of Bengal

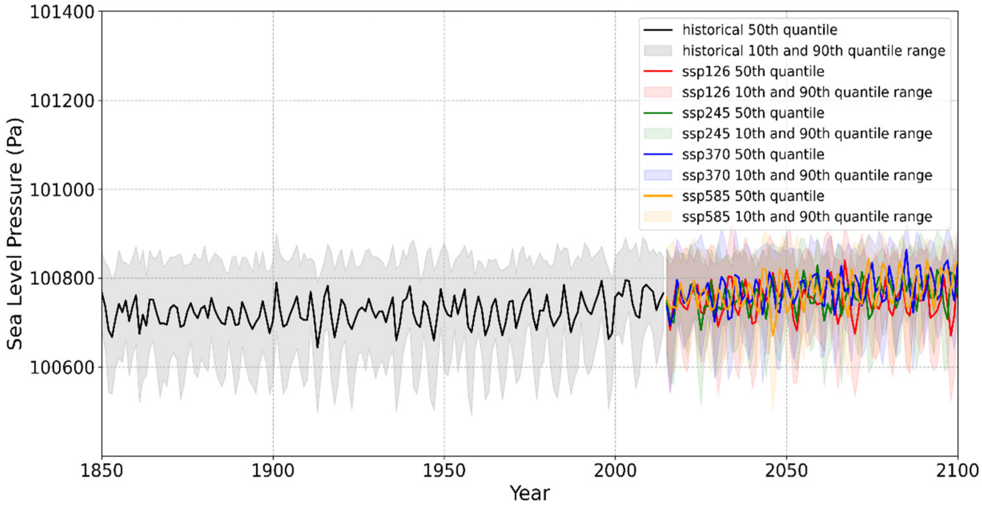


Figure 3.4d Sea level pressure – southern Bay of Bengal

3.2.5 Sea surface salinity

The historical and projected sea surface salinity (SSS) for the Arabian Sea and Bay of Bengal from 1850 to 2100 indicates relatively stable future projections, with a slight decreasing trend, particularly under the SSP3-7.0 and SSP5-8.5 scenarios. Salinity values in the North Arabian Sea fluctuate between 36 psu and 37 psu, showing a minor decline towards 2100 (Figure 3.5a). Similarly, salinity in the South Arabian Sea fluctuates between 36 psu and 36.5 psu, with a slight downward trend by 2100 (Figure 3.5b). In the North Bay of Bengal, salinity values range between 32 psu and 33.5 psu (Figure 3.5c). At the same time, in the South Bay of Bengal, they fluctuate between 33.5 psu and 34.5 psu (Figure 3.5d), both regions showing stable conditions with minimal changes projected toward the end of the century (Figure 3.5).

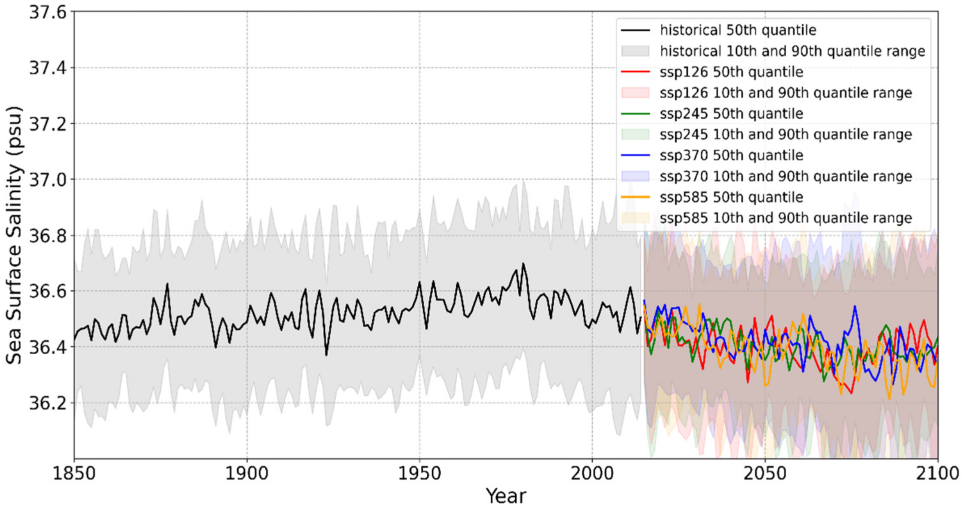


Figure 3.5a Sea surface salinity – northern Arabian Sea

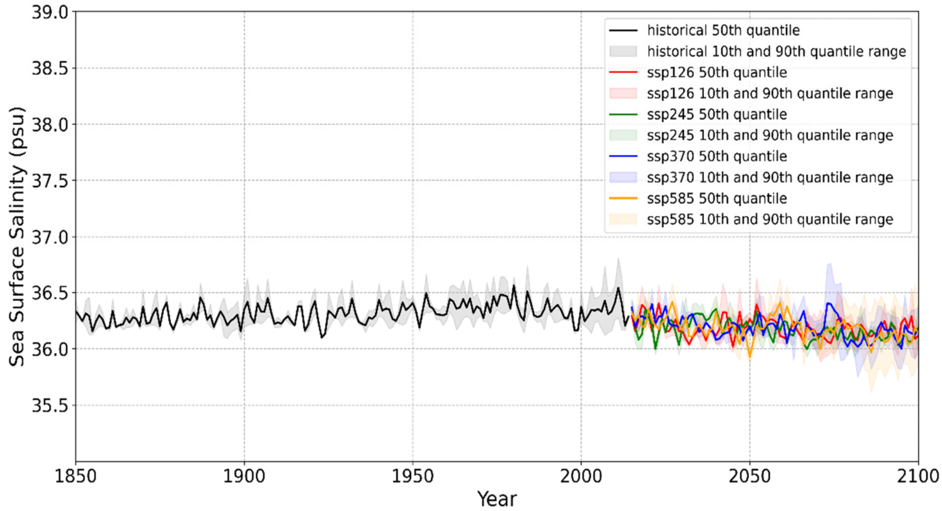


Figure 3.5b Sea surface salinity – southern Arabian Sea

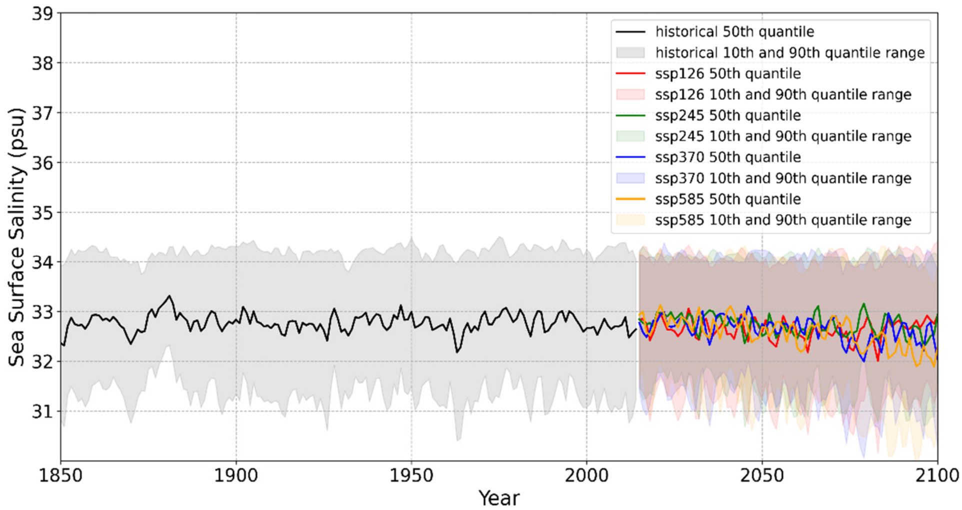


Figure 3.5c Sea surface salinity – northern Bay of Bengal

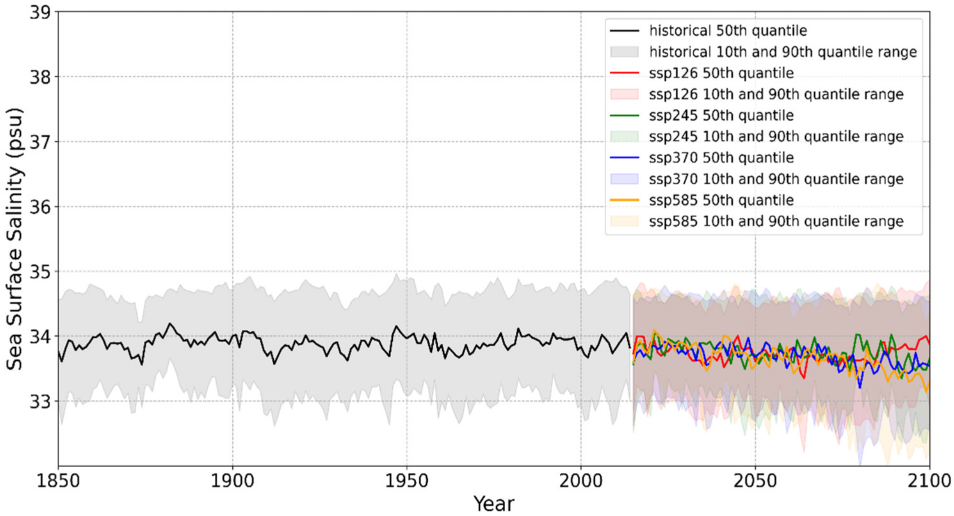


Figure 3.5d Sea surface salinity – southern Bay of Bengal

3.2.6 Precipitation

Historical data from 1850 to 2014 and future projections from various SSP scenarios (2015–2100) highlight increasing variability in precipitation across the Arabian Sea and the Bay of Bengal.

In all SSP scenarios, median precipitation values in the Arabian Sea show a slight upward trend over time, with higher emissions scenarios such as SSP3-7.0 and SSP5-8.5 exhibiting more pronounced increases and variability. By 2100, SSP5-8.5 shows the highest levels and variability in precipitation, underscoring the significant impact of higher emissions on precipitation patterns. In the North Arabian Sea, precipitation fluctuates between 0.00002 kg m^{-2} s^{-1} and 0.00004 kg m^{-2} s^{-1} (Figure 3.6a), while in the South Arabian Sea, it ranges from 0.00002 kg m^{-2} s^{-1} to 0.00005 kg m^{-2} s^{-1} (Figure 3.6b). In the North and South Bay of Bengal, precipitation fluctuates between 0.00004 kg m^{-2} s^{-1} and 0.00008 kg m^{-2} s^{-1}, indicating similar trends of increasing variability under future climate projections (Figure 3.6c & 3.6d).

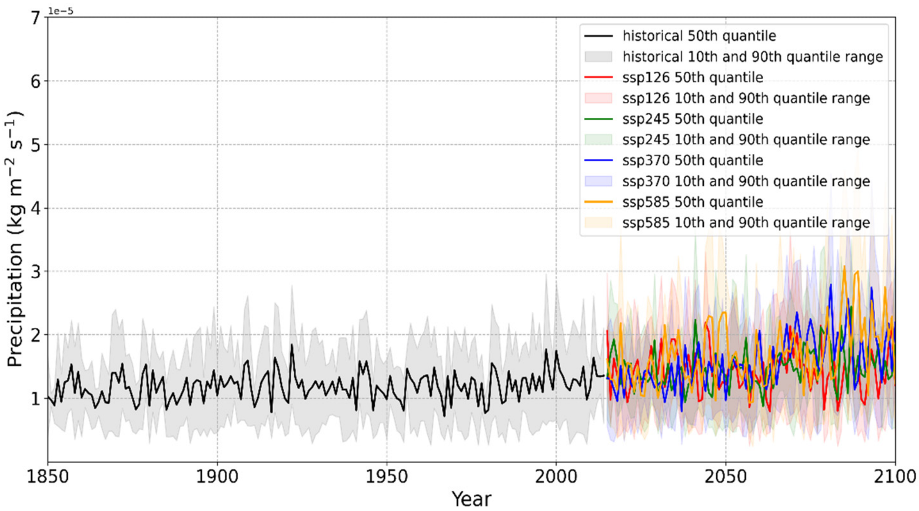


Figure 3.6a Precipitation – northern Arabian Sea

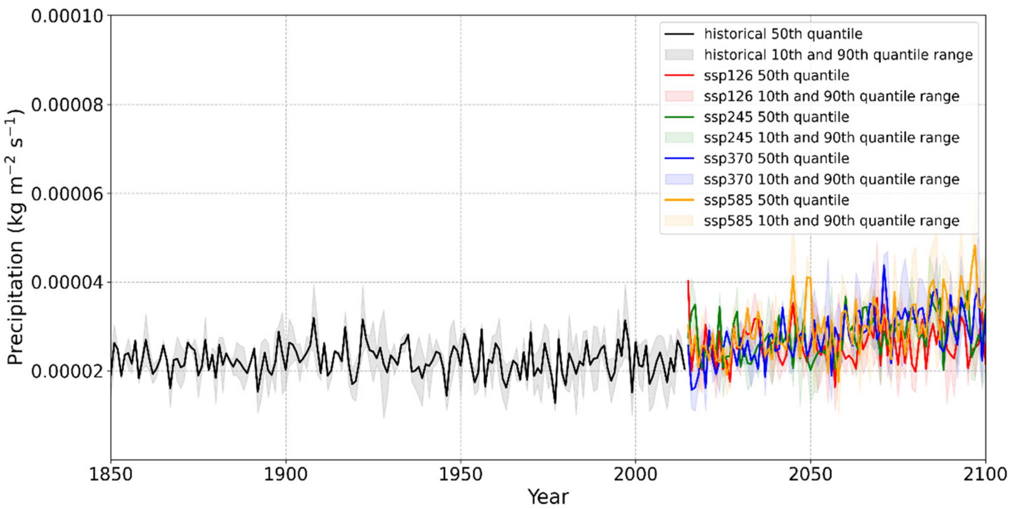


Figure 3.6b Precipitation – southern Arabian Sea

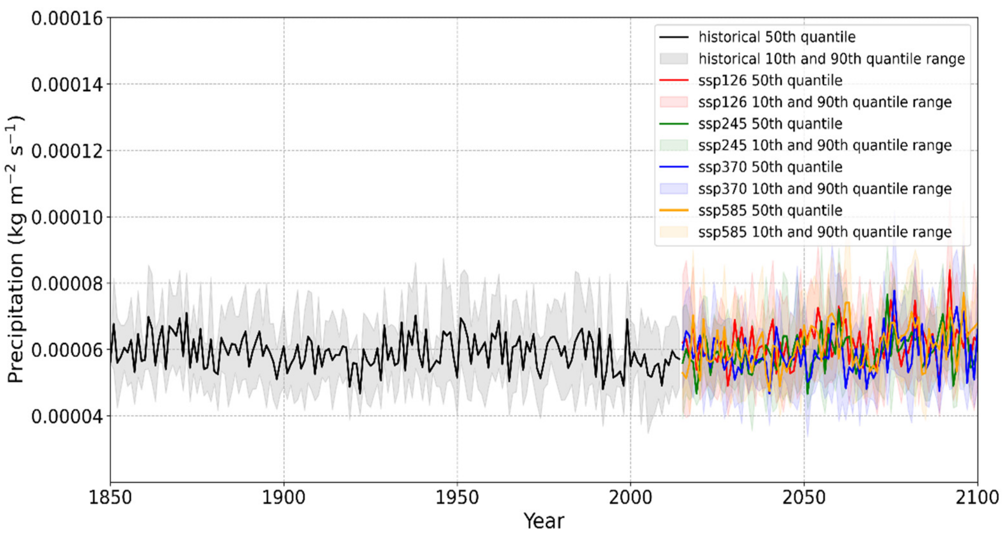


Figure 3.6c Precipitation – northern Bay of Bengal

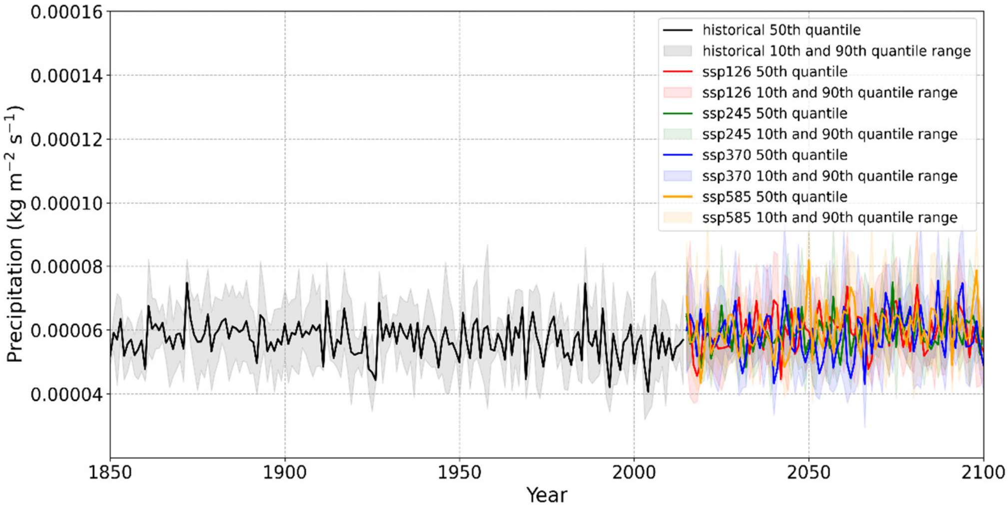


Figure 3.6d Precipitation – southern Bay of Bengal

3.2.7 Total cloud cover percentage

Historical data on total cloud cover percentage from 1850 to 2014 and future projections under various SSP scenarios (2015–2100) indicate stable conditions with minimal fluctuations. The total cloud cover percentage remains relatively steady across all SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5).

In the North Arabian Sea, future projections show cloud cover fluctuating between 35% and 45% (Figure 3.7a), while in the South Arabian Sea, it ranges between 45% and 55% (Figure 3.7b). Similarly, in the North Bay of Bengal, total cloud cover is projected to remain within 45% to 55% (Figure 3.7c), and in the South Bay of Bengal, it is expected to fluctuate between 60% and 80% (Figure 3.7d). These projections highlight minimal variability in cloud cover despite different emission scenarios (Figure 3.7).

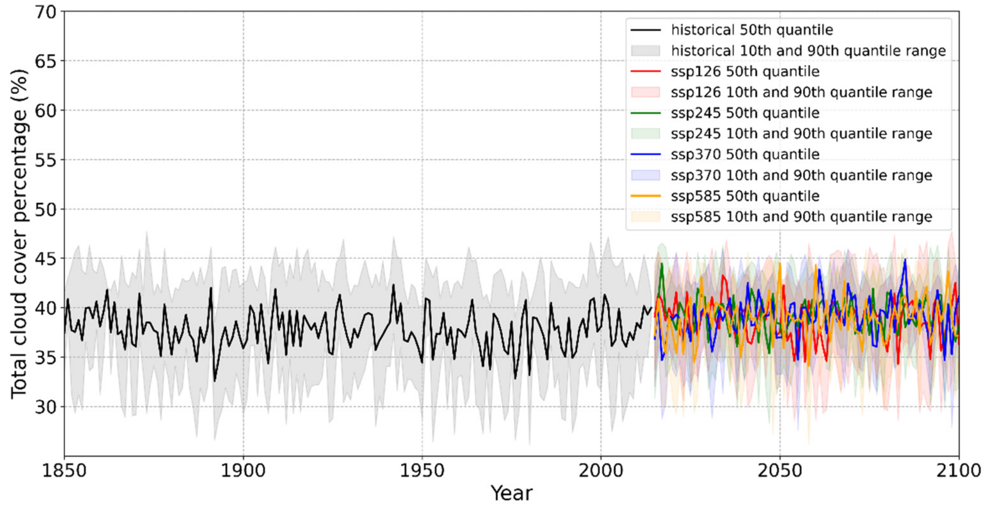


Figure 3.7a Total cloud cover percentage – northern Arabian Sea

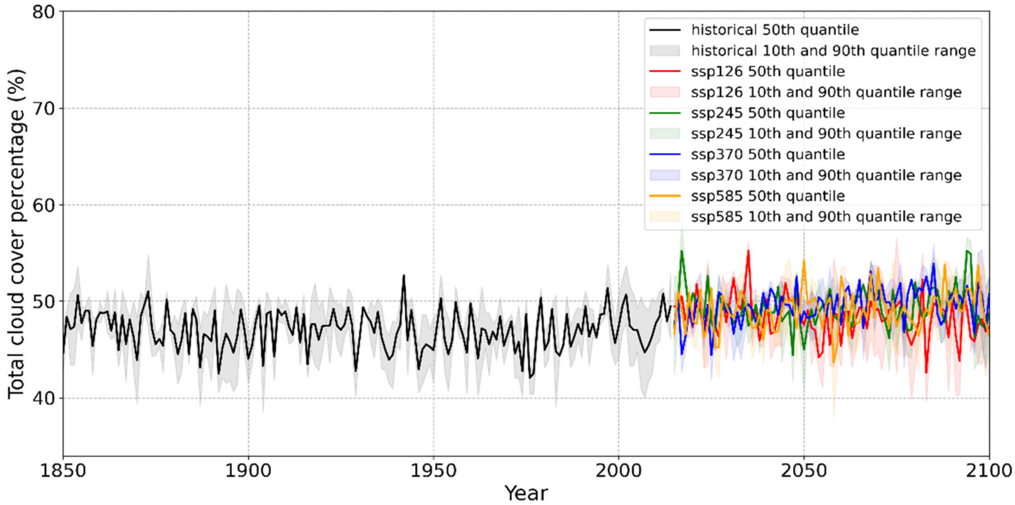


Figure 3.7b Total cloud cover percentage – southern Arabian Sea

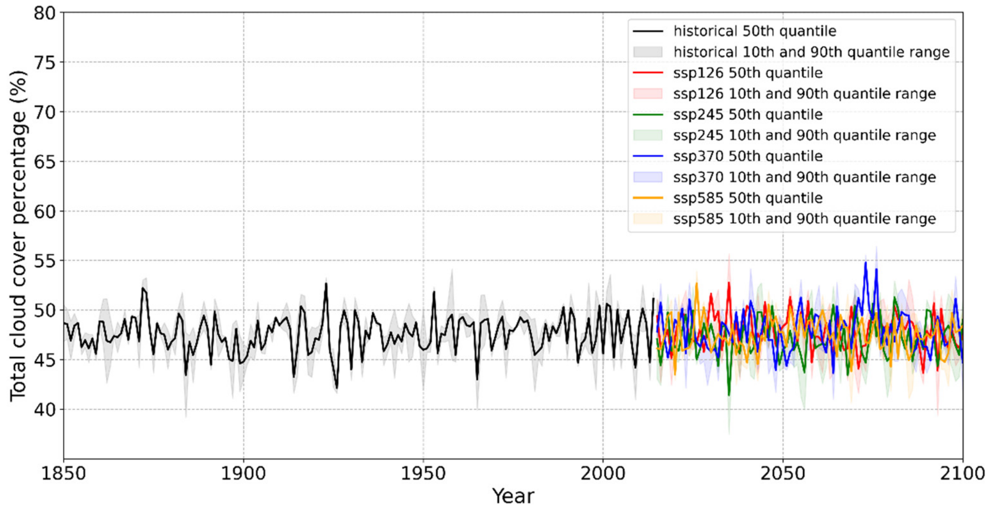


Figure 3.7c Total cloud cover percentage – northern Bay of Bengal

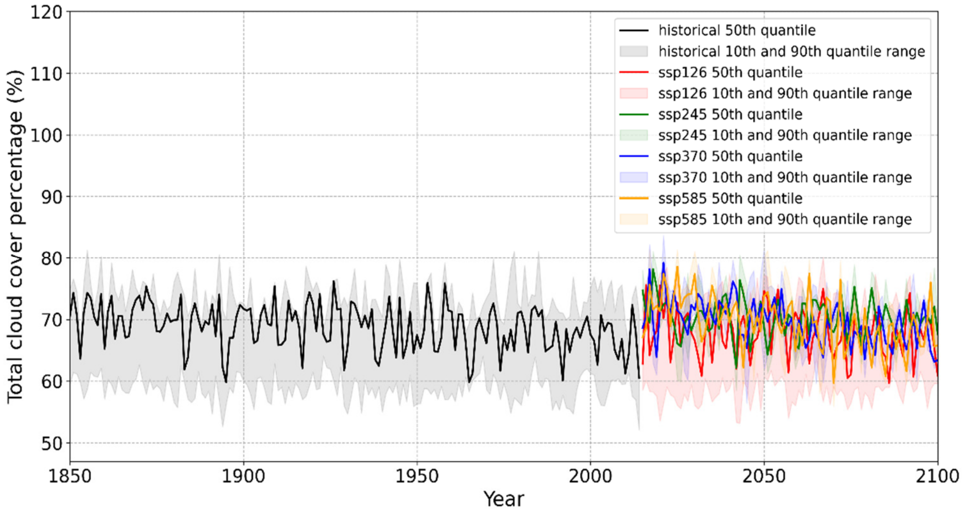


Figure 3.7d Total cloud cover percentage – southern Bay of Bengal

3.2.8 Near-surface wind

Historical data of near-surface wind from 1850 to 2014 and future projections under various SSP scenarios from 2015 to 2100 indicate relatively stable wind speeds with slight fluctuations.

In the North Arabian Sea, historical wind speeds range between 6 m/s and 7 m/s, while future projections show a slight decrease, particularly in the SSP3-7.0 and SSP5-8.5 scenarios, where wind speeds are expected to range between 5 m/s and 7 m/s (Figure 3.8a). The South Arabian Sea shows a more stable trend during the historical period, with wind speeds around 6.5 m/s, but future projections indicate a decline, with speeds ranging from 5 m/s to 6 m/s by 2100 (Figure 3.8b). All SSP scenarios suggest a stable future in the North Bay of Bengal, with wind speeds between 4.5 m/s and 5.5 m/s (Figure 3.8c). Similarly, wind speeds in the South Bay of Bengal fluctuate between 5 m/s and 6 m/s, with minimal variability throughout the projections (Figure 3.8d).

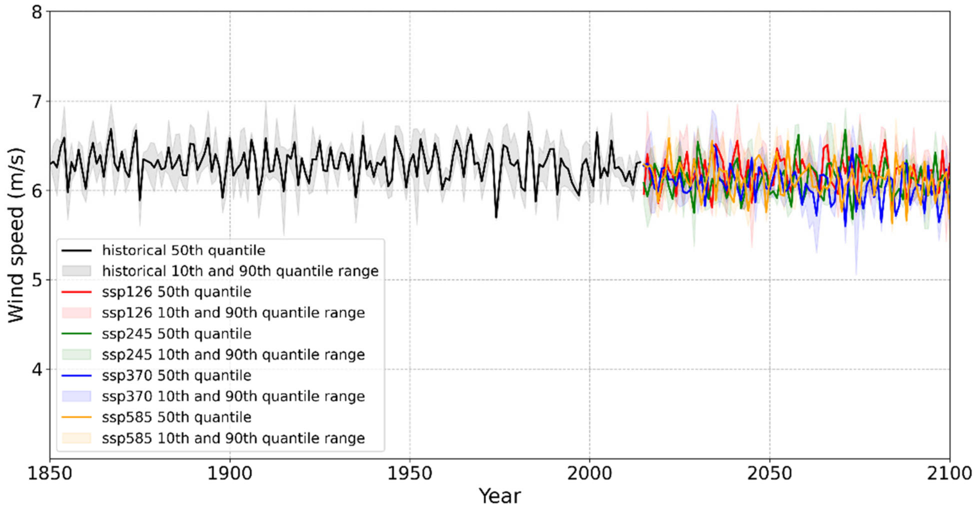


Figure 3.8a Near-surface wind – northern Arabian Sea

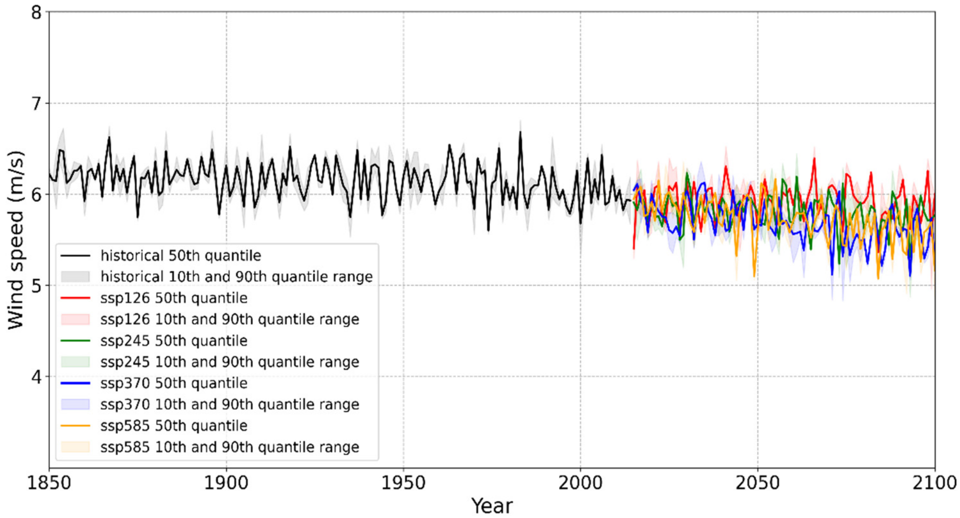


Figure 3.8b Near-surface wind – southern Arabian Sea

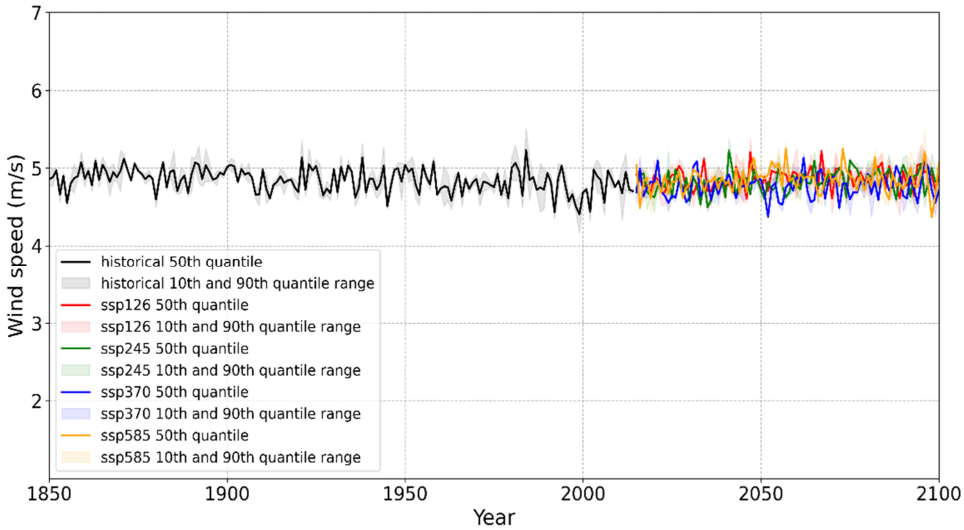


Figure 3.8c Near-surface wind – northern Bay of Bengal

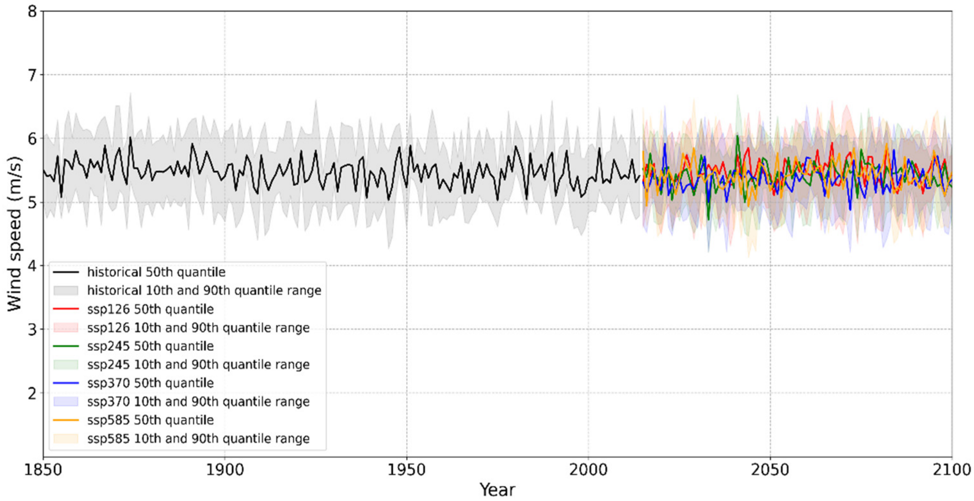


Figure 3.8d Near-surface wind – southern Bay of Bengal

CHAPTER 4

PRESENT ENVIRONMENTAL CONDITIONS IN THE SEDIMENTARY BASINS IN THE INDIAN EEZ

4.1 Baseline data of all major sedimentary basins, within the EEZ of India

4.1.1 Gulf of Kutch

The Kutch basin, located in the northwestern part of India's western continental margin, lies at the southern edge of the indus shelf. Spanning latitudes 22° 30' to 24° 30' N and longitudes 68° 00’ to 72° 00’ E, the basin covers about 71,000 sq. km, with 43,000 sq. km on land and 28,000 sq. km offshore. It features up to 4,500 m of mesozoic and tertiary sediments, thickening towards the southwest. The Kutch basin is adjacent to Pakistan's south indus basin, where oil and gas fields have been discovered. The gulf of Kutch, within the basin, has a depth ranging from 20 m at its head to over 60 m in outer regions, though navigation is challenged by shoals that require periodic dredging.

4.1.1.1 Meteorological Conditions in the gulf of Kutch

The meteorological and oceanographic data for the gulf of Kutch show distinct seasonal variations, mainly driven by the monsoon season. Air temperatures range from 20.24 °C in January to a peak of 30.70 °C in June, reflecting the onset of the hot season. Correspondingly, sea surface temperatures also rise, with a maximum of 29.52°C in June. Wind speeds gradually increase from 1.96 m/s in October to a maximum of 6.19 m/s in July, coinciding with the monsoon months when relative humidity is also at its highest (81.61% in August). This period is marked by the most intense wave activity, with maximum wave heights of 3.81m and significant swell heights of 1.80 m in July. The mean wave period also peaks in July at 8.41 seconds, suggesting the presence of long-period, high-energy waves. Atmospheric pressures are highest in winter (101021.22 Pa in January) and lowest during the monsoon (99545.56 Pa in July), indicating the typical pressure drops associated with monsoon systems. Overall, the gulf of Kutch experiences calm conditions in winter, with lower wind speeds, wave heights, and humidity, while the monsoon season brings more dynamic conditions, with stronger winds, higher waves, and elevated sea surface temperatures.

Table 4.1 Meteorological parameters in the Gulf of Kutch

Gulf of Kutch	Air Temp (^{0}C)	Wind speed (m/s)	Surface air pressure (Pa)	Sea surface temp (^{0} C)	Relative Humidity (%)	Mean Sea Level Pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height (m)	Significant height of total swell (m)
Jan	20.24	2.70	101021.22	22.29	44.16	101560.55	296.94	5.47	1.08	0.42
Feb	22.55	2.30	100856.99	22.50	46.16	101393.39	278.42	5.62	1.13	0.48
Mar	26.21	3.08	100616.24	24.33	51.21	101148.53	263.09	5.66	1.28	0.57
April	29.07	4.26	100326.23	26.82	60.03	100855.14	251.17	5.83	1.59	0.70
May	30.59	5.62	100026.30	28.71	68.43	100553.10	239.92	6.16	2.24	0.93
June	30.70	5.66	99607.96	29.52	72.77	100132.90	228.16	8.03	3.26	1.54
July	28.98	6.19	99545.56	28.83	79.64	100071.76	229.89	8.41	3.81	1.80
Aug	27.99	5.56	99747.62	27.87	81.61	100275.63	230.45	7.82	3.21	1.53
Sep	28.26	3.90	100099.21	28.15	76.76	100628.62	231.61	7.03	2.14	1.02
Oct	28.57	1.96	100501.07	28.33	58.47	101030.76	231.86	6.84	1.35	0.65
Nov	25.56	2.22	100805.66	26.83	44.71	101338.70	226.19	6.66	1.07	0.48
Dec	21.71	2.90	101003.86	24.25	42.93	101541.46	199.63	5.92	1.07	0.41
Min	20.24	1.96	99545.56	22.29	42.93	100071.76	199.64	5.47	1.07	0.41
Max	30.70	6.19	101021.22	29.52	81.61	101560.55	296.94	8.41	3.81	1.80

4.1.1.2 Cyclones in the Gulf of Kutch

Cyclone VAYU, originating in the Arabian Sea on 10th June 2019 at 11.7° N, 71.0° E, progressed northward along the western coast of India, eventually reaching 22.5° N, 67.8° E near Gujarat on 17th June 2020. Initially classified as a Depression (D), the system intensified, peaking as a Very Severe Cyclonic Storm (VSCS) on 11th June 2019 with wind speeds of 65 knots and a central pressure of 980 hPa before gradually weakening into a Depression (D) by 17th June 2020. The cyclone's transverse velocity varied, with maximum speeds recorded at 18.60 km/h. During its lifecycle, Cyclone VAYU impacted several key sedimentary basins, including the Kutch, Mumbai Offshore, Kerala-Konkan-Lakshadweep, and Saurashtra basins, bringing strong winds, rough seas, and heavy rainfall to these regions.

Table 4.2 Cyclone events that impacted the Gulf of Kutch (1980–2020)

Serial Number of system during year	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (degrees)	Longitude (degrees)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)[or "delta P"]	Grade (text)	Distance (in degree)	Kilometers(km)	Time interval (Hour)	Transverse velocity (km/hr)
1	AS		10/06/2019	0000	11.7	71.0	1.5	998	25	3	D				
1	AS		10/06/2019	0600	12.5	70.9	2.0	997	30	4	DD	0.81	89.95	6	14.99
1	AS		10/06/2019	1800	13.9	70.6	2.5	995	35	6	CS	1.43	159.75	12	13.31
1	AS		11/06/2019	1200	16.1	70.6	3.5	986	55	15	SCS	2.2	245.46	18	13.64
1	AS	V	11/06/2019	1800	17.1	70.6	4.0	980	65	21	VSCS	1	111.57	6	18.60
1	AS	A	16/06/2019	0000	20.7	65.5	3.5	983	60	18	SCS	6.24	696.51	114	6.11
1	AS	Y	16/06/2019	1500	21.2	65.5	3.0	990	45	10	CS	0.5	55.79	15	3.72
1	AS	U	17/06/2020	0300	21.8	66.8	2.0	996	30	5	DD	1.43	159.75	12	13.31
1	AS		17/06/2020	0900	22.2	67.4	1.5	998	25	4	D	0.72	80.46	6	13.41
1	AS		17/06/2020	1200	22.5	67.8	1.5	998	20	3	D	0.5	55.79	3	18.60
1	AS		17/06/2020	1800			Weakened into a well-marked low-pressure area over the northeast Arabian Sea and adjoining areas of Saurashtra & KUTCh								

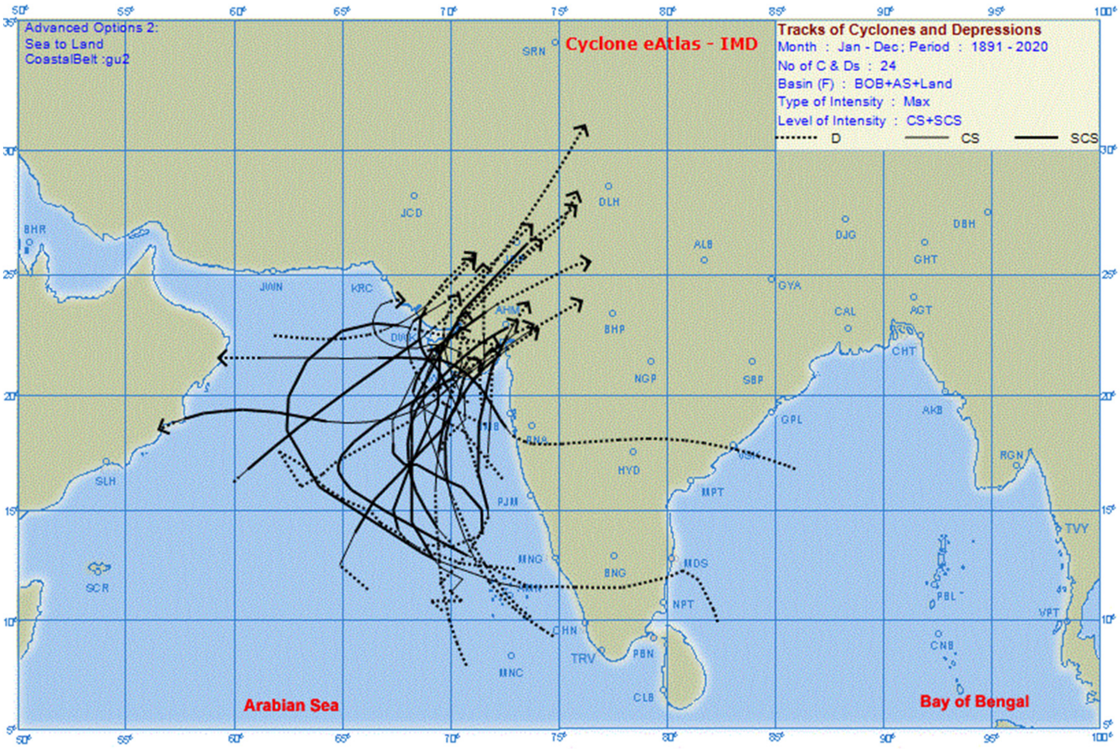


Figure 4.1 Cyclonic/severe cyclonic storms formed/ dissipated over the Gulf of Kutch basin

4.1.2 Saurashtra basin

The Saurashtra basin, located in the northern part of India's western continental margin, trends NNW-SSE and includes the Saurashtra peninsula. It lies between the commercially proven Mumbai offshore to the south and the highly prospective Kutch basin to the north, with the Cambay basin to the east. Offshore, the basin's shelf extends less than the average western offshore, with a shelf break at 200m depth. The region’s topography gently slopes towards the sea, and the soluble limestone creates a coarse landscape with various geomorphic features, including sand bars, mudflats, mangroves, and oyster beds along the coast. The limestone strata in the region are 30-45 m thick.

4.1.2.1 Meteorological conditions in the Saurashtra basin

The climatology data shows the seasonal variations in the Saurashtra basin's meteorological conditions, with the hottest and most humid conditions occurring during the monsoon months (June-August). The average air temperature ranges from a low of 21.41°C in January to a high of 30.32°C in May. The region experiences cooler and drier conditions during winter (December- February). Wind speeds are higher during the monsoon season, reflecting the weather systems and strong pressure gradients associated with this period. Wind speeds are highest in July (6.53 m/s) and lowest in October (1.85 m/s). The sea surface temperature ranges from 24.00°C in January to 29.45°C in June. The temperatures reflect seasonal heating and cooling, with the warmest sea temperatures during the pre-monsoon period. Relative humidity is lowest in November (49.37%) and highest in August (82.21%), indicating the strong influence of the monsoon season, which brings in moist air and increases humidity levels. The surface air pressure is highest in January (101078.63 Pa) and lowest in July (99745.07 Pa). The mean sea level pressure follows a similar trend to surface air pressure, with the highest value recorded in January (101501.46 Pa) and the lowest in July (100158.50 Pa). The mean wave direction shifts between 257° and 157° throughout the year, indicating a gradual shift in prevailing wind or wave generation areas. The highest wave direction is around 273°, likely around mid-year, and the lowest is 157°, occurring at the end of the year. The maximum wave height ranges from 1.34 m to 4.65 m, with the highest values in the middle of the year, likely corresponding to the monsoon season. Significant swell heights range from 0.53 m to 2.12 m, with an evident rise during the monsoon season, reflecting long-period waves generated by distant storms or strong local winds.

Table 4.3 Meteorological parameters in Saurashtra basin

Saurashtra basin	Air Temp (^{0}C)	Wind speed (m/s)	Surface air pressure (Pa)	Sea surface temp (^{0}C)	Relative Humidity (%)	Mean Sea Level Pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height (m)	Significant height of the total swell (m)
Jan	21.41	3.20	101078.63	24.00	47.73	101501.46	257.06	5.94	1.38	0.53
Feb	23.15	2.71	100936.43	24.05	47.79	101357.05	273.83	6.19	1.34	0.57
Mar	26.25	3.03	100712.59	25.33	51.26	101129.90	256.47	6.42	1.44	0.64
April	28.85	3.84	00447.94	27.26	60.38	100862.64	243.54	6.65	1.72	0.78
May	30.32	5.05	100180.18	28.85	68.75	100593.46	235.66	6.86	2.37	1.06
June	30.22	5.51	99787.89	29.45	74.43	100200.15	228.88	8.32	3.89	1.84
July	28.58	6.53	99745.07	28.62	80.64	100158.50	233.12	8.47	4.65	2.12
Aug	27.70	5.86	99934.82	27.73	82.21	100349.60	233.05	7.99	3.89	1.80
Sep	28.01	3.73	100246.09	28.24	77.78	100661.81	228.87	7.60	2.47	1.19
Oct	28.46	1.85	100604.22	28.75	61.12	101019.96	215.37	7.71	1.60	0.78
Nov	26.01	2.58	100877.77	27.58	49.37	101296.04	189.87	7.20	1.37	0.62
Dec	22.87	3.28	101058.52	25.50	47.84	101480.11	157.98	6.38	1.39	0.55
Min	21.41	6.53	99745.07	24.00	47.73	100158.50	157.98	5.94	1.34	0.53
Max	30.32	1.85	101078.63	29.45	82.21	101501.46	273.8	8.47	4.65	2.12

4.1.2.2 Cyclones in the Saurashtra basin

Between 1980 and 2020, the Saurashtra basin experienced 10 cyclonic and severe cyclonic storms, including 2 Severe Cyclonic Storms (SCS), 1 Cyclonic Storm (CS), 3 Deep Depressions (DD), and 4 Depressions (D). These storms had an average transverse velocity of 4.578 m/s, with the highest recorded at 8.268 m/s during an SCS on 9th November, 1982, and the lowest at 2.435 m/s as a Depression on 12th June, 2011. Notable storms include the SCS of November 1982, which intensified to 65 kt and significantly impacted the Saurashtra and Kutch basins, and the June 1998 cyclone, which peaked at 90 kt with a central pressure of 960 hPa before crossing near Porbandar. Several other storms, such as those in 1989, 1996, and 2009, also affected the region, demonstrating the recurring vulnerability of the Saurashtra basin to cyclonic systems, especially during the pre-monsoon and post-monsoon seasons.

Table 4.4 Cyclone events that impacted the Saurashtra basin

Serial Number of the system	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (degrees)	Longitude (degrees)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)[or "delta P"]	Grade (text)	Distance(in degree)	Kilometers(km)	Time interval (Hour)	Transverse velocity (km/hr)
1			04/11/1982	1200	11.5	66.0	1.5	999	25	3	D	0	0		
1			05/11/1982	0000	11.7	65.7	2.0	997	30	5	DD	0.36	40.23	12	3.35
1			05/11/1982	0300	12.5	65.0	2.5	995	35	7	CS	1.06	118.60	3	39.53
1			06/11/1982	0300	14.0	65.5	3.5	986	55	16	SCS	1.58	176.41	24	7.35
1			07/11/1982	1200	16.5	67.5	4.0	980	65	22	VSCS	3.20	357.21	33	10.82
1	AS		08/11/1982	1200	20.5	70.5	5.0	962	90	40	ESCS	5	557.87	24	23.24
1			08/11/1982	Crossed Gujarat coast close to the east of between 1100 & 1200 UTC of 8th Nov									0		
1			09/11/1982	0000	22.5	73.0		990	50	12	SCS	3.20	357.21	12	29.77
1			10/11/1982	0300	23.0	73.5		995	35	7	CS	0.71	78.89	3	26.30
1			11/11/1982	1200	23.5	75.0		999	25	3	D	1.58	176.41	33	5.35
1			10/11/1982	0300	Weakened into a WML over southwest Madhya Pradesh							0	0		
													0		
2			06/10/1985	0300	19.5	71.5	1.5		25	3	D	0	0		
2	System crossed the Saurashtra coast near Mahuva in the early hours of 07.10.1985											0	0		
2	AS		09/10/1985	0300	24.0	77.0	-		25	3	D	7.11	792.88	72	11.01
2			10/10/1985	1200	Weakened into the low-pressure area over NW MP							0	0		
2			11/10/1985	0300	20.0	69.5	1.5		25	3	D	8.5	948.38	15	63.23
2		System crossed the Saurashtra coast from east of Veraval around 1800 UTC on 9th										0	0		
3			09/06/1989	0300	20.0	69.5	1.5		25	3	D	0	0		
3	AS		System crossed the Saurashtra coast from east of Veraval around 1800 UTC on 9th									0	0		
3			10/06/1989	0300	21.9	70.6	2.0		30	4	DD	2.20	244.96	24	10.21
3			10/06/1989	1200	22.5	67	1.5		25	3	D	3.65	407.21	9	45.25
3	System weakened rapidly over the northwest Arabian Sea in the midnight of 12th											0	0		
													0		
4			17/06/1996	0900	17.5	69.5	1.5	990	25	3	D	0	0		
4			17/06/1996	1800	18.0	69.5	2.0	986	30	5	DD	0.5	55.79	9	6.20
4			18/06/1996	0900	19.5	70.5	2.5	982	35	8	CS	1.80	201.14	15	13.41
4	AS		18/06/1996	1800	20.5	70.5	3.5	976	55	15	SCS	1	111.57	9	12.40
4			The system crossed the Gujarat coast close to Diu around 2300 UTC									0	0		
4			19/06/1997	0300	21.5	71.5	-	-	45	10	CS	1.41	157.79	9	17.53
4			19/06/1997	1800	23.0	71.5	-	-	30	6	DD	1.5	167.36	15	11.16
4			20/06/1996	0000	23.5	71.5	-	-	25	4	D	0.5	55.79	6	9.30
4				1200		WML						0	0		
													0		
5			04/06/1998	0600	10.5	69.5	1.5	1004	25	4	D	0	0		
5			04/06/1998	1200	11.0	69.0	2.0	1004	30	6	DD	0.71	78.90	6	13.15
5	AS		05/06/1998	0900	12.5	70.0	2.5	998	35	8	CS	1.8	201.14	21	9.58
5			06/06/1998	0600	12.5	69.0	3.5	989	55	15	SCS	1	111.57	21	5.31
5			07/06/1998	0900	15.5	68.0	4.0	979	65	21	VSCS	3.16	352.83	27	13.07
5			08/06/1998	0600	18.5	68.0	5.0	970	90	40	ESCS	3	334.72	21	15.94
5			08/06/1998	1800	20.5	68.5	5.0	960	80	40	VSCS	2.06	230.02	12	19.17

5			09/06/1998	CROSSED COAST NEAR PORBANDAR BETWEEN 01 AND 02 UTC.								0	0		
5			09/06/1998	1200	23.5	70.5	-	988	50	12	SCS	3.61	402.29	18	22.35
5			09/06/1998	1800	24.5	71.5	-	992	40	8	CS	1.41	157.79	6	26.30
5			10/06/1998	0000	26.0	73.0	-	994	30	6	DD	2.12	236.68	6	39.45
5			10/06/1998	0900	27.5	75.0	-	998	25	3	D	2.5	278.94	9	30.99
													0		
6			11/10/1998	1200	14.0	67.5	1.5	1002	25	4	D		0	0	
6			12/10/1998	0900	14.5	66.5	2.0	998	30	6	DD	1.12	124.74	21	5.94
6			13/10/1998	1200	16.0	64.0	1.5	998	25	6	D	2.92	325.29	27	12.05
6	AS		15/10/1998	1200	16.5	64.0	2.0	994	30	6	DD	0.5	55.79	48	1.16
6			16/10/1998	1200	19.0	68.0	2.5	996	35	8	CS	4.72	526.29	24	21.93
6			17/10/1998	The system crossed Gujarat coast near Veraval (42909) between 0100 and 0200 UTC.									0		
6			18/10/1998	0300	22.5	73.0		overland			DD	6.1	680.97	39	17.46
													0		
7			23/06/2009	0000	18.0	71.5	1.5	998	25	4.0	D	0	0		
7	The system crossed the Gujarat coast near Diu between 1300 & 1400 UTC of 23 June.											0	0		
7	AS		24/06/2009	0000	21.5	70.5	-	998	25	4.0	D	3.64	406.13	24	16.92
7		The system weakened into a well-marked low-pressure area over Saurashtra &										0	0		
7		Kutch and the neighbourhood at 0300 UTC of 24th june.										0	0		
													0		
8		--	6/11/2011	1200	20.0	71.5	1.5	996	25	4	D	0	0	0	
8	AS	--	The system crossed the Saurashtra (Gujarat) coast near lat. 20.8°N/71.2°E around 2200 UTC of 11th june, 2011									0	0		
8			6/12/2011	0600	21.0	70.5	--	996	20	3	D	1.41	157.79	18	8.77
8		--	The system weakened into a well marked low pressure area over Saurashtra and adjoining northeast Arabian Sea									0	0		
													0		
9			28.10.2012	1200	9.5	85.0	1.5	1003	25	3	D	0	0		
9			29.10.2012	0000	9.5	84.0	2.0	1000	30	4	DD	1	111.57	12	9.30
9			30.10.2012	0300	9.0	82.0	2.5	998	35	6	CS	2.06	230.02	27	8.52
9	BoB	NILAM	The system crossed north Tamilnadu coast near Mahabalipuram, south of Chennai (near latitude 12.50 °N and longitude 80.20 °E) between 1600 and 1700 hrs IST									0	0		
9			31.10.2012	1800	13.0	78.5	--	998	30	5	DD	5.32	593.02	39	15.21
9			01.11.2012	0000	13.0	77.5	--	999	20	4	D	1	111.57	6	18.60
9			02.11.2012	0000	Weakened into a well marked low pressure area over Rayalaseema and neighbourhood							0	0		
													0		
10			6/22/2015	0300	20.0	67.0	1.5	990	25	4	D	0	0		
10			6/23/2015	0300	20.5	70.5	2.0	988	30	6	DD	3.54	394.47	24	16.44
10	AS		6/23/2015	The system crossed south Gujarat coast near Diu between 0900 -1000 UTC								0	0		
10			6/24/2015	1200	23.5	74.0	-	992	25	3	D	4.61	514.33	33	15.59
10			6/25/2015	0000	The system weakened into a well-marked low pressure area over northwest Madhya Pradesh and neighbourhood								0		

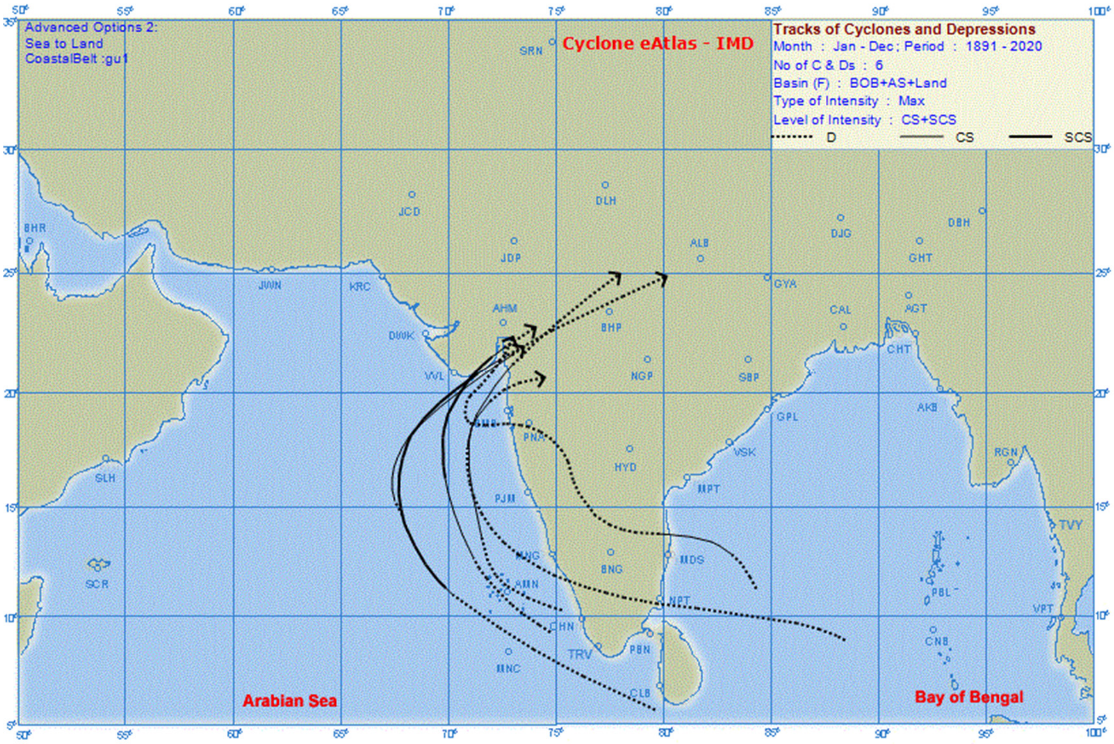


Figure 4.2 Cyclonic/severe cyclonic storms were formed/ dissipated over Saurashtra basin

4.1.3 Mumbai offshore

The Mumbai offshore basin, located on India's western continental shelf, lies between the Saurashtra basin to the northwest and the Kerala-Konkan basin to the south. The basin is divided into five structural provinces: the Surat depression (Tapti-Daman block) in the north, the Panna-Bassein-Heera block in the east-central part, Ratnagiri in the south, Mumbai high/ Platform-Deep Continental Shelf (DCS) in the mid-west, and the shelf margin adjoining DCS and Ratnagiri shelf. The basin contains both clastic and carbonate reservoir facies across various Tertiary sections from the paleocene to the middle miocene.

4.1.3.1 Meteorological conditions at Mumbai offshore

Air and sea surface temperatures rise from winter through spring, peaking just before the May and June monsoons. The air temperature ranges from a low of 22.16°C in January to a high of 28.76°C in May. The sea surface temperature varies from 25.21°C in February to 29.64°C in June. The region experiences its strongest winds, highest humidity levels during the monsoon months (June-August), and lower surface air pressure. Wind speeds are generally low, with the highest average of 4.65 m/s in July and the lowest at 0.91 m/s in October. Relative humidity is lowest in February (50.75%) and highest in July and August (~ 89%), coinciding with the peak of the monsoon season when moisture levels are highest. The post-monsoon period (October-December) sees a return to calmer winds, lower temperatures, and increased air pressure. Surface air pressure gradually decreases from January (97983.69 Pa) to July (97127.13 Pa) and then increases towards December. Mean sea level pressure follows a similar trend to surface air pressure, with the highest value in January (101385.28 Pa) and the lowest in July (100499.66 Pa). Wave directions range from 228° to 312°, with most waves coming from the southwest to west during the year. The mean wave period increases from 5.80 s in January to a peak of 8.56 s, likely during the monsoon months, indicating stronger and more energetic waves. Maximum wave heights vary from 1.26 m in calmer months to a peak of 4.41 m during the monsoon. Swell heights follow a similar pattern, ranging from 0.55 m to a peak of 2.16 m during monsoon months.

Table 4.5 Meteorological parameters at Mumbai offshore

Mumbai Offshore	Air Temp (^{0}C)	Wind speed (m/s)	Surface air pressure (Pa)	Sea surface temp(^{0} C)	Relative Humidity (%)	Mean Sea Level Pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height(m)	Significant height of total swell (m)
Jan	22.16	1.69	97983.69	25.24	54.05	101385.28	312.32	5.80	1.36	0.55
Feb	23.51	1.67	97893.52	25.21	50.75	101283.38	293.52	5.88	1.32	0.57
Mar	26.18	1.68	97740.19	26.54	51.74	101110.11	273.45	6.17	1.40	0.65
April	28.09	2.00	97571.86	28.34	61.09	100929.80	259.20	6.54	1.60	0.78
May	28.76	2.86	97408.35	29.60	70.24	100766.95	248.95	7.00	2.07	1.03
June	27.09	3.69	97129.78	29.64	83.37	100493.43	239.55	8.42	3.66	1.82
July	25.51	4.65	97127.13	28.40	89.66	100499.66	245.11	8.56	4.41	2.16
Aug	25.12	4.14	97261.43	27.74	89.48	100640.64	245.35	8.08	3.73	1.83
Sep	25.58	2.12	97451.51	28.34	86.03	100833.63	240.31	7.58	2.35	1.18
Oct	26.33	0.91	97681.84	28.77	69.12	101059.26	228.94	7.57	1.48	0.74
Nov	24.99	1.71	97865.59	27.78	55.86	101253.15	242.10	7.04	1.26	0.59
Dec	22.97	1.83	97985.13	26.52	53.62	101384.75	295.89	6.35	1.28	0.55
Min	22.16	0.91	97127.13	25.21	50.75	100493.43	228.94	5.80	1.26	0.55
Max	28.76	4.65	97985.13	29.64	89.66	101385.28	312.32	8.56	4.40	2.16

4.1.3.2 Cyclones in the Mumbai offshore

Between 2009 and 2020, two significant cyclonic systems affected the Mumbai offshore basin: Cyclone Phyan in November 2009 and Cyclone Nisarga in June 2020. Phyan, a cyclonic storm, formed in the Arabian Sea and made landfall between Alibag and Mumbai on November 10, 2009, with maximum sustained winds of 35 kt and an average transverse velocity of 18.97 m/s. It caused notable weather disturbances and coastal impacts with a central pressure drop of 996 hPa. Cyclone Nisarga, a Severe Cyclonic Storm, hit the Maharashtra coast on June 3rd, 2020, with sustained winds of 60 kt, gusts reaching 70 kt, and an average transverse velocity of 17.56 m/s. It made landfall near Alibag, causing significant storm surges, coastal flooding, and heavy rainfall, with a central pressure of 992 hPa before weakening over Madhya Pradesh.

Table 4.6 Cyclone events that impacted the Mumbai offshore (1980–2020)

Serial Number of	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (degrees)	Longitude (degrees)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)[or "delta P"]	Grade (text)	Distance(in degree)	Kilometers(km)	Time interval (Hour)	Transverse velocity (km/hr)
1	A	PHYAN	11/9/2009	0900	11.0	72.0	1.5	1000	25	4.0	D				
1	R	PHYAN	11/10/2009	0300	13.0	70.5	2.0	998	30	5.0	DD	2.5	278.93	18	15.50
1	B	PHYAN	11/10/2009	1800	15.0	71.0	2.5	996	35	6.0	CS	2.06	230.02	15	15.33
1	The system crossed the Maharashtra coast between Alibag and Mumbai near lat. 18.7°N/ long. 73.0°E during 1000 & 1100 UTC.											0	0		
1			11/11/2009									0	0		
1	A	PHYAN	11/11/2009	1200	19.5	73.5	-	996	30	5.0	DD	5.15	574.36	18	31.91
1	R B	PHYAN	11/11/2009	1800	20.0	74.0	-	1000	20	4.0	D	0.71	78.89	6	13.15
The system weakened into a well marked low-pressure area over north Maharashtra at 0000 UTC of 12 November.												0	0		
													0		
2		NISARGA	01/06/2020	0000	13	71.4	1.5	1004	25	3	D	0	0		
2		NISARGA	6/2/2020	0000	15	71.2	2	1000	30	6	DD	2.01	224.26	24	9.34
2		NISARGA	6/2/2020	0600	15.6	71.2	2.5	999	35	7	CS	0.6	66.94	6	11.16
2		NISARGA	6/3/2020	0000	17.3	72.1	3	992	50	12	SCS	1.92	214.62	18	11.92
2		NISARGA	6/3/2020	Crossed Maharashtra coast close to the south of Alibag near 18.35ºN/72.95ºE, as severe cyclonic storm with a maximum sustained wind speed of 60 kt gusting to 70 kt between 0700-0900 UTC of 03rd June								0	0		
2	A	NISARGA	6/3/2020	1200	19	73.7	-	998	40	8	CS	2.33	260.47	12	21.71
2	R	NISARGA	6/3/2020	1500	19.6	74	-	1000	30	6	DD	0.67	74.85	3	24.93
2	B	NISARGA	6/4/2020	0000	20.5	76	-	1004	25	4	D	2.19	244.70	9	27.19
2		NISARGA		1200	Weakened into a well-marked low-pressure area over central parts of Madhya pradesh								0		

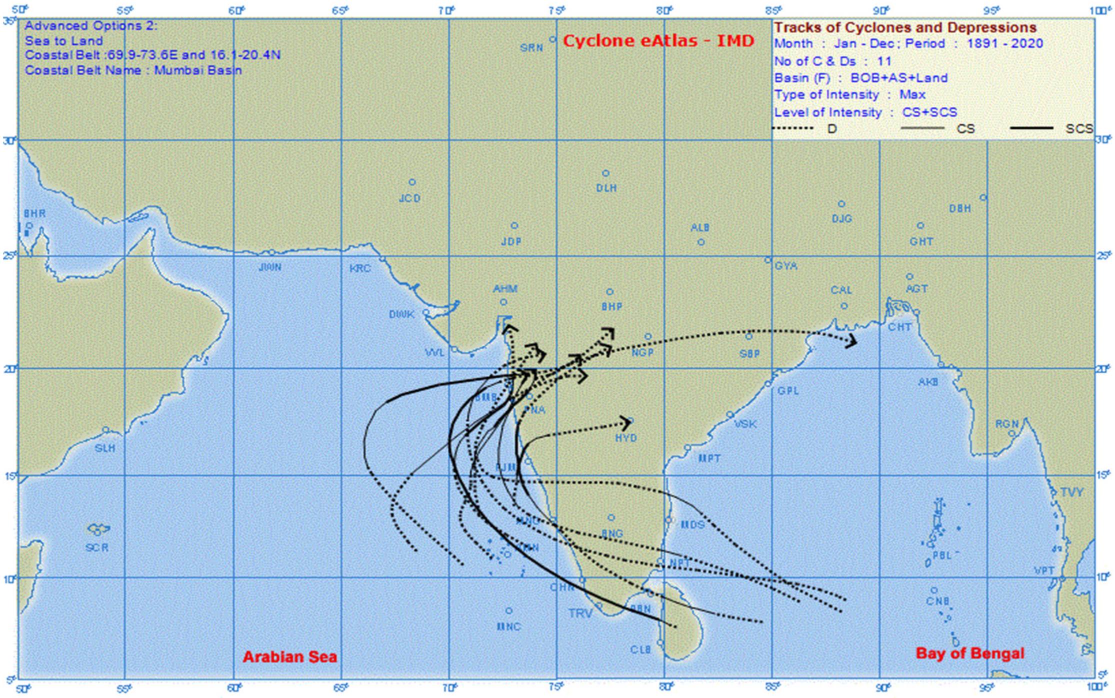


Figure 4.3 Cyclonic/severe cyclonic storms were formed/ dissipated over Mumbai basin.

4.1.4 Kerala-Lakshadweep-Konkan basin

The Kerala-Lakshadweep-Konkan basin, located south of 16 °N latitude, forms the southern part of India's western continental margin, stretching from Goa in the north to Cape Comorin in the south and extending westward to the Arabian abyssal plain. Bounded by the peninsular shield to the east, the basin evolved through early and post-rift phases, accumulating over 5 km of cretaceous to recent sediments. As confirmed by drilling results and gas anomalies, these post-rift sediments contain sufficient organic carbon for hydrocarbon generation.

4.1.4.1 Meteorological conditions at Kerala-Lakshadweep-Konkan basin

The region experiences relatively stable temperatures throughout the year, with a notable increase from March to May, culminating in the highest average temperature of 28.85°C in May. This warming trend can be attributed to the pre-monsoon heating typical of tropical regions. Similarly, the sea surface temperature shows a gradual increase leading up to May, which aligns with the period of intense solar heating before the monsoon arrives. Wind speeds increase dramatically from May, peaking in July at 5.83 m/s. This is characteristic of the southwest monsoon, which brings strong winds to the region. The wind speeds decrease after August, marking the monsoon retreat by October. Relative humidity values increase significantly during the monsoon months (June to September), reaching a peak of around 84.8% in July and August. This indicates the moist air brought in by the southwest monsoon, which leads to higher humidity levels and extensive rainfall during this period. Both pressure measurements show a distinct seasonal variation, with lower values during the monsoon (June to September) and higher values in winter (January and February). The low pressure during the monsoon results from the intense heating of the landmass, which causes air to rise and reduces surface pressure. The drop in surface air pressure and mean sea level pressure during the monsoon season clearly indicates the monsoon trough's presence over the region, which is associated with low-pressure systems and cyclonic circulations that enhance rainfall. The peak in wind speed, humidity, and lower pressure during the monsoon months suggests an increased likelihood of extreme weather events, such as heavy rains, storms, and potential flooding. The wave direction varies between 196° and 254°, indicating that waves generally come from the southwest and west-southwest directions. The mean wave period increases from around 7.03 s to a maximum of 8.82 s in August, coinciding with the peak of the monsoon. The maximum wave height reaches 4.44 m in July and October, which aligns with the monsoon period, where wave energy is highest. The swell height increases significantly during the monsoon period (June to August), reaching up to 2.17 m in July and October.

Table 4.7 Meteorological parameters at Kerala-Konkan-Lakshwadeep

Kerala-Konkan-Lakshwadeep	Air Temp(^{0}C)	Wind speed (m/s)	Surface air pressure (Pa)	Sea surface temp (^{0}C)	Relative Humidity (%)	Mean Sea Level Pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height (m)	Significant height of total swell (m)
Jan	24.97	2.24	98679.63	27.97	63.29	101277.05	241.80	7.04	1.65	0.80
Feb	25.92	2.26	98614.81	28.11	61.68	101201.88	246.51	7.11	1.69	0.81
Mar	27.53	2.12	98498.45	28.84	62.96	101072.11	230.03	7.56	1.74	0.86
April	28.74	2.38	98359.69	29.72	66.16	100924.65	218.52	8.13	1.87	0.94
May	28.85	3.41	98234.97	29.98	70.60	100799.38	225.69	8.22	2.40	1.20
June	26.90	5.17	98134.60	29.13	82.19	100709.21	249.32	8.65	4.14	2.02
July	25.93	5.83	98183.42	28.03	84.78	100764.99	254.74	8.82	4.44	2.17
Aug	25.65	5.24	98268.48	27.64	84.88	100853.81	248.50	8.52	3.80	1.88
Sep	25.90	3.54	98347.36	28.07	82.97	100933.58	233.33	8.19	2.81	1.40
Oct	26.35	1.58	98459.72	28.71	76.57	101045.64	207.95	8.31	2.08	1.06
Nov	25.99	1.74	98565.31	28.83	69.26	101157.75	196.35	7.97	1.71	0.87
Dec	25.22	2.13	98663.23	28.45	64.77	101262.50	202.21	7.41	1.65	0.81
Min	24.97	1.58	98134.6	27.64	61.68	100709.21	196.35	7.03	1.64	0.80
Max	28.85	5.83	98679.63	29.98	84.88	101277.05	254.74	8.81	4.44	2.17

4.1.4.2 Cyclones in the Kerala-Konkan-Lakshadweep basin

In the Kerala-Konkan-Lakshadweep basin, Cyclone Ockhi formed and was recorded as a Very Severe Cyclonic Storm (VSCS) on 30th November, 2017. The average transverse velocity during the storm was 4.766 m/s.

Cyclone Ockhi, which formed in late November 2017 over the Bay of Bengal, significantly impacted the Kerala and Lakshadweep regions. Initially emerging with a central pressure of 1004 hPa and sustained winds of 25 kt, the cyclone rapidly intensified, reaching a peak strength of 988 hPa and maximum sustained winds of 65 kt by 1st December, classifying it as a Very Severe Cyclonic Storm. Its trajectory brought it dangerously close to the southwestern coast, resulting in heavy rainfall, strong winds, and coastal flooding. It exhibited an average transverse velocity of 17.84 m/s. By 5th December, Ockhi had weakened into a well-marked low-pressure area.

Table 4.8 Cyclone events that impacted the Kerala-Konkan-Lakshadweep basin (1980–2020)

Serial Number of system	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (lat)	longitude (Long)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)[or	Grade (text)	Distance(in degree)	Kilometers(km)	Time interval (Hour)	Transverse velocity (km/hr)
1	BOB		29/11/2017	0300	6.5	81.8	1.5	1004	25	3	D		0		
1	BOB		29/11/2017	2100	6.5	78.6	2	1001	30	5	DD	3.2	357.04	18	19.84
1	BOB		30/11/2017	0300	7.5	77.5	2.5	999	35	7	CS	1.49	165.867	6	27.64
1	BOB		1/12/2017	0000	8.8	74	3	992	50	14	SCS	3.73	416.58	21	19.84
1	BOB	OCKHI	1/12/2017	0900	9.1	73	4	988	65	21	VSCS	1.04	116.49	9	12.94
1	BOB		4/12/2017	1800	16.5	69.8	3.5	990	55	16	SCS	8.06	899.54	75	11.99
1	BOB		5/12/2017	0300	17.7	70.7	3	996	45	10	CS	1.5	167.36	9	18.60
1	BOB		5/12/2017	0900	18.3	71.2	2	1000	30	6	DD	0.78	87.14	6	14.52
1	BOB		5/12/2017	1500	18.8	71.6	1.5	1003	25	4	D	0.64	71.44	6	11.91
1	BOB		5/12/2017	2100	Weakened into a well-marked low-pressure area over the northeast Arabian Sea and adjoining south coastal Gujarat and north coastal Maharashtra										

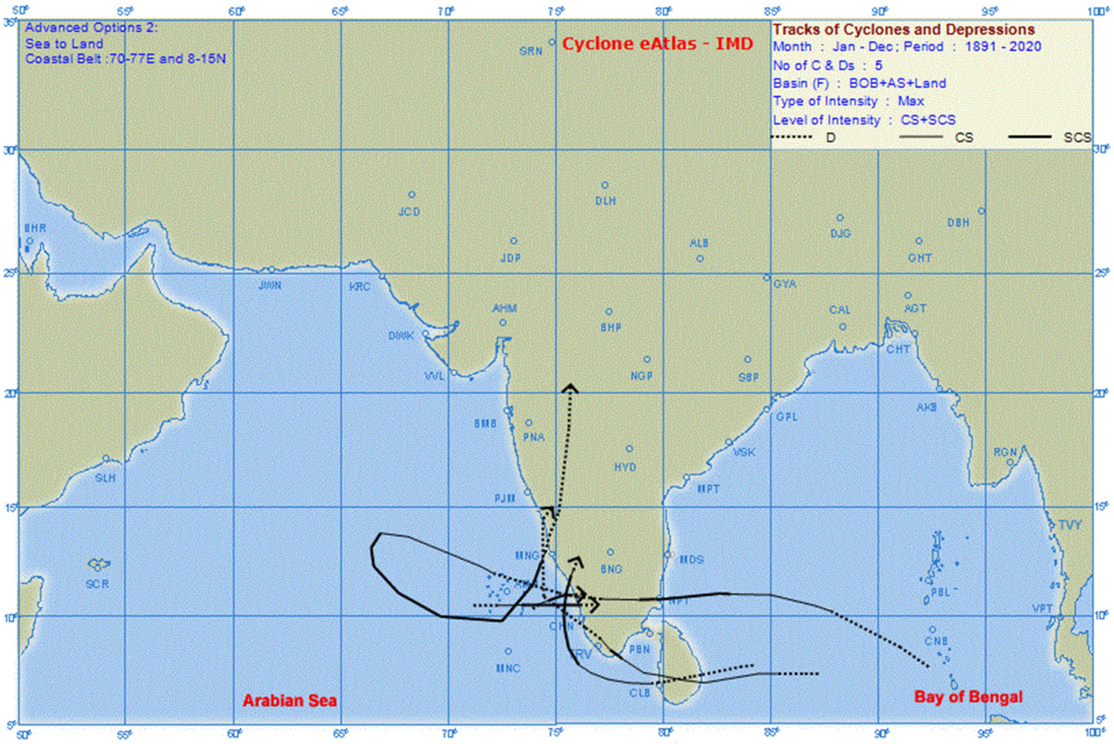


Figure 4.4 Cyclonic/ severe cyclonic storms formed/ dissipated over Kerala, Konkan, and the Lakshadweep basin.

4.1.5 Cauvery basin

The Cauvery basin, located along India's east coast between 08°-12° N latitude and 78°-80° E longitude, has been explored for hydrocarbons since the late 1950s, with the first deep exploration well drilled in 1964. Covering an area of 1.5 lakh sq. km, the basin includes 25,000 sq. km of inland and 30,000 sq. km of shallow offshore areas, and 95,000 sq. km of deeper offshore regions. Formed due to the fragmentation of Gondwanaland during the Late Jurassic/ Early Cretaceous, the basin contains 5-6 km of sediments, mainly shale, sandstone, and minor limestone, ranging from the late Jurassic to the recent period.

4.1.5.1 Meteorological conditions at Cauvery basin

The climatology shows a clear seasonal cycle in air temperature, with temperatures peaking in April (28.76°C) and May (28.42°C), the hottest months. The air temperature then declines during the monsoon months (June to September), reaching a low of 23.62°C in December. The sea surface temperature (SST) also follows a similar pattern, peaking in April at 30.08°C, the warmest month. The SST drops to its lowest in

August (26.55°C) during the peak of the monsoon, likely due to the cooling effect of the monsoon rains and increased ocean mixing. Wind speeds are generally low throughout the year, with a noticeable increase during the monsoon season (June to September). The highest wind speed occurs in July (3.05 m/s), consistent with the onset of the southwest monsoon that brings strong winds to the region. The surface air pressure varies seasonally, with the highest pressure in January (96285.81 Pa) during the cooler, drier months. This high pressure is associated with stable atmospheric conditions. The lowest surface air pressure is observed in June (95755.83 Pa), coinciding with the onset of the monsoon. This pressure drop is typical of monsoon climates, where intense heating over the landmass creates low-pressure systems that draw in moist ocean air. Mean sea level pressure follows a similar pattern, with high values during the winter (e.g., 101350.30 Pa in January) and lower values during the monsoon. Relative humidity is lowest in March (57.57%) and highest in October (78.19%). The low humidity in March corresponds with the dry pre-monsoon period, while the high humidity in October reflects the lingering moisture from the monsoon rains. The increase in humidity from June onwards marks the onset of the monsoon, which brings moist air masses and significantly increases atmospheric moisture. During the monsoon season (June to September), air and sea surface temperatures decrease, reflecting the cooling influence of heavy rainfall, cloud cover, and the influx of moist air. The relative humidity increases substantially, peaking in the post-monsoon month of October. Wind speeds increase during the monsoon, with July experiencing the strongest winds. The low surface air pressure during the monsoon is typical of the region's climate and is associated with active monsoon depressions and cyclonic circulations. October shows high relative humidity and moderate temperatures, indicating a transition period as the monsoon withdraws. The wave direction varies from 198° to 254°, suggesting a general southwesterly to westerly direction for the waves. The longest wave periods are observed during the monsoon months (June to September), peaking at 8.40 s in July and December. Maximum wave heights range from 0.91 m to 2.47 m, with the highest values seen in July (2.47 m) during the monsoon. The swell height shows a similar seasonal pattern, peaking at 1.33 m in July and December.

Table 4.9 Meteorological parameters at Cauvery basin

Cauvery Basin	Air Temp (^{0}C)	Wind speed (m/s)	Surface air pressure (Pa)	Sea surface temp (^{0} C)	Relative Humidity (%)	Mean Sea Level Pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height (m)	Significant height of total swell (m)
Jan	23.86	1.68	96285.81	28.30	64.55	101350.30	222.65	6.85	0.91	0.46
Feb	25.57	1.41	96211.46	28.60	58.82	101257.49	236.30	6.65	1.00	0.51
Mar	27.68	1.14	96087.90	29.41	57.57	101111.72	226.97	7.03	1.10	0.56
April	28.76	0.99	95938.71	30.08	64.13	100950.06	216.19	7.76	1.18	0.62
May	28.42	1.60	95791.16	29.78	68.83	100800.29	225.77	7.81	1.59	0.84
June	26.83	2.94	95755.83	28.38	73.63	100779.25	249.17	8.23	2.44	1.32
July	26.14	3.05	95803.15	27.00	74.56	100834.89	254.96	8.40	2.47	1.33
Aug	26.00	2.76	95858.12	26.55	74.7	100893.30	249.05	8.19	2.19	1.18
Sep	26.04	1.90	95909.91	27.27	75.35	100945.52	235.62	7.83	1.78	0.94
Oct	25.43	0.64	96025.01	28.34	78.19	101068.14	212.81	8.04	1.39	0.74
Nov	24.39	1.18	96142.05	28.80	77.34	101197.41	200.36	8.05	1.04	0.55
Dec	23.62	1.74	96260.92	28.58	71.72	101327.89	198.82	7.46	0.91	0.46
Min	23.62	0.64	95755.83	26.55	57.57	100779.25	198.82	6.65	0.91	0.46
Max	28.76	3.05	96285.81	30.08	78.19	101350.3	254.96	8.40	2.47	1.33

4.1.5.2 Cyclones in the Cauvery basin

The Cauvery basin has experienced a total of 23 cyclonic systems, including 2 Very Severe Cyclonic Storms (VSCS), 6 Severe Cyclonic Storms (SCS), 3 Cyclonic Storms (CS), and several Depressions (DD and D), with an average transverse velocity of 4.05 m/s. Notable events include the October 1982 cyclone, which intensified from a weak system with a central pressure of 990 hPa to 50 knots before landfall, causing heavy rainfall along the Tamil Nadu coast. In December 1984, a cyclone reached peak intensity with winds of 115 knots and impacted the region significantly. Cyclone Thane in December 2011 made landfall near Cuddalore, leading to flooding and alterations in sedimentary structures. Cyclone Gaja in November 2018 exhibited fluctuations in intensity before making landfall near Nagapattinam, while Cyclones Nivar and Burevi in November 2020 brought considerable wind and rainfall, further impacting local agriculture and infrastructure. The trajectory of these storms often resulted in significant distances travelled, showcasing the interaction of tropical systems with land and the subsequent effects on the region's weather patterns and environmental conditions. The frequency of Very Severe Cyclonic Storms (VSCS) and Severe Cyclonic Storms (SCS) underscores the increasing severity of storms in the region, likely linked to changing climatic conditions.

Table 4.10 Cyclone events that impacted the Cauvery basin (1980–2020)

Serial Number of system during year	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (degrees)	longitude (degrees)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)]	Grade (text	Distance(in degree)	Kilometers(km)	Time interval	Transverse velocity (km/hr)
1			16/10/1982	1200	9.4	84.0	1.5	990	25	3	D				
1			17/10/1982	1200	11.0	82.5	2.0	992	30	4	DD	2.19	244.70	24	10.20
1			17/10/1982	1800	12.0	82.0	2.5	994	35	6	CS	1.12	124.74	6	20.79
1	B O B		18/10/1982	0000	12.5	81.5	3.0	986	50	14	SCS	0.71	78.89	6	13.15
1			18/10/1982	Crossed south AP coast between Sriharikota and Durgarajpatnam between 1600-1700 UTC of 18th								0	0		
1			19/10/1982	0000	15.0	79.5		995	30	5	DD	3.20	357.21	24	14.88
1			19/10/1982	1200	16.0	78.5		997	25	3	D	1.41	157.79	12	13.15
1			22/10/1982	0300	Weakened into a WML over south Tamilnadu and neighbourhood								0		
1													0		
													0		
2			02/12/1982	1200	7.5	84.0	1.5		25	3	D		0		
2	B O B		04/12/1982	0000	9.7	79.0	1.5		25	3	D	5.46	609.48	36	16.93
2			04/12/1982	Crossed south Tamilnadu coast near Tondi between 0000 and 0200 UTC of 4th									0		
2												0	0		
2			05/12/1982	0300	Weakened into a WML over south Tamilnadu and neighbourhood								0		
													0		
													0		
3	B		09/11/1984	1200	9.5	87.5	1.5		25	3	D		0		

3	O	10/11/1984	0300	9.5	87.5	2.0		30	5	DD	0	0	15	0
3	B	11/11/1984	1200	11.0	81.5	2.5		40	8	CS	6.18	690.05	33	20.91
3		12/11/1984	0300	12.0	80.5	3.5		55	15	SCS	1.41	157.79	15	10.52
3		12/11/1984	1200	12.5	80.5	5.0		90	40	ESCS	0.5	55.79	9	6.20
3		System crossed coast bet Sriharikota and Durgarajupatnam bet 0230 and 0330 UTC on 14th										0		
3		14/11/1984	1200	13.5	79.5	4.0		65	21	VSCS	1.41	157.79	48	3.29
3		15/11/1984	0300	Weakend into well marked low-pressure area								0		
												0		
4		27/11/1984	1200	8.5	85.5	1.5		25	3	D		0		
4		28/11/1984	1200	9.5	84.5	2.0		30	4	DD	1.41	157.79	24	6.57
4		29/11/1984	0900	9.5	84.5	3.0		45	10	CS	0	0	21	0
4		30/11/1984	0000	9.5	84.5	3.5		55	15	SCS	0	0	15	0
4	B O	30/11/1984	0300	9.5	84.5	6.0		115	66	ESCS	0	0	3	0
4	B	01/12/1984	System crossed tn coast just n of Karaikal bet 0900 and 0930 UTC near (10.9N/ 79.8E) of 1st									0		
4		01/12/1984	1200	11.0	79.0	3.5		55	15	SCS	5.7	636.07	33	19.27
4		01/12/1984	1800	11.5	77.5	2.0		30	4	DD	1.58	176.41	6	29.40
4		02/12/1984	0300	11.5	74.0	1.5		25	3	D	3.5	390.51	9	43.39
4		02/12/1984	1200	Weakend into well marked low pressure area								0		
												0		
5		11/12/1985	0600	OVER SE BAY		1.5		25	3	D		0		
5	B	11/12/1985	1200	8.0	88.0	2.0		30	4	DD			6	
5	O	12/12/1985	1200	10.0	84.5	3.0		35	6	CS	4.03	449.77	24	18.74
5	B	System crossed near Sri harikota around 1800 UTC										0		
5		14/12/1985	0300	14	79.5	1.5		25	3	D	6.40	714.42	27	26.46
5			1200	Weakend into the low-pressure area									0	
												0		
6		31/10/1987	0300	11.5	86.5	1.5	997	25	3	D		0		
6		31/10/1987	0600	12.0	86.0	2.0	995	30	5	DD	0.71	78.89	3	26.30
6		31/10/1987	1200	12.5	85.5	2.5	993	35	7	CS	0.71	78.89	6	13.15
6	B O B	02/11/1987	0000	13.5	82.5	3.5	986	50	14	SCS	3.16	352.83	36	9.800776879
6		02/11/1987	Crossed Andhra coast close to north of Nellore between 2200 to 2300 UTC on 2nd									0		
6		02/11/1987										0		
6		03/11/1987	0300	14.5	79.0	-	988	45	12	CS	3.64	406.14	27	15.04

6		03/11/1987	1200	15.5	78.0	-	996	25	4	D	1.41	157.79	9	17.53
6		03/11/1987	1800	Weakened into a WML over Rayalseema and adjoining Telangana and interior Karnataka								0	6	0
												0		
7		28/11/1996	0300	11.5	86.5	1.5	1004	25	3	D		0		
7		29/11/1996	0300	12.5	85.0	2.0	1002	30	5	DD	1.80	201.14	24	8.38
7		30/11/1996	1200	15.5	88.5	1.5	1004	25	3	D	4.61	514.33	33	15.59
7		01/12/1996	1200	14.5	88.5	2.0	1002	30	5	DD	1	111.57	24	4.65
7	B	02/12/1996	0000	14.0	87.0	2.5	996	35	7	CS	1.58	176.41	12	14.70
7	O	03/12/1996	0300	14.0	84.5	3.5	992	55	16	SCS	2.5	278.93	27	10.33
7	B	03/12/1996	1200	14.5	83.5	4.0	988	65	20	VSCS	1.12	124.74	9	13.86
7		05/12/1996	0000	15.0	81.3	3.5	992	55	16	SCS	2.26	251.72	36	6.99
7		05/12/1996	0600	14.5	81.7	3.0	994	45	10	CS	0.64	71.44	6	11.91
7		06/12/1996		Crossed between Chennai and Pondicherry near Mahabalipuram								0		
7		06/12/1996		Between 1600 UTC and 1700 UTC								0		
7		07/12/1996	WML									0		
												0		
8		26/11/2000	0300	8.5	91.5	1.5	1004	25	4	D		0		
8		26/11/2000	1500	10.0	90.0	2.0	1004	30	6	DD	2.12	236.68	12	19.72
8		27/11/2000	0900	11.0	86.5	2.5	998	35	10	CS	3.64	406.14	18	22.56
8		28/11/2000	0000	11.5	84.0	3.5	992	55	15	SCS	2.55	284.46	15	18.96
8	B	28/11/2000	0600	11.5	83.0	4.0	986	65	20	VSCS	1	111.57	6	18.60
8	O	28/11/2000	1500	11.5	81.8	5.0	968	90	40	ESCS	1.2	133.89	9	14.88
8	B	29/11/2000	0600	11.5	80.5	4.5	976	77	30	VSCS	1.3	145.05	15	9.67
8		29/11/2000	Crossed Tamilnadu coast near Cuddalore around 1130 UTC									0		
8		29/11/2000	1200	11.5	80.0		998	55	10	SCS	0.5	55.79	6	9.30
8		29/11/2000	1800	11.0	78.5		998	45	10	CS	1.58	176.41	6	29.40
8		30/11/2000	0300	11.5	78.0		1002	30	4	DD	0.71	78.89	9	8.77
8		30/11/2000	0600	11.5	77.0		1004	25	2	D	1	111.57	3	37.19
												0		
9		23/12/2000	0300	8.0	86.0	1.5	1006	25	4	D		0		
9		24/12/2000	0000	8.0	84.0	2.0	1004	30	6	DD	2	223.15	21	10.63
9	B	25/12/2000	0300	8.5	83.0	2.5	1004	35	6	CS	1.12	124.74	27	4.62
9	O	25/12/2000	1200	8.5	83.0	3.5	994	55	16	SCS	0	0	9	0
9	B	25/12/2000	1800	8.5	83.0	4.0	990	65	20	VSCS	0	0	6	0
9		26/12/2000	1200	8.5	81.0	5.0	970	90	40	ESCS	2	223.15	18	12.40
9		26/12/2000	First landfall near Trincomalee (43418) around 261200 UTC.									0		

9			26/12/2000	1800	8.5	81.0	4.5	982	77	30	VSCS	0	0	6	0
9			27/12/2000	1200	8.5	78.5	3.5	990	65	20	SCS	2.5	278.94	18	15.50
9			27/12/2000	2100	8.5	78.0	3.0	1002	55	10	CS	0.5	55.79	9	6.20
9			27/12/2000	2nd landfall south of Tuticorin (43379) on early morning hours of 28th									0		
9			28/12/2000	0600	8.5	77.0	2.0	1004	30	6	DD	1	111.57	9	12.40
9			28/12/2000	1200	9.0	76.5	1.5	1006	25	4	D	0.71	78.89	6	13.15
9			29/12/2000	0000	9.0	75.5	1.0	1002			L	1	111.57	12	9.30
													0		
10			06/12/2005	0300	10.5	89.5	1.5	1006	25	4	D		0		
10	BOB	FANOOS	06/12/2005	0900	11.0	89.0	2.0	1004	30	5	DD	0.71	78.89	6	13.15
10			07/12/2005	0300	11.0	87.5	2.5	1000	35	6	CS	1.5	167.36	18	9.30
10				Close to Vedaranyam (43349)							DD				
10			10/12/2005	0300	10.4	79.8	-	1001	30	5	DD	7.72	861.72	72	11.97
				Crossing the coast near vedaranyam (10 4N/79.85E)											
10	BOB	FANOOS	10/12/2005	0600	10.5	79.5	-	1002	25	4	D	0.32	35.28	3	11.76
													0		
11			25-11-2008	0900	8.5	81.0	1.5	1001	25	4	D		0		
11	BOB	NISHA	25-11-2008	1200	8.5	81.0	2	1001	30	5	DD	0	0		
11			26-11-2008	0300	10.5	80.0	2.5	1000	40	8	CS	2.24	249.49	15	16.63
11			The system crossed the Tamilnadu coast north of Karaikal (43346) near lat.										0		
11			11.3°N and long.79. 8°E between 0000 and 0100 UTC.										0		
11			27-11-2008	0900	12.0	79.0	-	1000	30	5	DD	1.80	201.14	36	5.59
11	BOB	NISHA	27-11-2008	1200	12.0	78.5	-	1000	20	3	D	0.5	55.787	3	18.60
11			28.11.2008	0000	Weakened into a NWL pressure area over north interior								0		
					Tamil nadu and adjoining areas of south interior Karnataka								0		
					and Rayalaseema								0		
													0		
12			04/11/2010	0000	8.0	92.0	1.5	1002	25	3	D		0		
12			05/11/2010	0000	9.0	88.5	2.0	1000	30	5	DD	3.64	406.14	24	16.92
12			05/11/2010	0600	9.0	87.5	2.5	998	35	6	CS	1	111.57	6	18.60
12	BOB	JAL	05/11/2010	2100	10.0	86.0	3.5	990	55	16	SCS	1.80	201.14	15	13.41
				Close to vedaranyam over land									0		
12			07/11/2010	0600	12.0	82.5	3.0	992	45	12	CS	4.03	449.77	45	9.99
12			07/11/2010	1200	13.0	81.0	2.0	996	30	6	DD	1.80	201.14	6	33.52

12			07/11/2010		The system crossed north Tamilnadu and south Andhra pradesh coast close to north chennai (43279) near 13.3^{0}N and 80.2^{0}E around 1600 UTC								0		
12			07/11/2010										0		
12			08/11/2010	0000	14.0	79.0	--	1002	25	4	D	2.24	249.49	12	20.79
12			08/11/2010	0600	The system weakened into a low pressure area over Rayalaseema and adjoining south interior Karnataka								0		
12													0		
													0		
13			25.12.2011	1200	08.5	88.5	1.5	1000	25	3	D		0		
13			26.12.2011	0000	09.5	87.5	2.0	998	30	4	DD	1.41	157.79	12	13.15
13			26.12.2011	1800	11.0	87.5	2.5	996	35	7	CS	1.5	167.36	18	9.30
13			28.12.2011	0900	12.5	85.0	3.5	986	55	16	SCS	2.92	325.29	45	7.23
13	BOB	THANE	28.12.2011	1200	12.5	84.5	4.0	982	65	20	VSCS	0.5	55.79	3	18.60
13			The system crossed the tamil nadu coast close to south of Cuddalore between 0100 and 0200 UTC of 30th										0		
13			30.12.2011	0300	11.6	79.5	--	986	55	16	SCS	5.08	566.83	45	12.60
13			30.12.2011	0600	11.6	79.0	--	998	30	5	DD	0.5	55.79	3	18.60
13			30.12.2011	1200	11.6	78.2	--	1000	25	3	D	0.8	89.26	6	14.88
													0		
14		--	13.11.2013	0300	11.5	86.0	1.5	1004	25	3	D		0		
14	BOB	--	16.11.2013		Crossed Tamilnadu coast near Nagapattinam around 0730 UTC of 16.11.2013										
14		--	16.11.2013	1800	11.0	78.0	-	-	25		D	8.016	894.33	87	10.28
14		--	17.11.2013	0000	Weakened into a well marked low pressure area over north interior Tamilnadu										
													0		
15			12/6/2013	0300	10.0	84.0	1.5	1004	25	3	D		0		
15			12/6/2013	1800	10.4	84.0	2.0	1002	30	5	DD	0.4	44.63	15	2.98
15			12/7/2013	0000	10.5	84.1	2.5	998	35	7	CS	0.14	15.78	6	2.63
15			12/7/2013	0900	10.8	84.3	3.5	992	55	14	SCS	0.36	40.23	9	4.47
15			12/8/2013	0600	12.3	84.7	4.0	986	65	20	VSCS	1.55	173.21	21	8.25
15			12/9/2013	1200	14.6	84.7	3.5	988	60	18	SCS	2.3	256.62	36	7.12
15	BOB	MADI	12/10/2013	0300	15.3	85.3	4.0	988	65	16	VSCS	0.92	102.87	15	6.86
15			12/10/2013	1200	15.4	85.0	3.5	990	55	14	SCS	0.32	35.28	9	3.92
15			12/10/2013	2100	14.6	84.6	3.0	994	45	10	CS	0.90	99.79	9	11.09
15			12/11/2013	0300	14.0	83.8	2.0	998	30	6	DD	1	111.57	6	18.60
15			12/11/2013	1800	12.9	82.7	1.5	1000	25	4	D	1.56	173.57	15	11.57
15			12/12/2013		The system crossed Tamilnadu coast near Vedaranyam aound 1330 UTC and emerge into Palk straight and again crossed Tamilnadu coast near Tondi around 1700 UTC								0		
15			12/12/2013	1800	10.0	78.8	-	1004	20	3	D	4.86	542.25	24	22.59

15			12/13/2013	0000	Weakened into a well marked low pressure area over southeast AS and adjoining Kerala.								0	6	0
													0		
16			11/8/2015	0300	10.7	83.7	1.5	1003	25	3	D		0		
16			11/9/2015	0300	11.6	80.3	2.0	998	30	6	DD	3.52	392.42	24	16.35
16	BOB		11/9/2015		Crossed north tamilnadu coast close to Marakanam, north of Puducherry near latitude 12.2N/80.0E around 1400 UTC								0		
16			11/10/2015	0300	12.4	79.3	-	1002	20	4	D	1.28	142.88	24	5.95
16			11/10/2015	0600	Well marked low pressure area over north Tamilnadu and neighbourhood.								0		
													0		
17			12/6/2016	0900	8.5	91.0	1.5	1002.0	25	3	D		0		
17			12/7/2016	1800	10.8	90.5	2.0	1000.0	30	5	DD	2.35	262.61	33	7.96
17			12/8/2016	0000	11.2	90.5	2.5	998.0	35	6	CS	0.4	44.63	6	7.44
17			12/9/2016	1800	12.3	89.6	3.0	992.0	50	14	SCS	1.42	158.58	30	5.29
17			12/10/2016	1200	13.2	86.4	4.0	984.0	65	22	VSCS	3.32	370.89	18	20.60
17			12/12/2016	0900	13.1	80.3	3.5	975.0	60	26	SCS	6.10	680.69	45	15.13
17	BOB	VARDAH	12/12/2016		Crossed north Tamilnadu coast close to Chennai near 13.13N/80.3E during 0930-1130 UTC								0		
17			12/12/2016	1200	13.0	79.9	3.5	984.0	50	18	SCS	0.41	46.00	3	15.33
17			12/12/2016	1500	12.9	79.5	3.0	994.0	40	10	CS	0.412	46.00	3	15.33
17			12/12/2016	1800	12.7	79.1	2.0	1002.0	30	5	DD	0.45	49.90	3	16.63
17			12/13/2016	0000	12.5	78.0	1.5	1003.0	20	3	D	1.12	124.74	6	20.79
17			12/13/2016	0300	Well marked low pressure area over north interior Tamilnadu and south interior Karnataka								0		
													0		
18			10/11/2018	0300	11.7	92.5	1.5	1003	25	3	D	15.81	1763.57		
18			10/11/2018	1200	12.6	90.8	2.0	1001	30	5	DD	1.92	214.62	9	23.85
18			11/11/2018	0000	13.4	89.3	2.5	999	35	7	CS	1.7	189.68	12	15.81
18			15/11/2018	0300	11.3	82.6	3.0	994	50	12	SCS	7.02	783.41	99	7.91
18			15/11/2018	1500	10.6	80.7	4.0	984	65	21	VSCS	2.02	225.92	12	18.83
18	BOB	GAJA	15/11/2018		Crossed Tamil nadu and Puducherry coasts between Nagapattinam& Vedaranniyam near 10.45°N and 79.80°E during 1900 to 2100 UTC										
18			16/11/2018	0000	10.4	79.2	-	990	55	15	SCS	1.51	168.84	9	18.76
18			16/11/2018	0300	10.4	78.5	-	996	45	10	CS	0.7	78.10	3	26.03
18			16/11/2018	0600	10.5	77.6	-	1000	30	6	DD	0.91	101.03	3	33.68
18			16/11/2018	1200	10.1	76.4	1.5	1002	25	4	D	1.26	141.13	6	23.52
18			17/11/2018	0000	9.8	74.3	2.0	1003	30	5	DD	2.12	236.68	12	19.72
18			19/11/2018	0600	11.2	65.8	1.5	1004	25	4	D	8.61	961.16	54	17.80

18			19/11/2018	1200	11.2	65.0	1.5	1004	25	4	D	0.8	89.26	6	14.88
18			19/11/2018	1800	Weakened into a well marked low pressure area over southwest & adjoining southeast AS								0		
19			22/11/2020	2100	8.5	85.3	1.5	1002	25	3	D		0		
19			23/11/2020	1200	9.8	83.6	2	999	30	5	DD	2.14	238.78	15	15.92
19			24/11/2020	0000	10	83	2.5	997	35	7	CS	0.63	70.57	12	5.88
19			24/11/2020	1800	10.2	82.3	3.5	992	50	12	SCS	0.73	81.23	18	4.51
19			25/11/2020	0600	11.2	81	4	982	65	22	VSCS	1.64	182.99	12	15.25
19	ARB	NIVAR	25/11/2020		Crossed Tamilnadu and Puducherry coasts (near lat 12.1^0N and log 79.9^0 E) during 1800 – 2100 UTC of 25th										
19			25/11/2020	2100	12.1	79.9	-	986	60	18	SCS	1.42	158.58	15	10.57
19			11/26/2020	0300	12.6	79.4	-	996	40	8	CS	0.71	78.89	6	13.15
19			26/11/2020	0900	13.3	79.3	-	999	30	5	DD	0.71	78.89	6	13.15
19			26/11/2020	1800	14	79.6	-	1002	20	3	D	0.76	84.97	9	9.44
19			26/11/2020	0	Weakened into a well-marked low pressure area over south coastal Andhra pradesh and adjoining westcentral BoB										
													0		
20			30/11/2020	0000	7.5	88	1.5	1003	20	3	D		0		
20			1/12/2020	0000	7.8	86	2	1000	30	6	DD	2.022	225.64	24	9.40
20			1/12/2020	1200	7.9	84.8	2.5	999	35	7	CS	1.20	134.35	12	11.20
20			2/12/2020		Crossed Sri lanka coast close to north of Trincomalee (near lat 08.85^0N and log 81.0^0 E) during 1700 – 1800 UTC of 2nd								0		
20	BOB	BUREVI	3/12/2020		Crossed Pamban area (near lat 09.2^0N and log 79.35^0 E) during 0800 UTC of 3rd							0	0		
20			3/12/2020	1200	9.2	79.1	2	1000	30	6	DD	5.85	652.30	48	13.59
20			4/12/2020	1200	9.1	78.6	1.5	1002	25	4	D	0.51	56.89	24	2.37
20			5/12/2020	0600	Weakened into a well-marked low pressure area over gulf of Mannar close to Ramanathapuram district of Tamilnadu								0		

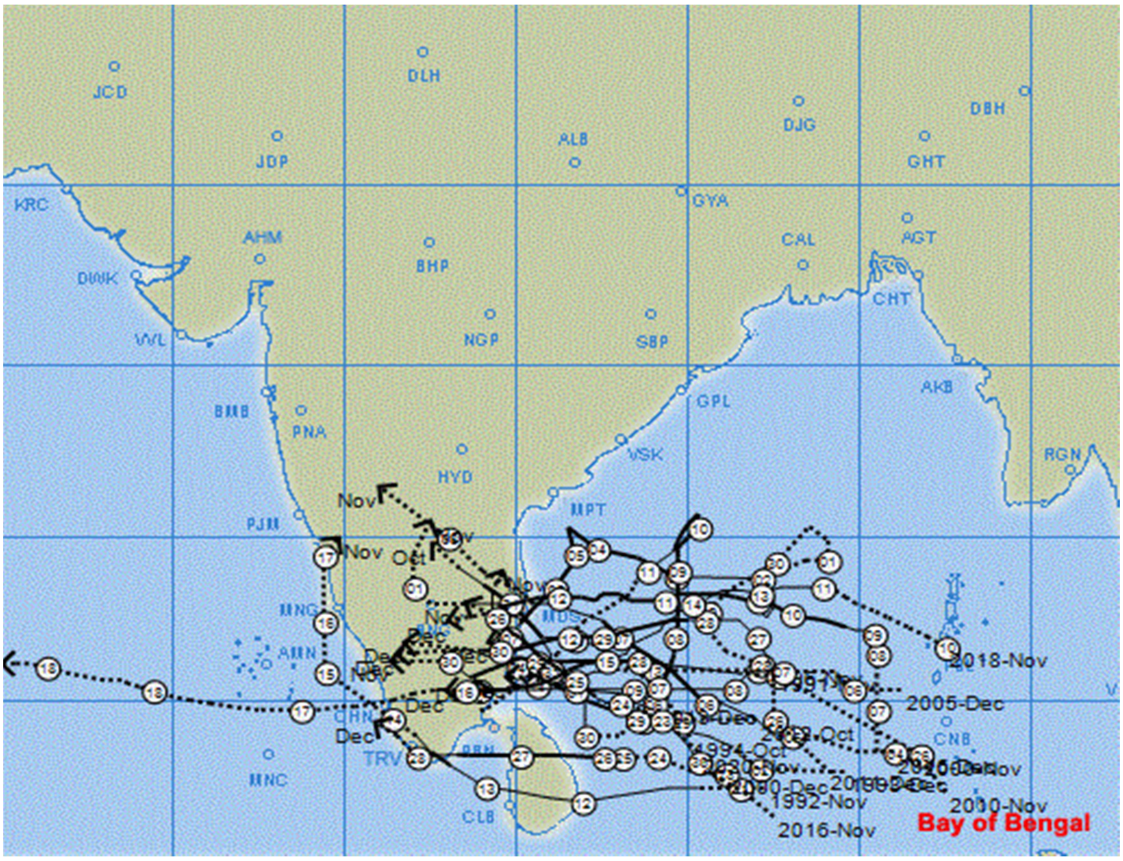


Figure 4.5 shows past cyclonic events in the Cauvery basin.

4.1.6 Krishna Godavari basin

The Krishna Godavari basin, a proven petroliferous basin on India's east coast, spans 15,000 sq. km inland and 25,000 sq. km offshore up to the 1000 m isobath. It contains about 5 km of sediments deposited from the Late Carboniferous to Pleistocene. The basin's major geomorphological features include upland plains, coastal plains, recent floodplains, and delta plains. It hosts oil and gas fields both inland and offshore, with entrapments ranging from Permo-Triassic to Pliocene sediments.

4.1.6.1 Meteorological conditions

Air temperature exhibits a clear seasonal variation, with the hottest months being April (30.66°C) and May (31.66°C). The coolest months are December (23.17°C) and January (23.40°C), which align with the winter season when temperatures are at their lowest. A gradual decrease in temperature is observed from May to September, influenced by the cooling effect of the monsoon rains. Sea surface temperature (SST) follows a similar trend, peaking in May (30.08°C) and reaching its lowest in January (26.50°C). The SST remains relatively high during the monsoon months (June to September), indicating the retention of heat in the ocean despite the monsoonal cooling on land. Wind speeds increase significantly during the monsoon season, with the highest speeds recorded in July (4.18 m/s) and June (3.86 m/s). This is typical of the southwest monsoon, which brings strong winds to the region. The lowest wind speeds are observed in October (0.97 m/s) and February (1.74 m/s), suggesting calmer conditions before and after the monsoon. Surface air pressure shows a seasonal pattern, with the highest pressure in January (97745.79 Pa) and the lowest in June (96777.95 Pa). The lower pressure during the monsoon season is associated with developing low-pressure systems that drive monsoon rains. Higher pressure values during the cooler months (December to February) indicate more stable and calm atmospheric conditions. Mean sea level pressure is highest in December (101436.16 Pa) and January (101427.20 Pa), which corresponds with the winter season. The lowest pressure is recorded in June (100400.86 Pa), aligning with the peak of the monsoon season. Relative humidity is lowest in March (51.89%) and highest in September (76.00%). The low humidity in March corresponds to the dry pre-monsoon season, while the high humidity in September reflects the peak monsoon period when the atmosphere is saturated with moisture. Humidity levels rise steadily from May to July, reaching a peak in the monsoon months (June to September), and then gradually decrease as the monsoon withdraws. The wave direction varies significantly throughout the year, from 92° to 188°, indicating a shift from predominantly easterly waves in the early part of the year to more southerly waves by mid-year. The mean wave period gradually increases from 6.10 s to a maximum of 7.16 s in October and December. Maximum wave heights range from 1.49 m to 2.66 m, with the highest values in June (2.66 m) during the monsoon. The significant swell height follows a similar trend, peaking at 1.13 m in June and December.

Table 4.11 Meteorological parameters at Krishna Godavery Basin

Krishna Godavery Basin	Air Temp (^{0}C)	Wind speed (m/s)	Surface air pressure (Pa)	Sea surface temp (^{0}C)	Relative Humidity (%)	Mean Sea Level Pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height (m)	Significant height of total swell (m)
Jan	23.40	1.94	97745.79	26.50	60.84	101427.20	104.48	6.14	1.70	0.80
Feb	25.55	1.74	97615.73	27.15	54.94	101277.31	127.91	6.41	1.49	0.72
Mar	28.39	1.80	97424.62	28.38	51.89	101061.00	151.13	6.57	1.53	0.72
April	30.66	2.06	97201.35	29.61	53.44	100818.90	161.86	6.59	1.85	0.84
May	31.66	2.45	96922.72	30.08	54.56	100529.12	172.02	6.66	2.42	1.06
June	29.34	3.86	96777.95	29.84	66.68	100400.86	187.16	6.60	2.66	1.13
July	27.49	4.18	96828.01	29.11	73.97	100464.60	188.80	6.82	2.57	1.11
Aug	27.04	3.89	96917.97	28.86	75.50	100560.42	187.11	6.94	2.51	1.10
Sep	27.12	2.37	97077.15	29.24	76.00	100722.65	176.49	7.13	2.22	1.04
Oct	26.50	0.97	97353.30	29.45	72.13	101007.68	144.80	7.16	1.91	0.91
Nov	24.72	2.23	97598.24	28.34	67.26	101269.74	99.00	6.34	2.22	0.97
Dec	23.17	2.33	97751.72	27.02	63.67	101436.16	92.22	6.10	2.23	0.96
Min	23.17	0.97	96777.95	26.5	51.89	100400.86	92.22	6.10	1.49	1.13
Max	31.66	4.18	97751.72	30.08	76.00	101436.16	188.80	7.16	2.66	0.72

4.1.6.2 Cyclones in the Krishna-Godavari basin

The cyclonic activity in the Krishna-Godavari basin reveals a notable frequency and variety of cyclonic systems, indicating the region's vulnerability to severe weather events. Over a span of years, a total of 16 cyclonic and severe cyclonic storms have formed or dissipated in this area, categorized into different intensities: 1 Severe Cyclonic Storm (SCS), 5 Cyclonic Storms (CS), 4 Deep Depressions (DD), and 6 Depressions (D). The average transverse velocity recorded across these events was

4.302 m/s, highlighting the dynamic nature of these storms, with a peak velocity of 7.305 m/s during a Deep Depression on November 13th, 1987, and a minimum of 2.041 m/s observed during a Depression on October 14th, 2019.

The individual cyclones present varied characteristics and impacts. The October 1985 cyclone was marked by rapid intensification, achieving maximum sustained winds of 35 knots before making landfall near Visakhapatnam. Its rapid weakening post-landfall illustrates the common pattern of cyclonic systems losing intensity upon interacting with land. Similarly, the August 1986 system also transitioned from a Deep Depression to a weaker Depression after making landfall, further emphasizing the vulnerability of coastal areas to cyclonic events.

Notably, the November 1996 cyclone demonstrated the capacity for significant intensification, classified as a severe cyclonic storm (SCS) before its impact on the Andhra Pradesh coast. Its lifecycle, from deepening to landfall and subsequent weakening, reflects the typical behaviour of cyclonic systems influenced by environmental conditions such as temperature, humidity, and pressure changes.

The impact of cyclonic systems on regional meteorology is underscored by the varied meteorological conditions recorded before and after landfall. Cyclones often exhibit drops in atmospheric pressure and increase in wind speeds, which indicates intensification. The gradual dissipation post-landfall is commonly accompanied by shifts in temperature and pressure, suggesting the interaction of these systems with land leads to a significant alteration in their characteristics. The diverse lifecycle patterns observed in these cyclones underscore the complexity of atmospheric processes and their implications for coastal communities.

Table 4. 12 Cyclone events that impacted the Krishna-Godavari Basin (1980–2020)

Serial Number	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (degrees)	Longitude (degrees)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)	Grade (text)	Distance(in degree)	Kilometers(km)	Time interval	Transverse velocity (km/hr)
1			09/10/1985	0300	12.5	90.0	1.5		25	3	D				
1			09/10/1985	1200	14.0	87.5	2.5		35	6	CS	2.92	325.29	9	36.14
1	BOB	SYSTEM CROSSED COAST NEAR VISAKHAPATNAM AT 2200 HRS UTC AT 17.5N/83.0E ON 10TH.											0.00		
1			12/10/1985	1200	19.3	81.5	2.5		35	6	DD	8.01	893.22	72	12.41
1			13/10/1985	0300	Weakend into well marked low pressure area over WMP								0.00		
													0.00		
2			10/08/1986	1200	18.0	88.0	1.5		25	3	D		0.00		
2			12/08/1986	1200	40KM SSW OF KLN		2.0		30	4	DD				
2	BOB		System Crossed Near Kalingapatnam In The Night of 12th										0.00		
2			13/08/1986	1200	120km ESE of Raipur		1.5		25	3	D				
2			14/08/1986	1200	80km NE of Seoni		1.5		25	3	D				
2			15/08/1986	0300	Weakend into well marked low pressure area								0.00		
													0.00		
3			11/11/1987	0600	14.5	89.0	1.5	1002	25	3	D		0.00		
3			11/11/1987	1800	14.5	86.5	2.0	1000	30	5	DD	2.50	278.94	9	30.99
3			11/12/1987	0300	14.5	84.5	2.5	997	35	6	CS	2.00	223.15	9	24.79
3			11/12/1987	1200	15.5	82.0	3.5	990	55	15	SCS	2.69	300.42	12	25.04
3	BOB		13/11/1987	0000	16.0	81.0	3.0	994	45	10	CS	1.12	124.74	3	41.58
3			13/11/1987	Crossed coast south of Machipatnam around 0100 UTC of 13th CS									0.00		
3			13/11/1987	0300	16.5	80.5	-	998	30	5	DD	0.71	78.89	3	26.30
3			13/11/1987	0600	17.0	80.0	-	1000	25	3	D	0.71	78.89	3	26.30
3			13/11/1987	1200	Weakened into a WML over south coastal Andhra Pradesh and adjoining Telengana								0.00		
3			13/11/1987										0.00		
													0.00		
4	BOB		01/10/1988	0300	17.5	84.5	2.0		30	4	DD		0.00		
4		System crossed near Visakhapatnam in the mid-day of 1st											0.00		
4			01/10/1988	1200	80 km NWW of VSW		1.5		25	3	D		0.00		
4	BOB		03/10/1988	0300	50 km NNE of Aurangabad		1.5		25	3	D		0.00		
4			03/10/1988	1200	weakend into low pressure area								0.00		
													0.00		
6			12/06/1996	1200	11.0	86.0	1.5	998	25	3	D		0.00		
6	BOB		13/06/1996	0300	12.5	83.0	2.0	996	30	5	DD	3.35	374.23	15	24.95
6			14/06/1996	0000	13.5	80.5	2.5	994	35	6	CS	2.69	300.42	21	14.31
6			16/06/1996	The system crossed Andhra Pradesh coast close to Visakhapatnam beyween 0500 & 0600 UTC									0.00		

6		16/06/1996	1200	WML								0.00		
												0.00		
7		04/11/1996	1500	16.0	88.0	1.5	1002	25	3	D		0.00		
7		05/11/1996	0300	16.0	86.5	2.0	1000	30	4	DD	1.50	167.36	12	13.95
7		05/11/1996	0900	16.0	86.0	2.5	992	35	6	CS	0.50	55.79	6	9.30
7		06/11/1996	0100	16.1	84.1	3.5	990	55	15	SCS	1.90	212.28	16	13.27
7	BOB	06/11/1996	0600	16.2	83.5	4.0	988	65	20	VSCS	0.61	67.87	5	13.57
7		06/11/1996	1800	16.7	82.0	3.5	990	55	16	SCS	1.58	176.41	12	14.70
7		06/11/1996		Crossed about 50 km south of Kakinada at 1600 UTC								0.00		
7		07/11/1996	0000	16.8	81.0	land	999	35	7	CS	1.00	112.13	6	18.69
7		07/11/1996	0300	17.0	80.0	-	1001	30	5	DD	1.02	113.78	3	37.93
7		07/11/1996	0600	17.5	79.0	-	1003	25	3	D	1.12	124.74	3	41.58
7		07/11/1996	1200	WML								0.00		
												0.00		
8		13/06/1998	1500	17.5	87.5	1.5	994	25	4	D		0.00		
8		13/06/1998	1800	17.5	86.0	2.0	995	30	5	DD	1.50	167.36	3	55.79
8	BOB	14/06/1998		Crossed Andhra pradesh coast near Visakhapatnam between 1500 and 1600 UTC								0.00		
8		14/06/1998	1800	18.5	81.5	land	994	25	4	D	4.61	514.33	24	21.43
8		15/06/1998	0000	19.5	80.5	land	996	20	3	D	1.41	157.79	6	26.30
8		15/06/1998	0300	20.0	80.0	land	-	-	-		0.71	78.89	3	26.30
												0.00		
9		13/10/1998	1200	15.5	82.5	1.5	1000	25	4	D		0.00		
9	BOB	13/10/1998	1800	15.5	82.0	2.0	1000	30	6	DD	0.50	55.79	6	9.30
9		14/10/1998		The system crossed Andhra pradesh coast near Narsapur (43187) at 1600 UTC.								0.00		
9		14/10/1998	1800	17.0	81.5	-	-	-	4	D	1.58	176.41		
												0.00		
10		13/11/1998	1200	13.0	87.5	1.5	1004	25	4	D		0.00		
10		14/11/1998	0300	13.5	86.5	1.5	1002	30	6	DD	1.12	124.74	15	8.32
10		14/11/1998	0900	14.0	86.0	2.5	998	35	8	CS	0.71	78.89	6	13.15
10		14/11/1998	1800	15.0	85.0	3.5	992	55	15	SCS	1.41	157.79	9	17.53
10	BOB	15/11/1998	0300	16.0	84.0	4.0	988	65	21	VSCS	1.41	157.79	9	17.53
10				Crossed north Andhra pradesh coast close to Visakhapatnam and								0.00		
10				south between 1100 and 1200 UTC.								0.00		
10		15/11/1998	1200	17.5	83.0	-	987	55	16	SCS	1.80	201.14	9	22.35
10		15/11/1998	1800	19.5	82.0	-	993	45	10	CS	2.24	249.49	6	41.58
10		16/11/1998	0300	20.5	82.0	-	998	30	5	DD	1.00	111.57	9	12.40
10		16/11/1998	0600	21.0	83.0	-	1000	20	3	D	1.12	124.74	3	41.58
												0.00		
11		14/10/2001	1200	13.5	84.0	1.5	1000	25	4	D		0.00		
11		15/10/2001	0900	13.5	81.5	2.0	1000	30	6	DD	2.50	278.94	21	13.28
11	BOB	15/10/2001	1200	13.7	81.0	2.5	998	35	8	CS	0.54	60.08	3	20.03
11		16/10/2001		The system crossed south Andhra pradesh cost near Nellore around 0000 UTC								0.00		
11		16/10/2001	1200	14.5	79.5		1002	30	6	DD	1.70	189.68	24	7.90
11		16/10/2001	1800	15.0	79.0		1004	25	4	D	0.71	78.89	6	13.15
												0.00		
12		11/12/2003	1200	4.5	90.5	1.5	1004	25	2	D		0.00		
12		13/12/2003	0300	9.0	87.5	2.0	1004	30	4	DD	5.41	603.43	39	15.47
12		13/12/2003	1200	9.5	87.0	2.5	1002	35	6	CS	0.71	78.89	9	8.77
12	BOB	14/12/2003	1200	12.0	83.5	3.5	992	55	14	SCS	4.30	479.90	24	20.00
12		15/12/2003		Crossed coast near to Machilipatnam around mid-night on 15^{th}								0.00		
12		15/12/2003	2100	16.5	81.0	-	996	45	10	CS	5.15	574.36	33	17.40
12		16/12/2003	0300	17.0	81.0	-	1000	30	6	DD	0.50	55.79	6	9.30
12		16/12/2003	0600	17.5	81.5	-	1002	25	4	D	0.71	78.89	3	26.30
												0.00		

13	BOB		21/06/2007	0300	15.5	86.0	1.5	994	25	4	D		0.00		
13			21/06/2007	1200	16.0	84.0	2.0	988	30	5	DD	2.06	230.02	9	25.56
13	The system crossed north andhra pradesh (north of Machilipatanam) between 0100 and 0300 UTC of 22nd												0.00		
13			23/06/2007	0300	18.0	76.0	-	992	25	4	D	8.25	920.06	39	23.59
13	BOB		23/06/2007	1200	Well marked low pressure over north Konkan and neighbourhood.								0.00		
												0.00	0.00		
14			13-11-2008	1200	11.5	85.5	1.5	1002	25	3	D		0.00		
14	BOB	KHAI MUK	14-11-2008	0300	12.5	85.0	2.0	1000	30	5	DD	1.12	124.74		
14			14-11-2008	1200	14.0	84.0	2.5	998	35	6	CS	1.80	201.14		
14			15-11-2008	0600	14.5	82.5	2.0	996	30	5	DD	1.58	176.41		
14	The system crossed the south andhra pradesh coast close to the north of kavali (43243) between 2200 and 2300 UTC.												0.00		
14	BOB	KHAI MUK	16-11-2008	0300	15.5	78.5	-	1004	25	3	D	4.12	460.03		
14			16-11-2008	0900	Weakened into a well marked low pressure area over								0.00		
14					Raylaseema and adjoining Telangana and interior Karnataka.								0.00		
													0.00		
15			17/05/2010	0600	10.5	88.5	1.5	1004	25	3	D		0.00		
15			17/05/2010	1200	11.0	88.0	2.0	1000	30	5	DD	0.71	78.89	6	13.15
15			18/05/2010	0000	11.5	86.5	2.5	998	35	6	CS	1.58	176.41	12	14.70
15			19/05/2010	0600	13.5	81.5	3.5	986	55	15	SCS	5.39	600.84	30	20.03
15	BOB	LAILA	20/05/2010	Severe cyclonic storm ‘Laila’ crossed Andhra Pradesh coast near Bapatla (16.00 N/80.50E) between 1100-1200 UTC.									0.00		
15			20/05/2010	1200	16.0	80.5	-	990	45	12	CS	2.69	300.42	30	10.01
15			21/05/2010	0300	16.5	81.0	-	995	30	5	DD	0.71	78.89	15	5.26
15			21/05/2010	0600	17.0	81.5	-	999	20	3	D	0.71	78.89	3	26.30
15			21/05/2010	1200	Weakened into a well marked low pressure area over								0.00		
15			21/05/2010		coastal Andhra pradesh and adjoining area								0.00		
													0.00		
16			07/12/2010	0300	14.0	82.0	1.5	1000	25	4	D		0.00		
16	BOB		07/12/2010	The system crossed south Andhra pradesh coast near Baptla around 2000 UTC of 7th									0.00		
16			08/12/2010	0000	16.0	80.0	1.5	1000	20	4	D	2.83	315.58	21	15.03
16			08/12/2010	0300	The system weakened into a well marked low pressure area over central Andhra pradesh								0.00		
													0.00		
17			11/19/2013	0000	14.5	86.5	1.5	1004	25	3	D		0.00		
17			11/19/2013	1500	15.0	85.0	2.0	1002	30	5	DD	1.58	176.41	15	11.76
17			11/20/2013	0300	15.0	84.0	2.5	1000	35	8	CS	1.00	111.57	12	9.30
17			11/21/2013	0000	15.6	83.5	3.0	994	50	15	SCS	0.78	87.14	21	4.15
17	BOB	HELEN	11/22/2013	The system crossed Andhra pradesh coast close to south of Machilliptnam near 16.1^0N/81.2^0E between 0800-0900 UTC									0.00		
17			11/22/2013	0900	16.1	81.2	-	1000	40	8	CS	2.35	262.61	33	7.96
17			11/22/2013	1200	15.9	80.7	-	1002	30	5	DD	0.54	60.08	3	20.03
17			11/22/2013	1800	15.9	80.4	-	1004	25	3	D	0.30	33.47	6	5.58
17			11/23/2013	0000	The system weakened into a well marked low pressure area over coastal Andhra Pradesh and neighbourhood.								0.00		
													0.00		
													0.00		
18			11/23/2013	1200	8.5	96.5	1.5	1004	25	3	D		0.00		
18	BOB	LEHAR	11/23/2013	1800	9.0	96.0	2.0	1002	30	5	DD	0.71	78.89	6	13.15
18			11/24/2013	0000	10.0	95.0	2.5	999	35	7	CS	1.41	157.79	6	26.30
18			11/24/2013	The system crossed Andaman & Nicobar island, south of Port Blair around 0000 UTC									0.00		

18			11/25/2013	0000	12.0	92.5	3.5	992	55	15	SCS	3.20	357.21	24	14.88
18			11/25/2013	2100	12.5	91.0	4.0	984	65	22	VSCS	1.58	176.41	21	8.40
18			11/27/2013	1200	14.5	85.0	3.5	988	55	17	SCS	6.32	705.66	39	18.09
18			11/27/2013	1800	15.0	84.0	3.0	996	45	10	CS	1.12	124.74	6	20.79
18			11/27/2013	2100	15.0	83.5	2.5	998	40	8	CS	0.50	55.79	3	18.60
18			11/28/2013	0000	15.5	82.0	2.0	1000	30	5	DD	1.58	176.41	3	58.80
18			11/28/2013		The system crossed Andhra Pradesh close to south of Machilipatnam near 15.90°N/81.10°E around 0830 UTC								0.00		
18			11/28/2013	0900	15.9	81.0	-	1002	25	4	D	1.08	120.17	9	13.35
18			11/28/2013	1800	Weakened into a well marked low pressure area over coastal Andhra Pradesh and adjoining Telengana.								0.00		
													0.00		
19			10/7/2014	0300	11.5	95.0	1.5	1004	25	3	D		0.00		
19			10/7/2014	1200	12.0	94.0	2.0	1000	30	5	DD	1.12	124.74	9	13.86
19			10/8/2014	0300	12.3	92.9	2.5	998	35	7	CS	1.14	127.21	15	8.48
19			10/8/2014		The system crossed Andaman & Nicobar islands near Long island (near lat. 12.4°N and long. 92.9°E) between 0300-0400 UTC								0.00		
19			10/9/2014	0300	13.8	89.0	3.5	988	55	16	SCS	4.18	466.21	24	19.43
19	BOB	HUDH UD	10/10/2014	0900	15.0	86.8	4.0	984	65	22	VSCS	2.51	279.60	30	9.32
19			10/11/2014	0600	16.1	85.1	5.0	966	90	40	ESCS	2.02	225.92	21	10.76
19			10/12/2014	1200	18.0	82.7	-	982	60	20	SCS	3.06	341.53	30	11.38
19			10/12/2014	1500	18.3	82.5	-	986	45	15	CS	0.36	40.23	3	13.41
19			10/12/2014	2100	18.7	82.3	-	988	40	13	DD	0.45	49.90	6	8.32
19			10/13/2014	0600	20.7	81.5	-	998	30	5	D	2.15	240.34	9	26.70
19			10/14/2014	0900	26.3	81.8	-	1000	20	3	D	5.61	625.71	27	23.17
19			10/14/2014	1200	Weakened into a well-marked low pressure area over east Uttar Pradesh and neighbourhood								0.00		
													0.00		
20			13/12/2018	0000	6.5	88.7	1.5	1004	25	3	D		0.00		
20			13/12/2018	1800	7.6	88.0	2.0	1002	30	5	DD	1.30	145.47	18	8.08
20			15/12/2018	1200	10.3	84.9	2.5	1000	35	7	CS	4.11	458.68	42	10.92
20			16/12/2018	0900	12.6	83.6	3.0	994	50	13	SCS	2.64	294.78	21	14.04
20			17/12/2018	0300	15.8	82.2	3.0	997	45	10	CS	3.49	389.71	18	21.65
20	BOB	PHET HAI	17/12/2018		Crossed Andhra Pradesh coast near 16.55°N and 82.25°E 25 km south of Yanam and 40 km south of Kakinada during 0800 to 0900 UTC								0.00		
20			17/12/2018	1200	16.9	82.4	2.0	1001	30	6	DD	1.12	124.74	9	13.86
20			17/12/2018		Crossed Andhra Pradesh coast close to Tuni during 1400 to 1500 UTC								0.00		
20			17/12/2018	1800	17.5	82.5	-	1006	25	3	D	0.61	67.87	6	11.31
20			18/12/2018	0000	Weakened into a well marked low pressure area over northwest and adjoining westcentral BoB and coastal Odisha.								0.00		
													0.00		
21	BOB		10/11/2020	0000	15.3	86.5	1.5	999	20	3	D		0.00		
21	BOB		10/12/2020	0300	15.7	85	2	997	30	5	DD	1.55	173.21	27	6.42
21	BOB		10/13/2020		Crossed north Andhra Pradesh coast close to Kakinada (near latitude 17.0°N & longitude 82.4°E)								0.00		
21	BOB		13/10/2020	0600	17.3	81.5	-	998	25	4	D	3.85	429.38	27	15.90
21	BOB		14/10/2020	0600	17.7	77	-	1000	20	3	D	4.52	504.06	24	21.00
21	BOB		14/10/2020	1200	Weakened into well marked low pressure area over south Maharashtra & neighbourhood								0.00		

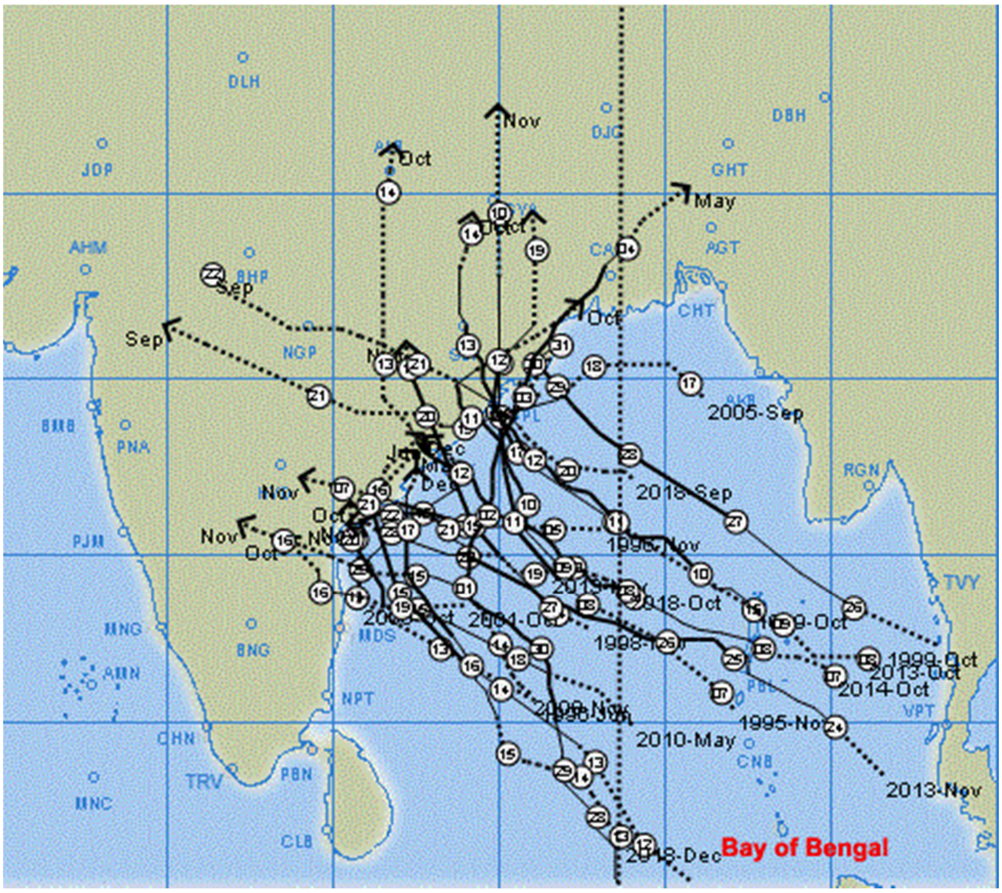


Figure 4.6 shows past cyclonic events in the KG basin

4.1.7 Mahanadi-Northeast basin

The Mahanadi basin, originating from the rifting of gondwana land, is located on India's east coast, spanning 14,000 km² in the shallow offshore region. It extends onshore in Orissa, with the offshore portion lying off the coasts of Andhra Pradesh and Orissa. The basin is situated between 80° 30' to 86° 50' east longitude and 19° 21' to 23° 35' north latitude, covering parts of Madhya Pradesh, Orissa, Bihar, and Maharashtra. The Mahanadi Basin, influenced by the Bengal deltaic system, shows potential for gas hydrates. Drilling in both onshore and offshore locations has revealed encouraging hydrocarbon indications.

4.1.7.1 Meteorological conditions

The air temperature varies from 20.34°C (in January and December) to 31.65°C (in May). The temperature is highest from April to June, indicating the summer season.

A cooling trend is observed from October to December, marking winter. Wind speed ranges from 0.75 m/s (October) to 2.48 m/s (July). The wind speed peaks during the monsoon season (June to August), suggesting strong winds and potentially heavy rainfall. Lower wind speeds occur in winter, corresponding to calmer weather conditions. Surface air pressure decreases from January (98127.67 Pa) to June (96769.53 Pa), then increases again towards December. The lowest surface air pressure occurs during summer (June to September), typical for regions experiencing high temperatures as warm air rises, reducing surface pressure. Higher pressures in winter are associated with cooler temperatures. Sea surface temperatures range from 25.10°C in January to 29.88°C in June. Temperatures gradually increase from January to June, indicating warming waters during the pre-monsoon period. The sea surface temperature stabilizes around 29°C from June to September, which aligns with the monsoon season. Relative humidity is lowest in March (49.26%) and highest in August (84.51%). Humidity gradually increases from April, peaks during the monsoon months (July to September), and then declines towards the end of the year. High humidity during the monsoon season correlates with increased rainfall and cloud cover. The mean sea level pressure follows a trend similar to surface air pressure, with the highest value in January (101525.81 Pa) and the lowest in June (100080.39 Pa). Lower pressures in summer and monsoon months indicate the formation of low-pressure systems, which are typical for monsoonal regions and often lead to precipitation. Mean wave direction ranges from 142° to 192°, indicating that the waves primarily come from the southeast to the south-southwest. The wave period ranges between 7.19 s and 8.87 s. From January to March, the period hovers around 7.43 s to 7.78 s but increases steadily, peaking at 8.87 s in October. The highest wave heights occur in May to August, with a peak of 3.40 m during June and July. The significant swell height ranges from 0.64 m in January to 1.53 m during the peak monsoon months.

Table 4.13 Meteorological parameters at Mahanadi- Northeast Coast basin

Mahanadi-Northeast Coast Basin	Air Temp (^{0}C)	Wind speed (m/s)	Surface air pressure(Pa)	Sea surface temp (^{0}C)	Relative Humidity (%)	Mean sea level pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height (m)	Significant height of total swell (m)
Jan	20.43	0.76	98127.67	25.10	58.51	101525.81	142.51	7.71	1.35	0.64
Feb	23.39	0.79	97951.27	25.99	53.42	101326.96	170.68	7.78	1.45	0.69
Mar	27.32	1.27	97691.56	27.59	49.26	101036.31	187.81	7.43	1.89	0.83
April	30.34	2.04	97391.42	28.49	49.82	100710.66	192.90	7.19	2.54	1.02
May	31.65	2.02	97047.21	29.38	54.13	100348.96	188.86	7.72	2.99	1.30
June	29.52	2.35	96769.53	29.88	70.98	100080.39	191.43	7.96	3.40	1.53
July	27.15	2.48	96791.94	29.30	83.42	100120.88	192.86	8.13	3.37	1.53
Aug	26.84	2.12	96893.26	29.21	84.51	100228.09	191.59	8.31	3.20	1.50
Sep	26.95	1.20	97206.18	29.58	82.60	100548.91	184.98	8.57	2.70	1.31
Oct	25.89	0.75	97666.28	29.55	72.62	101025.16	169.48	8.87	2.13	1.06
Nov	23.02	1.24	97991.79	27.84	62.67	101372.78	145.68	8.05	1.77	0.85
Dec	20.34	1.14	98158.93	25.93	58.95	101557.68	132.87	7.61	1.53	0.71
Min	20.34	0.75	96769.53	29.88	49.26	100080.39	132.87	7.19	1.35	0.64
Max	31.65	2.48	98158.93	25.1	84.51	101557.68	192.90	8.87	3.40	1.53

4.1.7.2 Cyclones in the Mahanadi-northeast coast basin

32 cyclonic and severe cyclonic storms have formed or dissipated over the Mahanadi-northeast coast basin. This includes 1 Extremely Severe Cyclonic Storm (ESCS), 3 Very Severe Cyclonic Storms (VSCS), 2 Severe Cyclonic Storms (SCS), 3 Deep Depressions (DD), and 23 Depressions (D). The average transverse velocity recorded was 4.359 m/s, with a maximum of 7.927 m/s during a Deep Depression on 21st September, 2018 and a minimum of 1.043 m/s during a Depression on 2nd August 1985.

During the period from May 31st to June 5th, 1982, a cyclone originating from the Bay of Bengal exhibited a notable intensification along the Mahanadi East Coast. The data indicates a gradual system strengthening, with the maximum sustained surface wind speed increasing from 25 knots on May 31st to 90 knots by June 3rd, alongside a significant pressure drop from 990 hPa to 952 hPa. The cyclone reached its peak intensity on June 3rd, categorizing it as an Extremely Severe Cyclonic Storm (ESCS). The data also highlights the cyclone's gradual weakening, as it transitioned into a well-marked low over West Uttar Pradesh after making landfall near Paradip on June 3rd, 1982.

In July 1982, a weather system originating from the Bay of Bengal progressed toward the Mahanadi east coast, with significant developments recorded between July 18th and July 20th. Initially, the system exhibited weak characteristics on July 18th, with maximum sustained winds of 25 knots and a gradual increase in central pressure to 30 knots by noon. The cyclone made landfall along the Odisha coast between Gopalpur and Puri during the early night of July 19th, marking a critical point in its trajectory. Following landfall, the system showed signs of weakening, as indicated by sustained winds dropping to 20 knots by July 20th. The final observations recorded on July 20th describe the system as a well-marked low over Central Odisha, signifying its dissipation after impacting coastal areas.

In August 1982, a cyclone system originating from the Bay of Bengal progressed towards the Odisha-West Bengal coast, with significant observations recorded from August 18th to August 20th. The system was relatively weak initially, with maximum sustained winds remaining constant at 25 knots over the initial observations on August 18th. It crossed the coast between Balasore and Contai during the night of August 18th, impacting coastal regions around that time. Following landfall, the system's intensity showed little variation, maintaining winds at 25 knots throughout August 19th, but it was categorised as a disorganised system with no significant pressure drop recorded. By August 20th, the system weakened further, transitioning into a well-marked low over Thailand and adjoining North Odisha and Chhattisgarh regions.

In late August 1982, a cyclone system emerged in the Bay of Bengal, with notable developments observed from August 27th to September 2nd. The initial observation on August 27 indicated weak conditions, with maximum sustained winds at 25 knots as the system approached the Odisha coast. It made landfall near Balasore on the night of August 28th, suggesting minimal intensity prior to crossing the coast. After landfall, the system remained relatively weak, with sustained winds recorded at 20 knots on September 2nd, highlighting a lack of significant intensification. By the end of the observation period on September 2nd, the system weakened into a well-marked low over western Uttar Pradesh, indicating a complete dissipation after its brief impact on coastal regions.

In September 1982, a cyclone system originating from the Bay of Bengal impacted the Odisha coast, with key observations recorded from September 9th to September 10th. On September 9th, the system exhibited relatively weak conditions, with maximum sustained winds at 25 knots and minimal pressure recorded. It made landfall near Puri in the early morning of September 10th, transitioning to a more organised system with winds recorded at 25 knots by 0300 UTC. Despite this slight intensification, the system was classified as weak, with no significant pressure drop observed. By the afternoon of September 10th, the cyclone weakened into a well-marked low over North Interior Odisha and adjoining Chhattisgarh, indicating a rapid dissipation following its landfall.

In June 1983, a cyclone system originating from the Bay of Bengal exhibited significant developments, particularly from June 24th to June 27th. Initial observations on June 24th indicated relatively weak conditions, with maximum sustained winds at 30 knots and a pressure classification of "Deep Depression" (DD). The system made landfall close to the northern region of Gopalpur at 1130 UTC on June 25th, marking a critical point in its progression. Following landfall, the cyclone demonstrated some intensification, with sustained winds remaining at 25 knots and increasing central pressure as recorded on June 26th and 27th. By June 27th, the system weakened into a well-marked low-pressure area, indicating a transition from a cyclonic system to a less organised state.

In late July and early August 1984, a cyclone system originating from the Bay of Bengal demonstrated significant developments, particularly from July 31st to August 7th. Initial observations on July 31st indicated weak conditions, with sustained winds recorded at 25 knots and a pressure classification of "Deep Depression." The system landed near Paradip before 1200 UTC on August 1st, impacting coastal regions. Following landfall, the cyclone exhibited a brief period of intensification, with maximum sustained winds reported at 25 knots on August 7th, when it was observed over the sea with a notable distance of 22.07 degrees logged. However, by the early hours of August 7th, the system weakened into a low-pressure area over the sea, indicating a rapid decline in intensity after landfall.

In mid-August 1984, a cyclone system originating from the Bay of Bengal exhibited notable activity, particularly from August 15th to August 19th. Initial observations on August 15 indicated the system had maximum sustained winds of 25 knots, classified as a "Deep Depression." The cyclone made landfall close to Chandbali around 1200 UTC on the same day, impacting coastal regions in Odisha. Following landfall, the system maintained its intensity, with recorded winds remaining at 25 knots on August 19. However, the system transitioned by this date into a well-marked low-pressure area, indicating a significant weakening after its coastal impact. The recorded distance of 13.42 degrees demonstrates its reach before dissipating.

In October 1984, a cyclone system developed in the Bay of Bengal, with significant observations recorded from October 13th to October 15th. On October 13th, the system exhibited weak conditions with maximum sustained winds of 25 knots, categorized as a "Deep Depression." By midday, the system showed signs of intensification, with winds increasing to 65 knots, classified as a "Very Severe Cyclonic Storm" (VSCS). It made landfall near Chandbali on the evening of October 14, marking a critical transition point as it impacted the Odisha coast. Following landfall, the cyclone maintained some intensity, with winds recorded at 55 knots (SCS) and then decreasing to 35 knots (CS) by midday on October 14th. By October 15th, the system weakened further, with sustained winds dropping to 25 knots (D). Ultimately, it dissipated into a well-marked low-pressure area shortly after.

In early August 1985, a cyclone system originating from the Bay of Bengal was monitored with significant observations from August 1st to August 2nd. Initial observations on August 1st indicated weak conditions, with maximum sustained winds at 25 knots, classified as a "Deep Depression." The system made landfall at the Odisha coast near Chandbali during the early hours of August 2nd, around 2200 UTC on August 1st, marking a pivotal moment in its development.

Following landfall, the cyclone maintained its weak classification, with sustained winds still at 25 knots as recorded at midnight on August 2nd. However, shortly thereafter, the system weakened significantly, dissipating into a low-pressure area by the morning of August 2nd.

In August 1985, another cyclone system developed in the Bay of Bengal, with significant observations recorded from August 6th to August 9th. Initial observations on August 6th indicated weak conditions, with maximum sustained winds at 25 knots, classified as a "Deep Depression." The system crossed the Odisha coast near the northern region of Chandbali at 0630 UTC, impacting the coastal areas shortly thereafter.

Following landfall, the cyclone demonstrated some activity, with winds recorded at 20 knots by August 9th, still classified as a "Deep Depression." However, the system weakened significantly by midday on the same day, transitioning into a low-pressure area.

In mid-August 1985, a cyclone system was monitored in the Bay of Bengal, with significant activity observed from August 14th to August 15th. On August 14th, the system exhibited weak conditions, with maximum sustained winds recorded at 25 knots, classified as a "Deep Depression."

By midnight on August 15, the cyclone intensified slightly, with winds still at 25 knots and moving closer to the Odisha coast. The system made landfall near Chandbali at 0000 UTC on the same day, indicating a significant moment in its progression. However, shortly after crossing the coast, the system weakened rapidly, transitioning into a well-marked low-pressure area by 0300 UTC.

Cyclone on July 1989 - The cyclone system affecting the Mahanadi East Coast in July 1989 exhibited significant activity, particularly between July 21st and July 25th. On July 21st, the system was located over the west-central and adjacent northwest Bay of Bengal, classified as a depression with a wind speed of 25 knots, indicative of low-intensity cyclonic conditions.

On July 22nd, there was an increase in activity, with observations showing wind speeds reaching 30 knots in the morning. By midday, the system intensified further, recorded at 45 knots, corresponding to a classification of "Cyclonic Storm" (CS). This escalation coincided with the system's crossing near Kalingapatnam between 1600 and 1700 UTC, which likely had significant impacts on the local coastal regions.

Following this peak intensity, on July 23rd, the system exhibited a slight decrease in wind speed, yet still maintained a classification of "Depression" with a wind speed of 30 knots. By July 25th, the cyclone had further weakened, transitioning into a well-marked low-pressure area.

The cyclone activity recorded in mid-August 1989, particularly on the 16th and 17th, exhibited significant developments. On August 16th, the system was classified as a depression with wind speeds of 25 knots and a central pressure that indicated relatively weak cyclonic conditions.

By August 17th, the system began to intensify, with observations showing wind speeds increasing to 30 knots by early morning, classified as "Deep Depression" (DD). This was likely a precursor to the system's crossing of the Kalingapatnam coast around noon, indicating a notable strengthening phase. The data recorded at noon showed a slight drop in wind speed to 25 knots, classified again as a depression, suggesting a temporary weakening phase as it approached landfall.

The following day, August 18th, the system weakened further into a low-pressure area, indicating its dissipation as it interacted with land and possibly encountered unfavourable conditions.

In early November 1989, a significant cyclonic system began as a depression on November 1st, gradually intensifying into a Cyclonic Storm (CS) by November 2nd, with wind speeds reaching 45 knots. It further strengthened to a Severe Cyclonic Storm (SCS) on November 3rd, achieving a peak intensity as an Extremely Severe Cyclonic Storm (ESCS) with wind speeds of 115 knots on November 4th. The cyclone subsequently crossed land, affecting regions in Burma and Thailand, which led to a weakening phase due to land interaction. By November 9th, the system had dissipated into a low-pressure area, marking the end of its impactful cyclonic activity after traversing the coast near Kavali, India.

In August 1997, a tropical depression developed in the Bay of Bengal, intensifying into a cyclonic system by August 20th. At 0300 UTC, it recorded wind speeds of 25 knots and a central pressure of 992 hPa. By 0600 UTC the same day, the system further intensified, with wind speeds reaching 30 knots and a pressure drop to 990 hPa as it approached the Orissa coast. The system crossed the coast near Chandbali around 0800 UTC, bringing significant rainfall and wind impacts. After making landfall, it weakened over land, with the last recorded observations on August 26th indicating a pressure of 992 hPa and wind speeds of 25 knots, before it transitioned into a well-marked low-pressure area over Punjab and adjacent Pakistan by August 27th. On August 28th, 1997, a tropical system in the Bay of Bengal was observed with wind speeds of 25 knots and a central pressure of 994 hPa at 0300 UTC. The system crossed the Orissa coast around 0600 UTC, causing weather disturbances in the region. By August 30, the system had weakened and was classified as a well-marked low-pressure area over eastern Uttar Pradesh and adjacent Bihar.

On October 15th, 1999, a tropical cyclone was tracked in the Bay of Bengal, with initial observations indicating wind speeds of 30 knots and a central pressure of 1000 hPa. Over the following days, the system intensified, reaching maximum sustained winds of 90 knots and a central pressure of 968 hPa by October 17th, ultimately classifying it as an Extremely Severe Cyclonic Storm (ESCS). The cyclone crossed the Orissa coast near Gopalpur early on October 18th. As it moved inland, it transitioned to a Severe Cyclonic Storm (SCS) and subsequently weakened, with wind speeds decreasing to 25 knots by October 19th.

From October 26th to October 31st, 1999, a significant tropical cyclone developed in the Bay of Bengal. Initial reports indicated wind speeds of 30 knots and a pressure of 1002 hPa, escalating to a Very Severe Cyclonic Storm (VSCS) with wind speeds of 65 knots and a pressure of 986 hPa by October 27th. The cyclone intensified further, achieving an Extremely Severe Cyclonic Storm (ESCS) classification with winds reaching 90 knots and a low pressure of 968 hPa on October 28th. It made landfall near Paradip on October 29th, resulting in sustained winds of 110 knots and a pressure drop to 950 hPa. As it moved inland, the cyclone weakened, transitioning to a Severe Cyclonic Storm (SCS) by October 30th before eventually dissipating into a depression by October 31st.

From July 2nd to July 5th, 2006, a tropical system formed in the Bay of Bengal, initially displaying moderate wind speeds of 25 knots and a pressure of 990 hPa. By the morning of July 2nd, wind speeds increased to 30 knots as the system approached the coast. The system made landfall between Paradip and Chandbali around 1500 UTC on July 2nd, with sustained winds reaching 30 knots and a pressure of 988 hPa. After crossing the coast, the system continued to exhibit significant activity, reaching a wind speed of 22 knots and a pressure of 990 hPa by July 5th. However, it ultimately weakened into a well-marked low-pressure area over Madhya Pradesh and adjoining southeast Rajasthan by the morning of July 5th.

From August 2nd to August 5th, 2006, a tropical system developed in the Bay of Bengal, characterized by initial wind speeds of 25 knots and a pressure of 990 hPa. By early August 2nd, wind speeds increased to 30 knots as the system approached the coast. It made landfall near Puri, South Orissa, around 0300 UTC, with sustained winds of 30 knots and a pressure drop to 988 hPa. Following the crossing, the system exhibited a wind speed of 20 knots by the morning of August 4th. However, by August 5th, the system weakened into a well-marked low-pressure area over Vidarbha and adjoining southeast Madhya Pradesh, indicating its transition from a cyclonic system to a more diffuse atmospheric feature as it moved inland.

On August 16th, 2006, a tropical system in the Bay of Bengal recorded initial wind speeds of 25 knots and a pressure of 990 hPa. The system made landfall on the North Orissa coast near Chandbali around 1400 UTC, marking its transition to an inland weather feature. By August 18th, at 0900 UTC, the system exhibited an increase in wind speed to 25 knots with a pressure of 994 hPa, indicating some residual strength. However, later that day, it weakened into a low-pressure area over northwest Madhya Pradesh and adjoining east Rajasthan by 1200 UTC, reflecting its dissipation as it moved further inland.

On August 29th, 2006, a tropical system in the Bay of Bengal recorded wind speeds of 25 knots and a pressure of 992 hPa before making landfall near Paradip on the North Orissa coast around noon. Following the landfall on September 1st, 2006, at 0600 UTC, the system's wind speed increased to 25 knots with a pressure of 994 hPa, indicating it maintained some strength. However, by 1200 UTC that same day, it weakened into a low-pressure area over west Madhya Pradesh and adjoining east Rajasthan, marking its dissipation as it moved inland.

On September 3rd, 2006, a depression in the Bay of Bengal, characterized by a wind speed of 25 knots and a pressure of 994 hPa, crossed the North Orissa coast near Chandbali around 0100 UTC. By September 4th, at 2100 UTC, the system reported a wind speed of 25 knots with a pressure of 994 hPa. However, it weakened into a low-pressure area over Chhattisgarh and adjoining east Madhya Pradesh around 0000 UTC on September 5th. The low-pressure system continued to move westward into southwest Rajasthan, eventually dissipating over western Rajasthan and surrounding areas by September 9th, 2006.

On August 5th, 2007, a depression in the Bay of Bengal was recorded with a wind speed of 25 knots and a pressure of 992 hPa. By 1800 UTC, the wind speed had increased to 30 knots, with a pressure of 988 hPa. The system crossed the Orissa coast between Chandbali and Paradip between 0100 and 0200 UTC on August 6th. Following the landfall, by August 7th at 0300 UTC, the wind speed was recorded at 25 knots with a pressure of 992 hPa. However, the system weakened into a well-marked low-pressure area over central Madhya Pradesh and adjoining areas by 1200 UTC on the same day.

On September 15th, 2008, a depression was reported in the Bay of Bengal, characterised and a pressure of 996 hPa. The following morning, on September 16th, the wind speed increased to 30 knots, with a pressure of 994 hPa. The system crossed the Orissa coast near Chandbali between 1600 and 1700 UTC that same day. By September 18th, the wind speed recorded was 25 knots, and the system maintained a pressure of 996 hPa. On September 19th, the system further intensified, reaching 26 knots, but ultimately weakened into a well-marked low-pressure area over central Uttar Pradesh and neighbouring regions later that day.

Cyclone Phailin, which occurred from October 8th to 14th, 2013, initially developed in the Bay of Bengal, with early conditions indicating a depression on October 8th, 2013, at 03:00 UTC, with a pressure of 1004 hPa and wind speeds of 25 knots. It intensified to a Deep Depression by October 9th, reaching a pressure of 1002 hPa and wind speeds of 30 knots before crossing the Andaman & Nicobar Islands. By October 10th, Phailin had reached Extremely Severe Cyclonic Storm status, with pressures as low as 966 hPa and wind speeds of up to 90 knots before making landfall near Gopalpur at 17:00 UTC. It weakened into a well-marked low-pressure area over southwest Bihar by October 14th.

Cyclone Titli, which impacted the region from October 8th to 12th, 2018, began with similar initial conditions, reporting a pressure of 1002 hPa and wind speeds of 25 knots. It intensified into a Severe Cyclonic Storm, with pressures of 994 hPa and wind speeds of 50 knots by October 9th, before crossing the north Andhra Pradesh and south Odisha coasts on October 10th. Titli weakened into a well-marked low-pressure area over Gangetic West Bengal by October 12th.

Cyclone Fani, occurring from April 26th to May 4th, 2019, started with a pressure of 998 hPa and wind speeds of 25 knots. By April 29th, it had intensified significantly, reaching 90 knots and a pressure of 962 hPa, crossing the Odisha coast near Puri on May 3rd. Fani also transitioned to a well-marked low-pressure area over central Assam after landfall.

Table 4.14 Cyclone events that impacted the Mahanadi-northeast coast basin (1980–2020)

Serial Number	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (degrees)	Longitude (degrees)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)[or "delta P"]	Grade (text)	Distance (in degree)	Kilometers(km)	Time interval	Transverse velocity (km/hr)
1			31/05/1982	1200	14.5	91.5	1.5	990	25	3	D				
1			31/05/1982	1800	19.0	91.3	2.0	988	30	4	DD	4.50	502.58	6	83.76
1			01/06/1982	0000	15.5	91.0	2.5	986	35	6	CS	3.51	391.94	6	65.32
1			02/06/1982	1200	18.0	89.0	3.0	982	45	10	SCS	3.20	357.21	36	9.92
1			03/06/1982	0300	19.0	88.0	4.0	972	65	22	VSCS	1.41	157.79	15	10.52
1	BOB		03/06/1982	0900	19.5	87.5	5.0	952	90	40	ESCS	0.71	78.89	6	13.15
1			04/06/1982	0000	21.5	86.0	4.0	970	65	22	VSCS	2.50	278.94	15	18.60
1			04/06/1982	0300	22.0	85.5	3.0	982	45	10	CS	0.71	78.89	3	26.30
1			04/06/1982	1200	23.0	84.0	2.0	988	30	4	DD	1.80	201.14	9	22.35
1			05/06/1982	0000	24.5	81.0	1.5	990	25	3	D	3.35	374.23	12	31.19
1			05/06/1982	300	25.0	81.5	1.5	991	20	3	D	0.71	78.89	3	26.30
1			05/06/1982	1200	Weakened into a WML over west UP .System crossed coast north of Paradip on 3rd evening								0.00		
													0.00		
2			18/07/1982	0300	18.0	88.0	1.5		25	4	D		0.00		
2			18/07/1982	1200	18.3	87.0	2.0		30	5	DD	1.04	116.49	9	12.94
2	BOB		19/07/1982	1200	19.0	85.5	1.5		25	4	D	1.66	184.69	24	7.70
2			19/07/1982	System crossed Odisha coast bet Gopalpur and Puri around early night (0800-1000 IST) or between 1430-1630 UTC of 19th.									0.00		
2			20/07/1982	0000	19.5	85.0	1.5		20	3	D	0.71	78.89	12	6.57
2			20/07/1982	0300	WML over central odisha								0.00		
													0.00		
3			18/08/1982	0300	21.0	88.0			25	3	D		0.00		
3			18/08/1982	1200	21.5	87.5			25	3	D	0.71	78.89	9	8.77
3	BOB B		18/08/1982		Crossed north Odisha, West Bengal coast between Balasore 18th Aug (2000-2400 IST)1500-1800 UTC								0.00		
3			19/08/1982	1200	22.2	86.0	-		25	3	D	1.66	184.69	24	7.70
3			20/08/1982	0300	Weakened into a WML over Thailand and adjoining north Odisha and Chattisgarh.								0.00		
													0.00		
4			27/08/1982	0300	19.0	88.5	1.5		25	3	D		0.00		
4	BOB		27/08/1982		Crossed Odisha coast near Balasore on 28th night (between 1500 & 1800 UTC)								0.00		
4			02/09/1982	1200	25.5	80.0			20	3	D	10.70	1193.89	153	7.80
4			02/09/1982	1800	Weakened into a WML over west UP								0.00		
													0.00		

5		09/09/1982	0300	18.0	89.0	1.5	25	3	D		0.00		
5	BOB			Crossed Odisha coast near Puri on 10th morning (0000-0100 UTC)							0.00		
5		10/09/1982	0300	20.5	85.5	1.5	25	3	D	4.30	479.90	24	20.00
5		10/09/1982	1200	Weakened into a WML over north interior Odisha and adjoining Chattisgarh							0.00		
											0.00		
6		24/06/1983	0300	18.0	87.0	2.0	30	4	DD		0.00		
6		System crossed coast close to north of Gopalpur at 1130 UTC on 25th									0.00		
6	BOB	26/06/1983	0300	20.0	83.5	-	25	3	D	4.03	449.77	48	9.37
6		27/06/1983	1200	23.5	78.0	-	25	3	D	6.52	727.37	33	22.04
6				Weakend into well marked low pressure area							0.00		
											0.00		
7		31/07/1984	0300	20.0	88.5	1.5	25	3	D		0.00		
7	BOB			Crossed coast close to Paradip before 1200 UTC							0.00		
7		07/08/1984	1800	25.0	67.0	1.5	25	3	D	22.07	2462.86	183	13.46
7		07/08/1984	0300	Weakend into low pressure area over sea							0.00		
											0.00		
8		15/08/1984	0000	19.5	90.5	1.5	25	3	D		0.00		
8	BOB			Crossed coast close to Chandbali around 1200 UTC of 15th							0.00		
8		19/08/1984	1200	25.5	78.5	-	25	3	D	13.42	1496.92	108	13.86
8		19/08/1984	1200	Weakend into well marked low pressure area							0.00		
											0.00		
9		13/10/1984	0000	19.0	88.0	1.5	25	3	D		0.00		
9		13/10/1984	0300	19.5	87.5	1.5	25	3	D	0.71	78.89	3	26.30
9		13/10/1984	1200	20.5	87.5	4.0	65	21	VSCS	1.00	111.57	9	12.40
9	BOB			System crossed coast Chandbali in the evening of 14th between 02 to 03 UTC							0.00		
9		14/10/1984	0300	20.7	86.8	-	55	15	SCS	0.73	81.23	15	5.42
9		14/10/1984	1200	21.5	86.0	-	35	8	CS	1.13	126.23	9	14.03
9		15/10/1984	0300	22.5	85.0	-	25	4	D	1.41	157.79	15	10.52
9		15/10/1984		Weakend into well marked low pressure area							0.00		
											0.00		
10		01/08/1985	0300	20.0	88.0	1.5	25	3	D		0.00		
10	BOB			System crossed at Odisha coast near Chandbali during early hours of 02.08.1985(2200 UTC of 1st)							0.00		
10		02/08/1985	0000	20.5	87.5	1.5	25	3	D	0.71	78.89	21	3.76
10		02/08/1985	0300	Weakend into low pressure area							0.00		
											0.00		
11		06/08/1985	0300	20.5	88.0	1.5	25	3	D		0.00		
11	BOB			System crossed coast near north of chandbali at 0630 UTC.							0.00		
11		09/08/1985	0300	24.0	79.0	1.5	20	2	D	9.66	1077.43	72	14.96
11			1200	Weakend into low pressure area						0.00	0.00		
											0.00		
12		14/08/1985	0300	18.5	88.0	1.5	25	3	D	0.00	0.00		
12	BOB	15/08/1985	0000	20.5	86.5	1.5	25	3	D	2.50	278.94	21	13.28
12		System crossed at odisha coast near Chandbali on 15.08.1985(0000 UTC)									0.00		
12			0300	Weakend into well marked low pressure area							0.00		

											0.00		
13		19/09/1985	0300	17.5	90.0	1.5	25	3	D		0.00		
13		19/09/1985	1800	18.5	88.0	2.0	30	4	DD	2.24	249.49	15	16.63
13		20/09/1985	0300	19.5	87.0	2.5	35	6	CS	1.41	157.79	9	17.53
13	BOB		System crossed at Odisha coast near Puri at 1300 UTC of 20th								0.00		
13		21/09/1985	0000	21.0	84.0	2.0	30	4	DD	3.35	374.23	21	17.82
13		21/09/1985	1200	22.0	82.0	1.5	25	3	D	2.24	249.49	12	20.79
13		22/09/1985	0300	Weakend into well marked low pressure area at NE							0.00		
											0.00		
14		17/07/1988	0300	18.0	86.0	1.5	25	3	D		0.00		
14	BOB			System crossed near Goplapur in the night of 17th							0.00		
14		18/07/1988	1200	50km wnw of Raipur		1.5	25	3	D				
14		19/07/1988	0300	Weaken into low pressure area							0.00		
											0.00		
15		21/07/1989	1200			1.5	25	3	D		0.00		
15		22/07/1989	0300	18.0	86.0	2.0	30	4	DD				
15		22/07/1989	1200	18.0	85.0	3.5	45	10	CS	1.00	111.57	9	12.40
15	BOB		System crossed near Kalingapatnam between 1600UTC and 1700 UTC of 22nd								0.00		
15		23/07/1989	0300	18.6	82.0	2.0	30	4	DD	3.06	341.35	15	22.76
15		25/07/1989	0300	23.6	72.6	1.5	25	3	D	10.65	1187.94	48	24.75
15		03/07/1989	0300	Weakend into well marked low pressure area							0.00		
											0.00		
17		16/08/1989	0300	16.5	86.0	1.5	25	3	D		0.00		
17		17/08/1989	0300	18.0	84.5	2.0	30	4	DD	2.12	236.68	24	9.86
17	BOB		System crossed coast near Kalingapatnam around noon time of 17th								0.00		
17		17/08/1989	1200	19.2	83.3	1.5	25	3	D	1.70	189.35	9	21.04
17		18/08/1989	0300	Weaken into low pressure area							0.00		
											0.00		
18		01/11/1989	0300	8.0	103.0	1.5	25	3	D		0.00		
18		02/11/1989	0300	8.5	102.5	3	45	10	CS	0.71	78.89	24	3.29
18		02/11/1989	1200	9.0	102.0	3.5	55	16	SCS	0.71	78.89	9	8.77
18	BOB	03/11/1989	0300	9.5	101.5	4.5	65	21	VSCS	0.71	78.89	15	5.26
18		The system intensified into a severe cyclonic storm in the forenoon of 3rd									0.00		
18		04/11/1989	0300	11.0	99.5	5.5	115	66	ESCS	2.50	278.94	24	11.62
18		System crossed the land strips of Burma & Thailand emerged into Andaman sea									0.00		
18		System crossed Andaman group of islands in the early morning of 6th									0.00		
18			0500	System intensified and moved WNW direction							0.00		
18		System crossed near Kavali around 1900UTC of 8th									0.00		
18	BOB	09/11/1989	0300	15.2	78.8	1.5	25	3	D	21.12	2356.64	120	19.64
18		09/11/1989	0600	Weakend into low pressure area							0.00		
											0.00		

19		20/08/1997	0300	20.5	87.5	1.5	992	25	4	D		0.00		
19	BOB	20/08/1997	0600	20.5	87.0	2.0	990	30	6	DD	0.50	55.79	3	18.60
19		20/08/1997	Crossed Orissa coast near Chandbali around 0800 UTC									0.00		
19		26/08/1997	1800	29.0	74.0	Over land	992	25	4	D	15.53	1732.99	156	11.11
19		27/08/1997	WML over Punjab and adjoining Pakistan									0.00		
												0.00		
20	BOB	28/08/1997	0300	19.5	87.0	1.5	994	25	4	D		0.00		
20		28/08/1997	Crossed Orissa coast around 0600 UTC of 28th august									0.00		
20		30/08/1997	1200	WML over east UP and adj Bihar								0.00		
												0.00		
21		15/10/1999	2100	15.3	89.0	2.0	1000	30	6	DD		0.00		
21	BOB	16/10/1999	0300	16.0	88.5	2.5	998	35	10	CS	0.86	95.98	6	16.00
21		16/10/1999	1500	17.6	86.0	3.5	992	55	16	SCS	2.97	331.17	12	27.60
21		17/10/1999	0000	17.7	86.0	4.0	988	65	20	VSCS	0.10	11.16	9	1.24
21		17/10/1999	1800	19.2	85.0	5.0	968	90	40	ESCS	1.80	201.14	18	11.17
21	Crossed Orissa coast near Gopalpur in the early morning hours of 18th											0.00		
21		18/10/1999	0000	19.5	85.0		970	85	38	VSCS	0.30	33.47	6	5.58
21	BOB	18/10/1999	0300	20.5	85.0	Over land	990	60	18	SCS	1.00	111.57	3	37.19
21		18/10/1999	0900	20.5	85.0		1000	40	8	CS	0.00	0.00	6	0.00
21		18/10/1999	1500	21.0	86.5		1003	30	5	DD	1.58	176.41	6	29.40
21		19/10/1999	0000	23.0	86.5		1004	25	4	D	2.00	223.15	9	24.79
												0.00		
22		26/10/1999	0000	13.5	96.5	2.0	1002	30	4	DD		0.00		
22		26/10/1999	0300	13.5	95.5	2.0	1002	35	6	CS	1.00	111.57	3	37.19
22		27/10/1999	0300	16.0	92.0	3.5	992	55	16	SCS	4.30	479.90	24	20.00
22		27/10/1999	1500	17.0	90.5	4.0	986	65	20	VSCS	1.80	201.14	12	16.76
22	BOB	28/10/1999	0600	18.0	88.5	5.0	968	90	40	ESCS	2.24	249.49	15	16.63
22		28/10/1999	1500	19.0	87.5	6.5	928	127	80	SUCS	1.41	157.79	9	17.53
22		29/10/1999	Crossed Orissa coast near Paradip between 0430 and 0630 UTC									0.00		
22		29/10/1999	1800	20.5	86.0		950	110.0	60.0	ESCS	2.12	236.68	27	8.77
22		30/10/1999	0000	20.5	86.0	Over land	994	55.0	16.0	SCS	0.00	0.00		
22		30/10/1999	0300	20.5	86.0		998	45.0	10.0	CS	0.00	0.00		
22		30/10/1999	1800	20.5	86.0		1002	30.0	6.0	DD	0.00	0.00		
22		31/10/1999	0300	21.0	87.0		1004	25.0	3.0	D	1.12	124.74	9	13.86
												0.00		
23		02/07/2006	0000	20.0	89.5	1.5	990	25	4	D		0.00		
23		02/07/2006	0300	20.5	89.0	2.0	988	30	5	DD	0.71	78.89	3	26.30
23	BOB	02/07/2006	The sysytem crossed the Orissa coast between Paradip and Chandbali around 1500 UTC									0.00		
23		04/07/2006	0900	21.5	80.0	-	988	25	4	D	9.06	1010.35	54	18.71
23		05/07/2006	0600	22.0	77.5	-	990	25	4	D	2.55	284.46	21	13.55
		05/07/2006	The system weakened into a well-marked low pressure area over west									0.00		
		05/07/2006	Madhya Pradesh and adjoining southeast Rajasthan around 0900 UTC of 5th.									0.00		
												0.00		
24	BOB	02/08/2006	0300	20.5	87.5	1.5	990	25	4	D		0.00		

24		02/08/2006	0900	20.0	87.0	2.0	988	30	5	DD	0.71	78.89	6	13.15
24		Near puri. The system crossed the south orissa coast between										0.00		
24			Puri and gopalpur around 0300 UTC.									0.00		
24	BOB	04/08/2006	0900	20.5	82.0	-	990	25	4	D	5.02	560.65	48	11.68
		05/08/2006	The system weakened into a well-marked low pressure area over Vidarbha									0.00		
		05/08/2006	And adjoining Southeast Madhya Pradesh at around 1200 UTC of 5th									0.00		
												0.00		
25		16/08/2006	0300	20.5	88.0	1.5	990	25	4	D		0.00		
25		16/08/2006	The system crossed the north Orissa coast near Chandbali around 1400 UTC.									0.00		
25	BOB B	18/08/2006	0900	23.5	77.0	-	994	25	4	D	11.40	1272.14	54	23.56
25		18/08/2006	The system weakened into a low pressure area over northwest Madhya Pradesh											
25		18/08/2006	And adjoining east Rajasthan around 1200 UTC of 18th											
26		29/08/2006	0300	20.5	87.5	1.5	992	25	4	D				
26		29/08/2006	The system crossed the north Orissa coast near Paradip around noon.											
26	BOB	01/09/2006	0600	26.0	76.5	-	994	25	4	D	12.30	1372.18	27	50.82
26		01/09/2006	The system weakened into a low pressure area over west Madhya Pradesh and									0.00		
26		01/09/2006	adjoining east Rajasthan around 1200 UTC of 1st									0.00		
												0.00		
27	BOB	03/09/2006	0300	20.0	90.0	1.5	994	25	4	D		0.00		
27	The depression crossed the north Orissa coast near Chandbali around 0100 UTC											0.00		
27	BOB	04/09/2006	2100	22.0	84.5	-	994	25	4	D	5.85	652.97	42	15.55
27	The system weakened into a low pressure area over Chhattisgarh and adjoining											0.00		
27	east Madhya Pradesh at around 0000 UTC of 5th september, but as a low pressure area											0.00		
27	It moved up to southwest Rajasthan and dissipated over west Rajasthan and											0.00		
27	adjoining areas on 9th september 2006.											0.00		
												0.00		
28		05/08/2007	0000	20.0	88.5	1.5	992	25	4	D		0.00		
28		05/08/2007	1800	20.0	87.5	2.0	988	30	5	DD	1.00	111.57	18	6.20
28	BOB	06/08/2007	Crossed Orissa coast between Chandbali and Paradip between 0100 & 0200 UTC of 6th August,2007									0.00		
28		07/08/2007	0300	21.0	82.0	-	992	25	4	D	5.59	623.72	33	18.90
28		07/08/2007	1200	Weakened into a well marked low pressure area over central								0.00		
28		07/08/2007	Madhya Pradesh and adjoining area at 1200 UTC of 7th August									0.00		
												0.00		
29		15-09-2008	1200	19.5	88.5	1.5	996	25	4	D		0.00		
29		16-09-2008	0600	20.0	87.5	2.0	994	30	5	DD	1.12	124.74	18	6.93
29	BOB	16-09-2008	The system cross the Orissa coast near Chandbali between 1600 &1700 UTC									0.00		
29		18-09-2008	0900	23.0	82.0	-	996	25	4	D	6.26	699.01	51	13.71
29		19-09-2008	0900	26.0	80.0	-	996	25	4	D	3.61	402.29	24	16.76
29		19-09-2008	1200											

29					The system weakened into a well marked low pressure area over central Uttar Pradesh and neighbourhood										
30			10/8/2013	0300	12.0	96.0	1.5	1004	25	3	D				
30			10/9/2013	0000	13.0	93.5	2.0	1002	30	5	DD	2.69	300.42	21	14.31
30			10/9/2013	System crossed Andaman & Nicobar Island near Maya Bandar between 0700-0800 UTC									0.00		
30			10/9/2013	1200	13.5	92.5	2.5	999	35	7	CS	1.12	124.74	12	10.40
30			10/10/2013	0300	14.5	91.0	3.5	990	55	15	SCS	1.80	201.14	15	13.41
30		P	10/10/2013	0600	15.0	90.5	4.0	984	65	22	VSCS	0.71	78.89	3	26.30
30	BOB	H	10/10/2013	1500	15.5	90.0	5.0	966	90	40	ESCS	0.71	78.89	9	8.77
30		AI LI	The VSCS crossed Odisha & adjoining north Andhra Pradesh coast near Gopalpur around 1700 UTC (landfall point : 19.20N and 84.90E)										0.00		
30		N	10/13/2013	0000	20.5	84.5	-	976	75	30	VSCS	7.43	829.33	57	14.55
30			10/13/2013	0300	21.0	84.0	-	990	55	15	SCS	0.71	78.89	3	26.30
30			10/13/2013	0600	21.5	84.0	-	992	40	13	CS	0.50	55.79	3	18.60
30			10/13/2013	1800	23.0	83.5	-	996	30	6	DD	1.58	176.41	12	14.70
30			10/14/2013	0300	24.0	84.1	-	1002	25	4	D	1.17	130.12	9	14.46
30			10/14/2013	0900	Weakened into a well marked low pressure area over southwest Bihar and neighbourhood								0.00		
													0.00		
31			6/20/2015	0300	18.0	86.0	1.5	990	25	4	D		0.00		
31			The system crossed Odisha coast between Gopalpur and Puri during 2000-2100 UTC										0.00		
31	BOB		6/21/2015	1800	21.0	84.5	-	992	25	3	D	3.35	374.23	39	9.60
31			6/22/2015	0000	The system weakened into a well-marked low pressure area over interior Odisha and adjoining Jharkhand and Chhattisgarh at 0000 UTC										
32			18/07/2017	0000	19	86	1.5	992	25	4	D				
32	BOB		18/07/2017	Crossed South Odisha coast close to south of Puri around 1500 UTC of 18th											
32			19/07/2017	0000	20.1	85.2	-	994	25	3	D	1.36	151.76	24	6.32
32			19/07/2017	0300	Weakened into a well-marked low pressure area over interior Odisha and neighbourhood										
33			19/10/2017	0000	16.5	86.5	1.5	999	25	3	D				
33				Crossed Odisha coast close to Paradip around 1400-1500 UTC of 19th											
33	BOB		21/10/2017	1800	24.3		-	998	20	3	D				
33			21/10/2017	Weakened into a well marked low pressure area over northeast Bangladesh and adjoining Meghalaya & south Assam at 0000 UTC of 22nd											
34			19/09/2018	1500	17.2	89.0	1.5	997	25	3	D				
34		D	20/09/2018	0300	17.5	87.0	2.0	995	30	5	DD	2.02	225.64	12	18.80
34	BOB	A	20/09/2018	1500	18.7	85.6	2.5	992	35	8	CS	1.84	205.73	12	17.14
34		Y E	20/09/2018	Crossed south Odisha and adjoining north Andhra Pradesh coasts close to Gopalpur near 19.270N/84.920E between 1900-2000 UTC of 20th September 2018									0.00		

34			21/09/2018	0000	20.0	83.7	-	994	30	6	DD	2.30	256.86	9	28.54
34			21/09/2018	1200	21.4	80.2	-	996	25	4	D	3.77	420.59	12	35.05
34			22/09/2018	0600	22.9	76.3	-	999	20	3	D	4.18	466.21	18	25.90
34			22/09/2018	1200	Weakened into a well-marked low pressure area over west Madhya Pradesh and adjoining east Rajasthan								0.00		
													0.00		
35			08/10/2018	0300	14.0	88.8	1.5	1002	25	3	D		0.00		
35			08/10/2018	1800	14.5	87.6	2.0	1000	30	5	DD	1.30	145.05	15	9.67
35			09/10/2018	0600	14.8	86.7	2.5	998	35	7	CS	0.95	105.85	12	8.82
35			09/10/2018	2100	15.7	85.8	3.0	994	50	12	SCS	1.27	142.01	15	9.47
35			10/10/2018	0600	17.0	85.6	4.0	982	70	24	VSCS	1.32	146.75	9	16.31
35		TI T LI	10/10/2018	Crossed north Andhra Pradesh and south Odisha coasts near 18.80N/84.50E during 2300 UTC of 10^{th} and -0000 UTC of 11^{th}									0.00		
35			11/10/2018	0600	19.3	83.8	-	988	60	18	SCS	2.92	325.86	24	13.58
35			11/10/2018	1200	19.9	83.7	-	996	45	10	CS	0.61	67.87	6	11.31
35			11/10/2018	1800	20.3	84.3	-	999	30	6	DD	0.72	80.46	6	13.41
35			12/10/2018	0900	20.9	85.5	-	1002	25	4	D	1.34	149.69	15	9.98
35			12/10/2018	2100	22.1	87.5	-	1004	20	3	D	2.33	260.23	12	21.69
35	BOB		13/10/2018	0000	Weakened into a well-marked low pressure area over Gangetic West Bengal and adjoining Bangladesh & BoB.								0.00		
													0.00		
36			26/04/2019	0300	2.7	89.7	1.5	998	25	4	D		0.00		
36			27/04/2019	0000	4.5	88.8	2.0	997	30	5	DD	2.01	224.54	21	10.69
36			27/04/2019	0600	5.2	88.6	2.5	995	35	7	CS	0.73	81.23	6	13.54
36			29/04/2019	1200	10.1	86.7	3.5	986	55	16	SCS	5.26	586.37	54	10.86
36			29/04/2019	2100	11.1	86.5	4.0	982	65	20	VSCS	1.02	113.78	9	12.64
36			30/04/2019	1200	13.3	84.7	5.0	962	90	40	ESCS	2.84	317.15	15	21.14
36	BOB	F A NI	03/05/2019	Crossed Odisha coast close to Puri (near lat. 19.75N and Long. 85.70E) between 0230 to 0430 UTC of 3^{rd} May, 2019									0.00		
36			03/05/2019	0600	20.2	85.9	-	966	85	36	VSCS	7.00	781.42	66	11.84
36			03/05/2019	1500	21.5	86.7	-	980	60	18	SCS	1.53	170.31	9	18.92
36			04/05/2019	0000	23.1	88.2	-	994	40	8	CS	2.19	244.70	9	27.19
36			04/05/2019	0300	23.6	88.8	-	996	30	6	DD	0.78	87.14	3	29.05
36			04/05/2019	0600	24.3	89.3	-	998	25	5	D	0.86	95.98	3	31.99
36			04/05/2019	1200	25.2	90.7	-	1000	20	4	D	1.66	185.70	6	30.95
36			04/05/2019	1800	Weakened into well marked low pressure area over central Assam & neighbourhood								0.00		

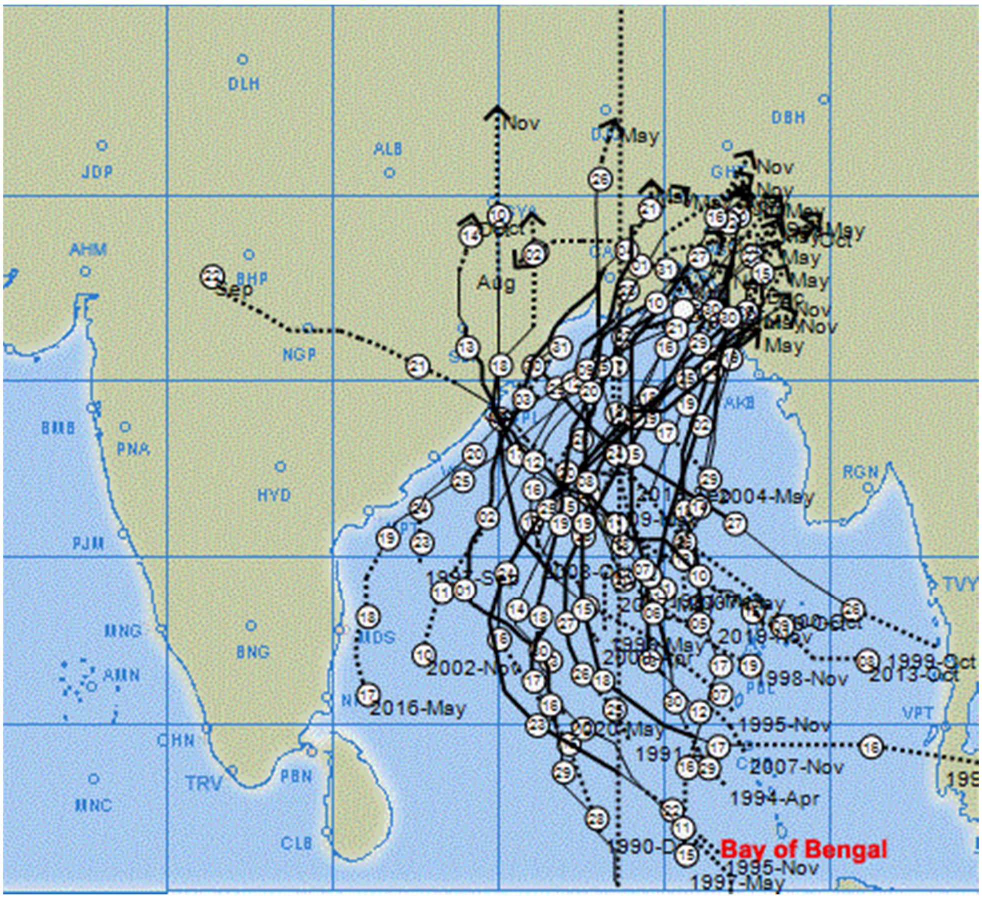


Figure 4.7 shows past cyclonic events in the Mahanadi basin

4.1.8 Andaman basin

The Andaman basin, stretching 1,200 km from Myanmar to Sumatra and 650 km from the Malay Peninsula to the Andaman & Nicobar islands, features 200 m to 2,000 m bathymetry. The main basin in the back-arc contains over 5,000 m of sediments from the late Cretaceous to recent times. It is considered a frontier area for petroleum exploration, with 14 wells drilled so far, primarily targeting the shallow fore-arc region. The Andaman Basin, influenced by discoveries in the surrounding Sumatra-Andaman-Myanmar region, is believed to have significant gas reserves.

4.1.8.1 Meteorological conditions at Andaman basin

The table 4.15 presents monthly climatological data for the Andaman basin. The air temperature remains relatively consistent, ranging from 26.5°C in January to 28.33°C in April. The highest temperatures are observed in the pre-monsoon period

(March to May). The temperature decreases slightly during the monsoon (June to September) and stabilizes again towards the end of the year. Wind speeds vary significantly, from 1.42 m/s in April to 7.70 m/s in June. The highest wind speeds occur during the monsoon months (June to August), suggesting stronger winds driven by the monsoonal activity. Wind speeds are much lower during the pre-monsoon and post-monsoon periods. Surface air pressure ranges from 100715.16 Pa in June to 101183.99 Pa in January. The pressure decreases steadily from January to June, aligning with the onset of the monsoon season. After June, the pressure stabilizes and slightly increases again towards the end of the year. Sea surface temperature ranges from 27.84°C in January to 30.16°C in April. The highest sea surface temperatures are observed in the pre-monsoon months (April and May). The temperature remains stable (around 28°C to 29°C) during the monsoon period, reflecting the moderation effect of continuous rainfall and cloud cover. Relative humidity is lowest in December (74.31%) and highest in September (84.16%). Humidity increases during the pre-monsoon period and remains high throughout the monsoon months, peaking in September. Post-monsoon, humidity levels gradually decreases. The mean sea level pressure follows a similar pattern to surface air pressure, with a peak in January (101203.07 Pa) and a trough in June (100734.08 Pa). The pressure decreases from January to June, aligning with the typical seasonal low-pressure formation during the monsoon. The pressure then starts increasing from September onwards. This analysis is consistent with the seasonal climate dynamics of tropical coastal regions influenced by the monsoon system, where seasonal changes are driven by temperature and pressure fluctuations. The wave direction shows significant seasonal variation, ranging from 126° in December to 222° in July and August. The waves predominantly come from the southeast to south-southwest, with a noticeable shift to the southwest during the monsoon period (May to August). The wave period ranges between 6.74 s in January and December to a peak of 9.61 s in April. Monsoon months (May to August) dominate in terms of wave height, with the highest value reaching 3.48 m in June. The significant swell height shows a seasonal increase, with values peaking at 1.46 m from June to August during the monsoon.

Table 4.15 Meteorological parameters at Andaman Basin

Andaman Basin	Air Temp (^{0}C)	Wind speed (m/s)	Surface air pressure (Pa)	Sea surface temp (^{0}C)	Relative Humidity (%)	Mean Sea Level Pressure (Pa)	Mean wave direction (degrees)	Mean wave period (s)	Maximum wave height (m)	Significant height of total swell (m)
Jan	26.50	4.88	101183.99	27.84	74.45	101203.07	138.03	6.74	1.82	0.82
Feb	26.72	4.03	101148.20	28.03	74.87	101167.25	184.24	7.42	1.62	0.78
Mar	27.39	2.63	101052.23	28.95	76.29	101071.24	199.97	8.60	1.54	0.78
April	28.33	1.42	100928.53	30.16	77.1	100947.49	203.18	9.61	1.70	0.87
May	28.10	4.28	100773.90	30.10	81.93	100792.83	214.03	8.69	2.62	1.21
June	27.72	7.70	100715.16	29.14	83.21	100734.08	221.13	7.75	3.48	1.45
July	27.39	7.51	100740.71	28.70	83.29	100759.65	219.84	7.83	3.43	1.46
Aug	27.23	7.56	100785.86	28.53	83.65	100804.82	222.44	7.80	3.45	1.46
Sep	26.96	5.57	100883.59	28.55	84.16	100902.58	219.56	8.23	2.84	1.30
Oct	26.97	2.07	100966.20	28.79	83.00	100985.19	203.98	8.75	2.17	1.07
Nov	27.19	3.51	101032.69	28.83	79.66	101051.69	168.80	7.68	2.01	0.93
Dec	26.99	5.13	101151.29	28.38	74.31	101170.35	126.50	6.79	2.02	0.87
Min	26.5	1.42	100715.16	27.84	74.31	100734.08	126.5	6.74	1.54	0.78
Max	28.33	7.7	101183.99	30.16	84.16	101203.07	222.44	9.61	3.48	1.46

4.1.8.2 Cyclones in the Andaman basin

A total of 4 cyclonic and severe cyclonic storms have developed or dissipated over the Andaman basin. These include 1 Severe Cyclonic Storm (SCS), 1 Cyclonic Storm (CS), 1 Deep Depression (DD), and 1 Depression (D). The average transverse velocity recorded was 5.219 m/s, with a maximum of 7.305 m/s during the Cyclonic Storm on 24th November 2013 and a minimum of 3.973 m/s during the Deep Depression on 9th October 2013.

Cyclone Phailin formed in the Bay of Bengal (BoB) and initially crossed the Andaman and Nicobar Islands near Maya Bandar on 9th October 2013. The system's maximum sustained surface winds were 25 knots, with an estimated central pressure of 1004 hPa as it developed near 12.0°N and 96.0°E. Over time, the system intensified, and on 9th October at 00:00 UTC, it reached maximum sustained winds of 30 knots with a pressure drop of 5 hPa. Phailin moved at a transverse velocity of 14.3 km/h, covering a distance of 300 km over 21 hours. It intensified into a severe storm after passing over the Andaman Islands and later made landfall on the east coast of India, causing significant destruction.

Cyclone Lehar developed in the Bay of Bengal on 23rd November 2013 near 8.5°N and 96.5°E. It began with wind speeds of 25 knots and a central pressure of 1004 hPa. By 23rd November 2013 at 18:00 UTC, the cyclone strengthened to 30 knots and a central pressure of 1002 hPa, moving at 13.15 km/h. Lehar continued to intensify, reaching 35 knots as it moved westward across the Andaman and Nicobar Islands south of Port Blair. The system crossed the islands on 24th November 2013 and subsequently moved towards the Indian mainland, weakening as it approached.

Cyclone Hudhud formed on 7th October 2014 near 11.5°N and 95.0°E in the Bay of Bengal, initially with 25 knots wind speed and a pressure of 1004 hPa. It intensified as it moved northwest and reached sustained winds of 35 knots by 8th October. The system crossed the Andaman and Nicobar Islands near Long Island between 03:00-04:00 UTC on 8th October. As it moved further west, it grew into a severe cyclonic storm, reaching 55 knots by 9th October, with a central pressure of 988 hPa. Hudhud moved at a velocity of 19.43 km/h, eventually making landfall near Visakhapatnam, causing extensive damage in the region.

Cyclone Pabuk entered the Andaman Sea from the Gulf of Thailand on 4th January 2019, initially having wind speeds of 45 knots and a pressure of 998 hPa near 8.5°N and 99.7°E. After weakening slightly over the next two days, it crossed the Andaman Islands near 11.6°N/ 92.7°E, close to Port Blair, on 6th January. At that time, it had weakened to 30 knots with a central pressure of 1002 hPa, moving at a speed of 16.75 km/h. The system later moved westward across the Bay of Bengal, gradually weakening further before dissipating.

On 13th November 1987, it had wind speeds of 30 knots and a central pressure of 998 hPa near 16.5°N and 80.5°E. Over the next few hours, the storm weakened as it moved inland, crossing the South Coastal Andhra Pradesh and Telangana regions. By 12:00 UTC, it had become a well-marked low-pressure area, dissipating shortly afterward without significant strengthening.

This depression formed in the Bay of Bengal on 1st October 1988 near 17.5°N and 84.5°E, with wind speeds of 30 knots. The cyclone crossed near Visakhapatnam by mid-day, weakening soon after. By 3rd October, the system moved inland, reaching 50 km north-northeast of Aurangabad. It dissipated after transitioning into a low-pressure area on 3rd October 1988.

The cyclone developed on 12th June 1996 near 11.0°N and 86.0°E. It initially had wind speeds of 25 knots, with a central pressure of 998 hPa. Over the next few days, the storm intensified, reaching 35 knots with a pressure of 994 hPa by 14th June. It moved toward Andhra Pradesh, crossing near Visakhapatnam on 16th June. The system weakened soon after landfall and dissipated into a low-pressure area.

On 4th November 1996, a cyclone formed near 16.0°N and 88.0°E in the Bay of Bengal. The system began with wind speeds of 25 knots and strengthened as it moved westward, reaching 65 knots and a central pressure of 988 hPa by 6th November. The storm crossed about 50 km south of Kakinada on 6th November. After landfall, it weakened gradually and dissipated by 7th November into a low-pressure area.

A cyclone developed on 13th June 1998 near 17.5°N and 87.5°E, with winds of 25 knots and a pressure of 994 hPa. The system moved westward, reaching wind speeds of 30 knots as it crossed Andhra Pradesh near Visakhapatnam on 14th June. After landfall, the cyclone weakened, dissipating into a low-pressure area over land by 15th June 1998.

A system formed on 13th October 1998 near 15.5°N and 82.5°E with winds of 25 knots and a central pressure of 1000 hPa. It moved westward and crossed the Andhra Pradesh coast near Narsapur on 14th October. By this time, it had intensified slightly to 30 knots. The system weakened after landfall, dissipating over inland areas by 14th October 1998.

On 13th November 1998, a system developed near 13.0°N and 87.5°E with wind speeds of 25 knots and a pressure of 1004 hPa. The cyclone intensified over the next two days, reaching 55 knots and a central pressure of 988 hPa as it crossed the Andhra Pradesh coast close to Visakhapatnam on 15th November. It weakened shortly after and dissipated by 16th November.

This depression formed near 13.5°N and 84.0°E on 14th October 2001 with wind speeds of 25 knots and a central pressure of 1000 hPa. Over the next day, it intensified, reaching 35 knots before crossing the South Andhra Pradesh coast near Nellore on 16th October. After crossing, it weakened into a low-pressure area, dissipating soon after.

A cyclone formed on 11th December 2003 near 4.5°N and 90.5°E with wind speeds of 25 knots. The storm intensified as it moved westward, reaching 55 knots and a central pressure of 992 hPa by 14th December. It crossed the Andhra Pradesh coast near Machilipatnam on 15th December. The cyclone weakened after landfall and dissipated by 16th December.

Cyclone Khaimuk formed in the Bay of Bengal near 11.5°N and 85.5°E on 13th November 2008 with wind speeds of 25 knots and a pressure of 1002 hPa. The system intensified as it moved westward, reaching 35 knots by 14th November before crossing the south Andhra Pradesh coast near Kavali. It weakened shortly after landfall and dissipated into a low-pressure area by 16th November.

Cyclone Laila formed on 17th May 2010 near 10.5°N and 88.5°E in the Bay of Bengal with wind speeds of 25 knots. It strengthened as it moved westward, reaching 55 knots by 19th May. The cyclone crossed the Andhra Pradesh coast near Bapatla on 20th May with wind speeds of 45 knots and a central pressure of 990 hPa. After landfall, Laila weakened and dissipated over inland regions.

The cyclone formed in the Bay of Bengal and landed near Baptla, Andhra Pradesh, on December 7th, 2010, characterized by sustained winds of 14.0 knots and a central pressure of 1000 hPa. Over the next few hours, it weakened into a well-marked low-pressure area as it moved inland. Despite its initial strength, the system showed a rapid decrease in intensity shortly after crossing the coast.

Cyclone HELEN emerged in the Bay of Bengal on November 19th, 2013, with a notable increase in intensity as it approached the Andhra Pradesh coast. It reached a maximum intensity of 50 knots with a central pressure of 994 hPa before making landfall close to Machilipatnam on November 22nd. HELEN caused significant rainfall and flooding, weakening to a low-pressure area shortly after landfall, which affected the coastal region and nearby areas.

Cyclone LEHAR developed on November 23rd, 2013, and initially showed a gradual strengthening with maximum sustained winds of 55 knots. It crossed the Andaman & Nicobar Islands and strengthened as it approached the Andhra Pradesh coast, making landfall on November 28th near Machilipatnam. Following its landfall, LEHAR weakened into a well-marked low-pressure area, resulting in widespread rainfall and disrupting normal life in the affected regions.

Cyclone PHETHAI developed in December 2018 and exhibited moderate intensity, with winds reaching up to 55 knots. It crossed the Andhra Pradesh coast south of Yanam on December 17th, causing considerable rainfall in the region. After landfall, PHETHAI weakened into a well-marked low-pressure area, leading to further rainfall but less destruction than previous cyclones. Its impact included localized flooding and disruptions to transportation and daily activities.

Cyclone 21 formed in the Bay of Bengal in October 2020, showcasing moderate intensity with sustained winds reaching up to 30 knots. It crossed the North Andhra Pradesh coast close to Kakinada on October 13th, bringing significant rainfall and wind to the region. After making landfall, the system weakened into a well-marked low-pressure area, resulting in localized flooding but less severe impacts compared to the more intense cyclones in previous years.

Table 4.16 Cyclone Events That Impacted the Andaman Basin (1980–2020)

Serial Number of system during	Basin of origin	Name	Date(DD/MM/YYYY)	Time (UTC)	Latitude (degrees)	longitude (degrees)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained Surface Wind	Pressure Drop (hPa)[or "delta P"]	Grade (text)	Distance(in degree)	Kilometers(km)	Time interval	Transverse velocity (km/hr)
1		PHAILIN	10/8/2013	0300	12.0	96.0	1.5	1004	25	3	D				
1	BOB	PHAILIN	10/9/2013	0000	13.0	93.5	2.0	1002	30	5	DD	2.69	300.42	21	14.31
1		PHAILIN	10/9/2013	System crossed Andaman & Nicobar Island near Maya Bandar between 0700-0800 UTC									0.00		
													0.00		
2		LEHAR	11/23/2013	1200	8.5	96.5	1.5	1004	25	3	D		0.00		
2	BOB	LEHAR	11/23/2013	1800	9.0	96.0	2.0	1002	30	5	DD	0.71	78.89	6	13.15
2		LEHAR	11/24/2013	0000	10.0	95.0	2.5	999	35	7	CS	1.41	157.79	6	26.30
2		LEHAR	11/24/2013	The system crossed Andaman & Nicobar island, south of Port Blair around 0000 UTC									0.00		
													0.00		
3		HUDHUD	10/7/2014	0300	11.5	95.0	1.5	1004	25	3	D		0.00		
3		HUDHUD	10/7/2014	1200	12.0	94.0	2.0	1000	30	5	DD	1.12	124.74	9	13.86
3	BOB	HUDHUD	10/8/2014	0300	12.3	92.9	2.5	998	35	7	CS	1.14	127.21	15	8.48
3		HUDHUD	10/8/2014	The system crossed Andaman & Nicobar islands near Long island (near Lat. 12.4°N and Long. 92.9°E) between 0300-0400 UTC									0.00		
3		HUDHUD	10/9/2024	0300	13.8	89.0	3.5	988	55	16	SCS	4.18	466.21	24	19.43
													0.00		
4		PABUK	04/01/2019	1200	8.5	99.7	-	998	45	10	CS		0.00		
4		PABUK	06/01/2019	0600	11.2	94.0	2.0	1002	30	6	DD	6.31	703.71	42	16.76
4		PABUK	06/01/2019	Crossed Andaman Islands near 11.6°N/ 92.7°E, close to south of Port Blair between 1300 and 1500 UTC of 6th January 2019									0.00		
4		PABUK	07/01/2019	0000	12.6	92	1.5	1004	25	4	D	2.44	272.39	18	15.13
4			13/11/1987	0300	16.5	80.5	-	998	30	5	DD			3	
4			13/11/1987	0600	17.0	80.0	-	1000	25	3	D	0.71	78.89	3	26.30
4			13/11/1987	1200	Weakened into a WML over south coastal Andhra Pradesh and adjoining Telengana								0.00		
4			13/11/1987										0.00		
	BOB														

												0.00		
5	BOB	01/10/1988	0300	17.5	84.5	2.0		30	4	DD		0.00		
5		System crossed near N Visakhapatnam in the mid-day of 1st										0.00		
5		01/10/1988	1200	80km WNW of VSK		1.5		25	3	D		0.00		
5	BOB	03/10/1988	0300	50km NNE of Aurangabad		1.5		25	3	D		0.00		
5		03/10/1988	1200	Weakend into low pressure area								0.00		
												0.00		
6		12/06/1996	1200	11.0	86.0	1.5	998	25	3	D		0.00		
6		13/06/1996	0300	12.5	83.0	2.0	996	30	5	DD	3.35	374.23		
6	BOB	14/06/1996	0000	13.5	80.5	2.5	994	35	6	CS	2.69	300.42		
6		16/06/1996	The system crossed Andhra Pradesh coast close to Visakhapatnam between 0500 & 0600 UTC									0.00		
6		16/06/1996	1200	WML								0.00		
												0.00		
7		04/11/1996	1500	16.0	88.0	1.5	1002	25	3	D		0.00		
7		05/11/1996	0300	16.0	86.5	2.0	1000	30	4	DD	1.50	167.36	12	13.95
7		05/11/1996	0900	16.0	86.0	2.5	992	35	6	CS	0.50	55.79	6	9.30
7		06/11/1996	0100	16.1	84.1	3.5	990	55	15	SCS	1.90	212.28	16	13.27
7		06/11/1996	0600	16.2	83.5	4.0	988	65	20	VSCS	0.61	67.87	5	13.57
7	BOB	06/11/1996	1800	16.7	82.0	3.5	990	55	16	SCS	1.58	176.41	12	14.70
7		06/11/1996	Crossed about 50 km south of Kakinada at 1600 UTC									0.00		
7		07/11/1996	0000	16.8	81.0	land	999	35	7	CS	1.00	112.13	6	18.69
7		07/11/1996	0300	17.0	80.0	-	1001	30	5	DD	1.02	113.78	3	37.93
7		07/11/1996	0600	17.5	79.0	-	1003	25	3	D	1.12	124.74	3	41.58
7		07/11/1996	1200	WML								0.00		
												0.00		
8		13/06/1998	1500	17.5	87.5	1.5	994	25	4	D		0.00		
8		13/06/1998	1800	17.5	86.0	2.0	995	30	5	DD	1.50	167.36	3	55.79
8	BOB	14/06/1998	Crossed Andhra Pradesh coast near Visakhapatnam between 1500 and 1600 UTC									0.00		
8		14/06/1998	1800	18.5	81.5	land	994	25	4	D	4.61	514.33	24	21.43
8		15/06/1998	0000	19.5	80.5	land	996	20	3	D	1.41	157.79	6	26.30
8		15/06/1998	0300	20.0	80.0	land	-	-	-		0.71	78.89	3	26.30
												0.00		
9		13/10/1998	1200	15.5	82.5	1.5	1000	25	4	D		0.00		
9	BOB	13/10/1998	1800	15.5	82.0	2.0	1000	30	6	DD	0.50	55.79	6	9.30
9		14/10/1998	The system crossed Andhra Pradesh coast near Narsapur (43187) at 1600 UTC.									0.00		

9		14/10/1998	1800	17.0	81.5	-	-	-	4	D	1.58	176.41		
												0.00		
10		13/11/1998	1200	13.0	87.5	1.5	1004	25	4	D		0.00		
10		14/11/1998	0300	13.5	86.5	1.5	1002	30	6	DD	1.12	124.74	15	8.32
10	BOB	14/11/1998	0900	14.0	86.0	2.5	998	35	8	CS	0.71	78.89	6	13.15
10		14/11/1998	1800	15.0	85.0	3.5	992	55	15	SCS	1.41	157.79	9	17.53
10		15/11/1998	0300	16.0	84.0	4.0	988	65	21	VSCS	1.41	157.79	9	17.53
10		Crossed north Andhra Pradesh coast close to Visakhapatnam and south of it										0.00		
10		between 1100 and 1200 UTC.										0.00		
10		15/11/1998	1200	17.5	83.0	-	987	55	16	SCS	1.80	201.14	9	22.35
10	BOB	15/11/1998	1800	19.5	82.0	-	993	45	10	CS	2.24	249.49	6	41.58
10		16/11/1998	0300	20.5	82.0	-	998	30	5	DD	1.00	111.57	9	12.40
10		16/11/1998	0600	21.0	83.0	-	1000	20	3	D	1.12	124.74	3	41.58
												0.00		
11		14/10/2001	1200	13.5	84.0	1.5	1000	25	4	D		0.00		
11		15/10/2001	0900	13.5	81.5	2.0	1000	30	6	DD	2.50	278.94	21	13.28
11		15/10/2001	1200	13.7	81.0	2.5	998	35	8	CS	0.54	60.08	3	20.03
11		16/10/2001	The system crossed south Andhra Pradesh cost near Nellore around 0000 UTC									0.00		
11		16/10/2001	1200	14.5	79.5		1002	30	6	DD	1.70	189.68	24	7.90
11	BOB	16/10/2001	1800	15.0	79.0		1004	25	4	D	0.71	78.89	6	13.15
												0.00		
12		11/12/2003	1200	4.5	90.5	1.5	1004	25	2	D		0.00		
12		13/12/2003	0300	9.0	87.5	2.0	1004	30	4	DD	5.41	603.43	39	15.47
12		13/12/2003	1200	9.5	87.0	2.5	1002	35	6	CS	0.71	78.89	9	8.77
12	BOB	14/12/2003	1200	12.0	83.5	3.5	992	55	14	SCS	4.30	479.90	24	20.00
12		15/12/2003	Crossed coast near to Machilipatnam around mid-night on december 15th									0.00		
12		15/12/2003	2100	16.5	81.0	-	996	45	10	CS	5.15	574.36	33	17.40
12		16/12/2003	0300	17.0	81.0	-	1000	30	6	DD	0.50	55.79	6	9.30
12		16/12/2003	0600	17.5	81.5	-	1002	25	4	D	0.71	78.89	3	26.30
												0.00		
13	BOB	21/06/2007	0300	15.5	86.0	1.5	994	25	4	D		0.00		
13		21/06/2007	1200	16.0	84.0	2.0	988	30	5	DD	2.06	230.02	9	25.56
13	The system crossed north Andhra Pradesh (north of Machilipatanam) between 0100 and 0300 UTC of 22nd June											0.00		
13	BOB	23/06/2007	0300	18.0	76.0	-	992	25	4	D	8.25	920.06	39	23.59
13		23/06/2007	1200	Well marked low pressure over north Konkan and neighbourhood.								0.00		
											0.00	0.00		

14		KHAIMUK	13-11-2008	1200	11.5	85.5	1.5	1002	25	3	D		0.00		
14	BOB	KHAIMUK	14-11-2008	0300	12.5	85.0	2.0	1000	30	5	DD	1.12	124.74		
14		KHAIMUK	14-11-2008	1200	14.0	84.0	2.5	998	35	6	CS	1.80	201.14		
14		KHAIMUK	15-11-2008	0600	14.5	82.5	2.0	996	30	5	DD	1.58	176.41		
14	The system crossed the south Andhra Pradesh coast close to the north of Kavali (43243) between 2200 and 2300 UTC.												0.00		
14		KHAIMUK	16-11-2008	0300	15.5	78.5	-	1004	25	3	D	4.12	460.03		
14	BOB	KHAIMUK	16-11-2008	0900	Weakened into a well marked low pressure area over Raylaseema and								0.00		
14					adjoining Telangana and interior Karnataka.								0.00		
													0.00		
15		LAILA	17/05/2010	0600	10.5	88.5	1.5	1004	25	3	D		0.00		
15		LAILA	17/05/2010	1200	11.0	88.0	2.0	1000	30	5	DD	0.71	78.89	6	13.15
15		LAILA	18/05/2010	0000	11.5	86.5	2.5	998	35	6	CS	1.58	176.41	12	14.70
15		LAILA	19/05/2010	0600	13.5	81.5	3.5	986	55	15	SCS	5.39	600.84	30	20.03
15	BOB		20/05/2010		Severe cyclonic storm ‘LAILA’ crossed Andhra Pradesh coast near Bapatla (16.00°N/80.50°E) between 1100-1200 UTC.								0.00		
15		LAILA	20/05/2010	1200	16.0	80.5	-	990	45	12	CS	2.69	300.42	30	10.01
15		LAILA	21/05/2010	0300	16.5	81.0	-	995	30	5	DD	0.71	78.89	15	5.26
15		LAILA	21/05/2010	0600	17.0	81.5	-	999	20	3	D	0.71	78.89	3	26.30
15		LAILA	21/05/2010	1200	Weakened into a well marked low pressure area over								0.00		
15			21/05/2010		coastal Andhra Pradesh and adjoining area								0.00		
													0.00		
16			07/12/2010	0300	14.0	82.0	1.5	1000	25	4	D		0.00		
16	BOB		07/12/2010		The system crossed south Andhra Pradesh coast near Baptla around 2000 UTC of 07th December 2010								0.00		
16			08/12/2010	0000	16.0	80.0	1.5	1000	20	4	D	2.83	315.58	21	15.03
16			08/12/2010	0300	The system weakened into a well marked low pressure area over central Andhra Pradesh								0.00		
													0.00		
17		HELEN	11/19/2013	0000	14.5	86.5	1.5	1004	25	3	D		0.00		
17		HELEN	11/19/2013	1500	15.0	85.0	2.0	1002	30	5	DD	1.58	176.41	15	11.76
17		HELEN	11/20/2013	0300	15.0	84.0	2.5	1000	35	8	CS	1.00	111.57	12	9.30
17		HELEN	11/21/2013	0000	15.6	83.5	3.0	994	50	15	SCS	0.78	87.14	21	4.15
17	BOB	HELEN	11/22/2013		The system crossed Andhra Pradesh coast close to south of Machilliptnam near 16.1°N/81.2°E between 0800-0900UTC								0.00		
17		HELEN	11/22/2013	0900	16.1	81.2	-	1000	40	8	CS	2.35	262.61	33	7.96
17		HELEN	11/22/2013	1200	15.9	80.7	-	1002	30	5	DD	0.54	60.08	3	20.03
17		HELEN	11/22/2013	1800	15.9	80.4	-	1004	25	3	D	0.30	33.47	6	5.58
17		HELEN	11/23/2013	0000	The system weakened into a well marked low pressure area over coastal Andhra Pradesh and neighbourhood.								0.00		
													0.00		
													0.00		

18		LEHAR	11/23/2013	1200	8.5	96.5	1.5	1004	25	3	D		0.00		
18		LEHAR	11/23/2013	1800	9.0	96.0	2.0	1002	30	5	DD	0.71	78.89	6	13.15
18		LEHAR	11/24/2013	0000	10.0	95.0	2.5	999	35	7	CS	1.41	157.79	6	26.30
18		LEHAR	11/24/2013	The system crossed Andaman & Nicobar island, south of Port Blair around 0000 UTC									0.00		
18		LEHAR	11/25/2013	0000	12.0	92.5	3.5	992	55	15	SCS	3.20	357.21	24	14.88
18		LEHAR	11/25/2013	2100	12.5	91.0	4.0	984	65	22	VSCS	1.58	176.41	21	8.40
18		LEHAR	11/27/2013	1200	14.5	85.0	3.5	988	55	17	SCS	6.32	705.66	39	18.09
18		LEHAR	11/27/2013	1800	15.0	84.0	3.0	996	45	10	CS	1.12	124.74	6	20.79
18		LEHAR	11/27/2013	2100	15.0	83.5	2.5	998	40	8	CS	0.50	55.79	3	18.60
18		LEHAR	11/28/2013	0000	15.5	82.0	2.0	1000	30	5	DD	1.58	176.41	3	58.80
18	BOB	LEHAR	11/28/2013	The system crossed Andhra Pradesh close to south of Machilipatnam near 15.90°N/81.10°E around 0830 UTC									0.00		
18		LEHAR	11/28/2013	0900	15.9	81.0	-	1002	25	4	D	1.08	120.17	9	13.35
18		LEHAR	11/28/2013	1800	Weakened into a well marked low pressure area over coastal Andhra Pradesh and adjoining Telengana.								0.00		
													0.00		
19		HUDHUD	10/7/2014	0300	11.5	95.0	1.5	1004	25	3	D		0.00		
19		HUDHUD	10/7/2014	1200	12.0	94.0	2.0	1000	30	5	DD	1.12	124.74	9	13.86
19		HUDHUD	10/8/2014	0300	12.3	92.9	2.5	998	35	7	CS	1.14	127.21	15	8.48
19		HUDHUD	10/8/2014	The system crossed Andaman & Nicobar islands near Long island (near Lat. 12.4°N and Long. 92.9°E) between 0300-0400 UTC									0.00		
19		HUDHUD	10/9/2014	0300	13.8	89.0	3.5	988	55	16	SCS	4.18	466.21	24	19.43
19	BOB	HUDHUD	10/10/2014	0900	15.0	86.8	4.0	984	65	22	VSCS	2.51	279.60	30	9.32
19		HUDHUD	10/11/2014	0600	16.1	85.1	5.0	966	90	40	ESCS	2.02	225.92	21	10.76
19		HUDHUD	10/12/2014	1200	18.0	82.7	-	982	60	20	SCS	3.06	341.53	30	11.38
19		HUDHUD	10/12/2014	1500	18.3	82.5	-	986	45	15	CS	0.36	40.23	3	13.41
19		HUDHUD	10/12/2014	2100	18.7	82.3	-	988	40	13	DD	0.45	49.90	6	8.32
19		HUDHUD	10/13/2014	0600	20.7	81.5	-	998	30	5	D	2.15	240.34	9	26.70
19		HUDHUD	10/14/2014	0900	26.3	81.8	-	1000	20	3	D	5.61	625.71	27	23.17
19		HUDHUD	10/14/2014	1200	Weakened into a well-marked low pressure area over east Uttar Pradesh and neighbourhood								0.00		
													0.00		
20		PHETHAI	13/12/2018	0000	6.5	88.7	1.5	1004	25	3	D		0.00		
20	BOB	PHETHAI	13/12/2018	1800	7.6	88.0	2.0	1002	30	5	DD	1.30	145.47	18	8.08
20		PHETHAI	15/12/2018	1200	10.3	84.9	2.5	1000	35	7	CS	4.11	458.68	42	10.92
20		PHETHAI	16/12/2018	0900	12.6	83.6	3.0	994	50	13	SCS	2.64	294.78	21	14.04
20		PHETHAI	17/12/2018	0300	15.8	82.2	3.0	997	45	10	CS	3.49	389.71	18	21.65

20		PHETHAI	17/12/2018	Crossed Andhra Pradesh coast near 16.55°N and 82.25°E 25 km south of Yanam and 40 km south of Kakinada during 0800 to 0900 UTC									0.00		
20		PHETHAI	17/12/2018	1200	16.9	82.4	2.0	1001	30	6	DD	1.12	124.74	9	13.86
20		PHETHAI	17/12/2018	Crossed Andhra Pradesh coast close to TUNI during 1400 to 1500 UTC									0.00		
20		PHETHAI	17/12/2018	1800	17.5	82.5	-	1006	25	3	D	0.61	67.87	6	11.31
20		PHETHAI	18/12/2018	0000	Weakened into a well marked low pressure area over northwest and adjoining west central Bay of Bengal and coastal Odisha.								0.00		
													0.00		
21			10/11/2020	0000	15.3	86.5	1.5	999	20	3	D		0.00		
21			10/12/2020	0300	15.7	85	2	997	30	5	DD	1.55	173.21	27	6.42
21	BOB		10/13/2020	Crossed North Andhra Pradesh coast close to Kakinada (near latitude 17.0°N & longitude 82.4°E)									0.00		
21			13/10/2020	0600	17.3	81.5	-	998	25	4	D	3.85	429.38	27	15.90
21			14/10/2020	0600	17.7	77	-	1000	20	3	D	4.52	504.06	24	21.00
21			14/10/2020	1200	Weakened into well marked low pressure area over south Madhya Maharashtra & neighbourhood								0.00		

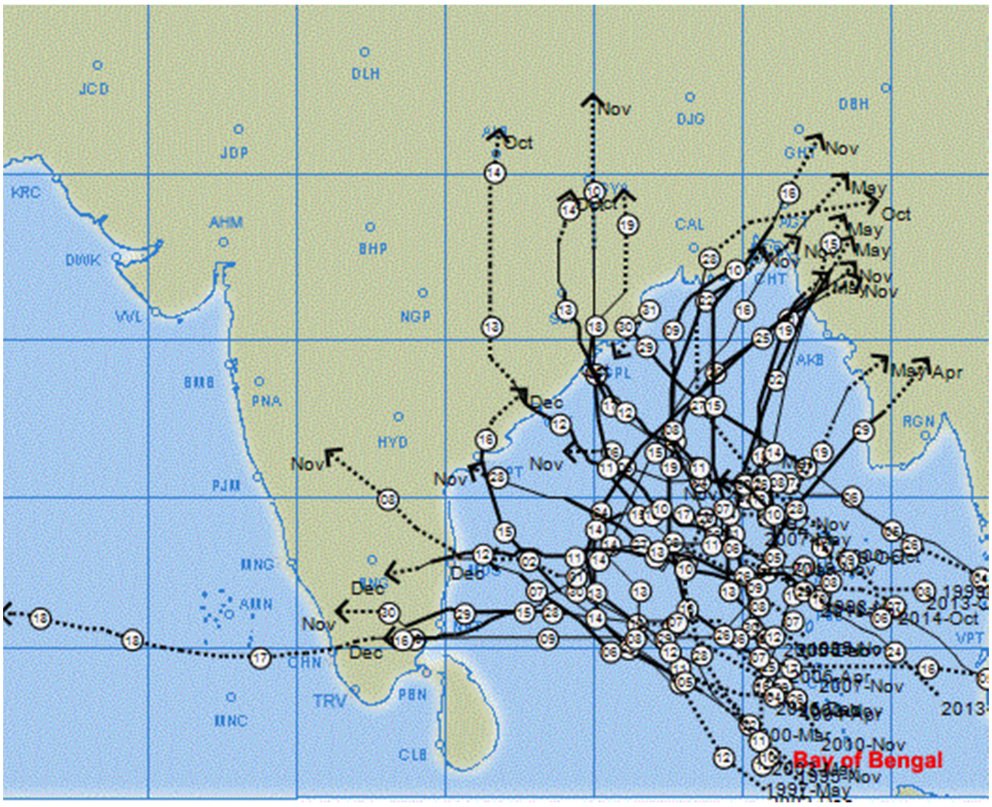


Figure 4.8 shows Past Cyclonic events in the Andaman Basin

4.2 Marine protected areas (MPAs) (Sanctuaries and National Parks) in India

The MPA network in India has been used to manage natural marine resources for biodiversity conservation and the well-being of the people dependent on them. Scientific monitoring and traditional observations confirm that depleted natural marine resources are being restored and/or pristine ecological conditions have been sustained in well-managed MPAs (Halpern 2003). India has designated four legal categories of protected areas: National Parks, Wildlife Sanctuary, Conservation Reserve and Community Reserve. India has created a network of PAs representing all its 10 biogeographic regions (Rodgers et al. 2002). A total of 690 protected areas have been established in India as of 1st April 2014, including 102 national parks, 527 wildlife sanctuaries, 57 conservation reserves and 4 community reserves. Besides, 26 wetlands have been designated as Ramsar sites.

In India, PAs that fall entirely or partially within the swathe of 500 m from the high tide line and the marine environment are considered to be in the MPA network. There are 25 MPAs in peninsular India and more than 105 MPAs in the country's islands (see Table 4.17 & 4.18). The 24 MPAs of the mainland have a total area of about 8214 km^2, which is about 5 % of the total area under the entire PA network of India and less than 0.3% of India's total land area. The Gulf of Mannar Marine National Park, Sundarbans National Park, Gulf of Kachchh National Park, Gahirmatha Marine Sanctuary, Coringa Wildlife Sanctuary and Chilika Wildlife Sanctuary on the mainland have unique marine biodiversity and provide a range of ecological services to the local communities. The total area of the Andaman and Nicobar Islands is 4947 km^2, of which 1510 km^2 is protected under the provisions of India's Wildlife (Protection) Act, 1972. There are 105 PAs in the Andaman and Nicobar Islands, and all are part of India's MPA network. These MPAs cover about 60% of the terrestrial area of the islands and protect more than 40% of the coastal habitat. Mahatma Gandhi Marine National Park and Rani Jhansi Marine National Park are important MPAs here. Pitti Island (0.01 km2) is the only island with an MPA status in the Lakshadweep group of islands.

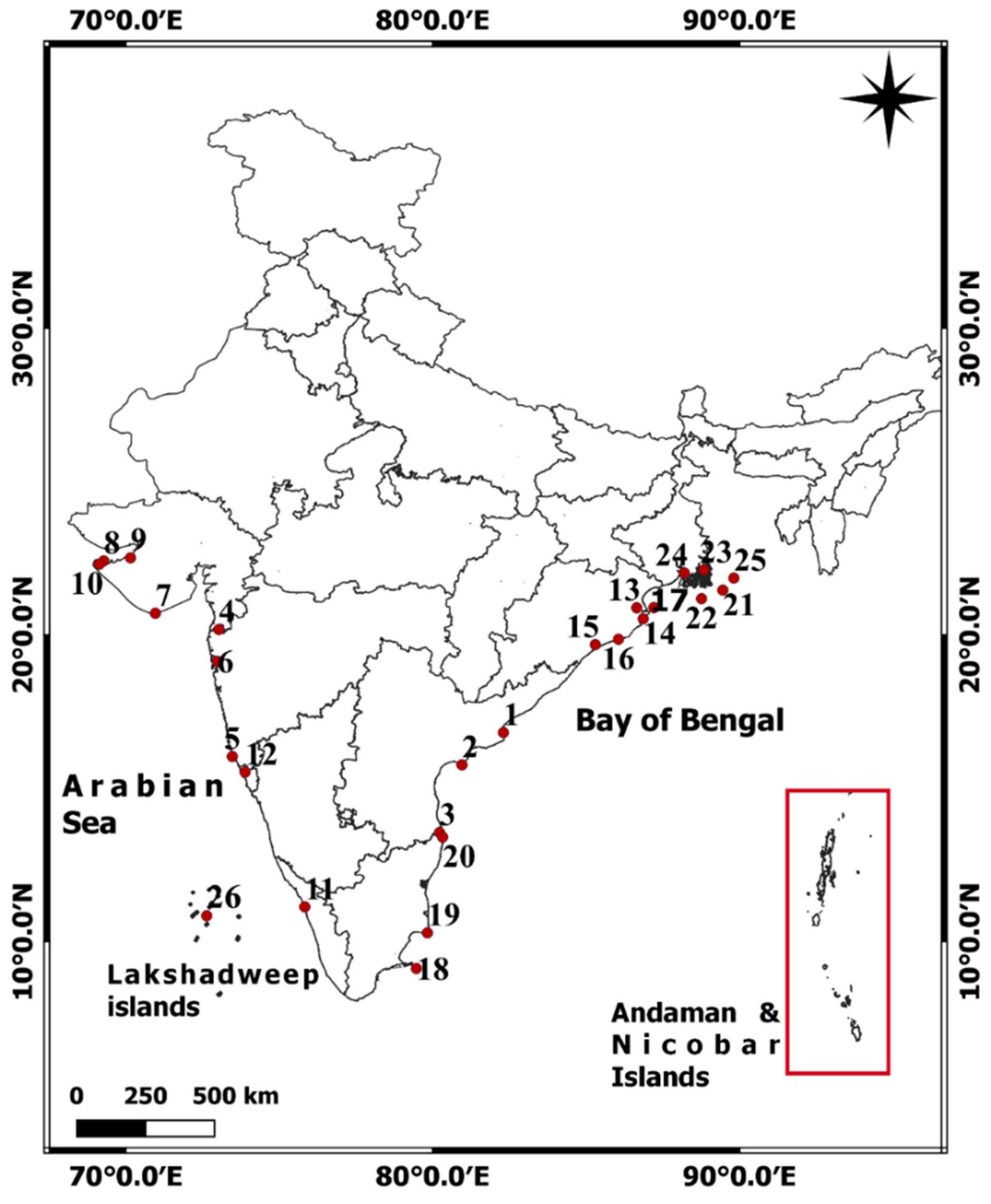


Figure 4.9 Marine Protected areas (Sanctuaries and National Parks) in India. Red dots and numbers indicate the corresponding Sanctuaries and National Parks shown in Table 3.59. The red rectangle box indicates the Andaman & Nicobar Islands. There were a total of 100 marine protected areas, and all details, including latitude and longitude, are shown in Table 3.60.

Table 4.17 List of Marine protected areas (MPA) in the sedimentary basins of India.

Sl. No	Sedimentary Basin	Name of MPA, State	Category	IUCN	Latitude	Longitude	Area (km^2)	Year of establishment
1.	Krishna Godavari	Coringa, Andhra Pradesh	Sanctuary	IV	16.82309	82.299375	235.7	1978
2.	Krishna Godavari	Krishna, Andhra Pradesh	Sanctuary	IV	15.77159	80.950646	194.81	1989
3.	Krishna Godavari	Pulicat Lake, Andhra Pradesh	Sanctuary	IV	13.56525	80.218039	500	1980
4.	Mumbai offshore	Dadra & Nagar Haveli	Sanctuary	IV	20.18336	73.025683	92.16	2000
5.	Mumbai offshore	Malvan Marine, Maharashtra	Sanctuary	IV	16.04537	73.466486	29.12	1987
6	Mumbai offshore	Thane Creek Flamingo, Maharashtra	Sanctuary	NA	19.14777	72.981736	16.905	2015
7.	Saurashtra	Fudam, Daman & Diu	Sanctuary	IV	20.71233	70.960270	2.18	1991
8.	Gulf of Kutch	Marine (Gulf of Kachchh) Gujarat	National park	II	22.40221	69.200954	162.89	1995
9.	Gulf of Kutch	Khijadia, Gujarat	Sanctuary	IV	22.52036	70.151646	6.05	1981
10.	Gulf of Kutch	Marine (Gulf of Kachchh), Gujarat	Sanctuary	IV	22.35237	69.157932	295.03	1980
11.	Kerala-Konkan-Lakshadweep	Kadalundi Vallikkunnu Community Reserve, Kerala	Community reserve	NA	11.13019	75.828930	1.50	2007
12.	Kerala-Konkan-Lakshadweep	Chorao Island, Goa	Sanctuary	IV	15.53624	73.884897	1.78	1988
13.	Mahanadi	Bhitarkanika, Odisha	National park	II	20.71408	86.820611	145	1998
14.	Mahanadi	Bhitarkanika, Odisha	Sanctuary	IV	20.71416	86.863912	672	1975
15.	Mahanadi	Chilika (Nalaban), Odisha	Sanctuary	IV	19.69045	85.293934	15.53	1987
16.	Mahanadi	Balukhand Konark, Odisha	Sanctuary	IV	19.86436	86.047845	71.72	1984
17.	Mahanadi	Gahirmatha, Odisha	Sanctuary	IV	20.79314	86.874699	1435	1997
18.	Cauvery	Gulf of Mannar Marine, Tamil Nadu	National park	II	9.126426	79.464956	6.23	1980
19.	Cauvery	Point Calimere, Tamil Nadu	Sanctuary	IV	10.28391	79.823913	172.6	1967
20.	Cauvery	Pulicat Lake, Tamil Nadu	Sanctuary	IV	13.41781	80.319661	153.67	1980
21.	Bengal	Sundarbans, West Bengal	National park	II	21.83577	88.884114	1330.1	1984
22.	Bengal	Haliday Island, West Bengal	Sanctuary	IV	21.66465	88.631789	5.95	1976
23.	Bengal	Sajnakhali, West Bengal	Sanctuary	IV	22.12377	88.831299	2091.12	1976
24.	Bengal	Lothian Island, West Bengal	Sanctuary	IV	21.66375	88.328882	38	1976
25.	Bengal	West Sundarban, West Bengal	Sanctuary	IV	21.85854	21.858542	556.45	2013
26	Kerala-Konkan-Lakshadweep	Pitti, Lakshadweep	Sanctuary	IV	10.84027	72.632621	0.01	2002

*NA- Not Available

Table 4.18 List of Marine Protected Areas in Andaman & Nicobars Islands Basin

S.No.	Name of MPA	Legal Status	IUCN category	Area of MPA	Year of Notification
		Andaman & Nicobars Islands Basin			
1	Brush Island	Sanctuary	IV	0.23	1977
2	Channel Island	Sanctuary	IV	0.13	1977
3	East Island	Sanctuary	IV	6.11	1977
4	Jungle Island	Sanctuary	IV	0.52	1977
5	Landfall Island	Sanctuary	IV	29.48	1977
6	Mayo Island	Sanctuary	IV	0.1	1977
7	Narcondam Island	Sanctuary	IV	6.81	1977
8	North Island	Sanctuary	IV	0.49	1977
9	Ox Island	Sanctuary	IV	0.13	1977
10	Paget Island	Sanctuary	IV	7.36	1977
11	Peacock Island	Sanctuary	IV	0.62	1977
12	Point Island	Sanctuary	IV	3.07	1977
13	Reef Island	Sanctuary	IV	1.74	1977
14	Ross Island	Sanctuary	IV	1.01	1977
15	Shearme Island	Sanctuary	IV	7.85	1977
16	Table (Delgarno) Island	Sanctuary	IV	2.29	1977
17	Table (Excelsior) Island	Sanctuary	IV	1.69	1977
18	Temple Island	Sanctuary	IV	1.04	1977
19	Tree Island	Sanctuary	IV	0.03	1977
20	Trilby Island	Sanctuary	IV	0.96	1977
21	Turtle Island	Sanctuary	IV	0.39	1977
22	West Island	Sanctuary	IV	6.4	1977
23	Wharf Island	Sanctuary	IV	0.11	1977
24	White Cliff Island	Sanctuary	IV	0.47	1977
25	Saddle Peak	National park	II	32.54	1987
26	Bamboo Island	Sanctuary	IV	0.05	1977
27	Bennett Island	Sanctuary	IV	3.46	1977
28	Blister Island	Sanctuary	IV	0.26	1977
29	Bondoville Island	Sanctuary	IV	2.55	1977
30	Buchanan Island	Sanctuary	IV	9.33	1977
31	Curlew (B.P.) Island	Sanctuary	IV	0.16	1977
32	Curlew Island	Sanctuary	IV	0.03	1977
33	Dot Island	Sanctuary	IV	0.13	1977

34	Dottrell Island	Sanctuary	IV	0.13	1977
35	Egg Island	Sanctuary	IV	0.05	1977
36	Entrance Island	Sanctuary	IV	0.96	1977
37	Gander Island	Sanctuary	IV	0.05	1977
38	Girjan Island	Sanctuary	IV	0.16	1977
39	Goose Island	Sanctuary	IV	0.01	1977
40	Interview Island	Sanctuary	IV	133.87	1977
41	Kwangtung Island	Sanctuary	IV	0.57	1987
42	Latouche Island	Sanctuary	IV	0.96	1977
43	North Reef Island	Sanctuary	IV	3.48	1977
44	Oliver Island	Sanctuary	IV	0.16	1977
45	Orchid Island	Sanctuary	IV	0.1	1977
46	Oyster Island-I	Sanctuary	IV	0.08	1977
47	Ranger Island	Sanctuary	IV	4.26	1977
48	Roper Island	Sanctuary	IV	1.46	1977
49	Rowe Island	Sanctuary	IV	0.01	1977
50	Sea Serpent Island	Sanctuary	IV	0.78	1977
51	Shark Island	Sanctuary	IV	0.6	1977
52	Snake Island-I	Sanctuary	IV	0.73	1977
53	Spike Island-I	Sanctuary	IV	0.42	1977
54	South Reef Island	Sanctuary	IV	1.17	1977
55	Surat Island	Sanctuary	IV	0.31	1977
56	Swamp Island	Sanctuary	IV	4.09	1977
57	Middle Button Island	National park	II	0.44	1987
58	North Button Island	National park	II	0.44	1987
59	Barren Island	Sanctuary	IV	11.99	1977
60	Cone Island	Sanctuary	IV	0.65	1977
61	Elat Island	Sanctuary	IV	9.36	1977
62	Hump Island	Sanctuary	IV	0.47	1977
63	Mask Island	Sanctuary	IV	0.78	1977
64	Mangrove Island	Sanctuary	IV	0.39	1977
65	Oyster Island-II	Sanctuary	IV	0.21	1977
66	Parkinson Island	Sanctuary	IV	0.34	1977
67	Spike Island-II	Sanctuary	IV	11.7	1977
68	Stoat Island	Sanctuary	IV	0.44	1977
69	Tuft Island	Sanctuary	IV	0.29	1977
70	Mount Harriett	National park	II	46.62	1987

71	Rani Jhansi	National park	II	256.14	1996
72	South Button Island	National park	II	0.03	1987
73	Arial Island	Sanctuary	IV	0.05	1977
74	Belle Island	Sanctuary	IV	0.08	1977
75	Bingham Island	Sanctuary	IV	0.08	1977
76	Bluff Island	Sanctuary	IV	1.14	1977
77	Clyde Island	Sanctuary	IV	0.54	1977
78	Cuthbert Bay	Sanctuary	IV	5.82	1997
79	Defence Island	Sanctuary	IV	10.49	1977
80	Duncan Island	Sanctuary	IV	0.73	1977
81	East of Inglis Island	Sanctuary	IV	3.55	1977
82	James Island	Sanctuary	IV	2.1	1977
83	Kyd Island	Sanctuary	IV	8	1977
84	Montogemery Island	Sanctuary	IV	0.21	1977
85	Patric Island	Sanctuary	IV	0.13	1977
86	Pitman Island	Sanctuary	IV	1.37	1977
87	Potanma Islands	Sanctuary	IV	0.16	1977
88	Sir Hugh Rose Island	Sanctuary	IV	1.06	1977
89	Sandy Island	Sanctuary	IV	1.58	1977
90	Talabaicha Island	Sanctuary	IV	3.21	1977
91	Mahatma Gandhi Marine	National park	II	281.5	1983
92	Cinque Islands	Sanctuary	IV	9.51	1977
93	Lohabarrack	Sanctuary	IV	22.21	1977
94	North Brother Island	Sanctuary	IV	0.75	1977
95	Passage Island	Sanctuary	IV	0.62	1977
96	Sisters Island	Sanctuary	IV	0.36	1977
97	Snake Island-II	Sanctuary	IV	0.03	1977
98	South Sentinel Island	Sanctuary	IV	1.61	1977
99	South Brother Island	Sanctuary	IV	1.24	1977
100	Campbell	National park	II	426.23	1992
101	Galathea	National park	II	110	1992
102	Battimalv Island	Sanctuary	IV	5.03	1977
103	Galathea Bay	Sanctuary	IV	11.44	1997
104	Megapode Island	Sanctuary	IV	0.12	1977
105	Tillongchang Island	Sanctuary	IV	36.43	1977

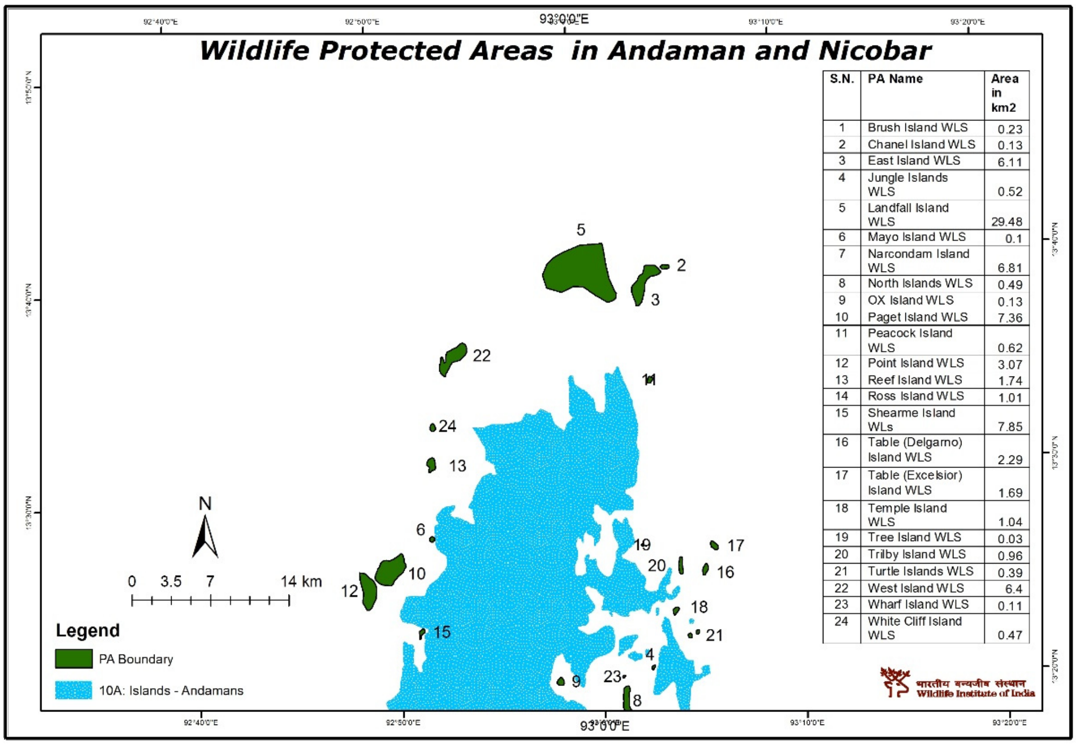


Figure 4.10 Marine protected areas in Andaman and Nicobar Islands Tile 1.

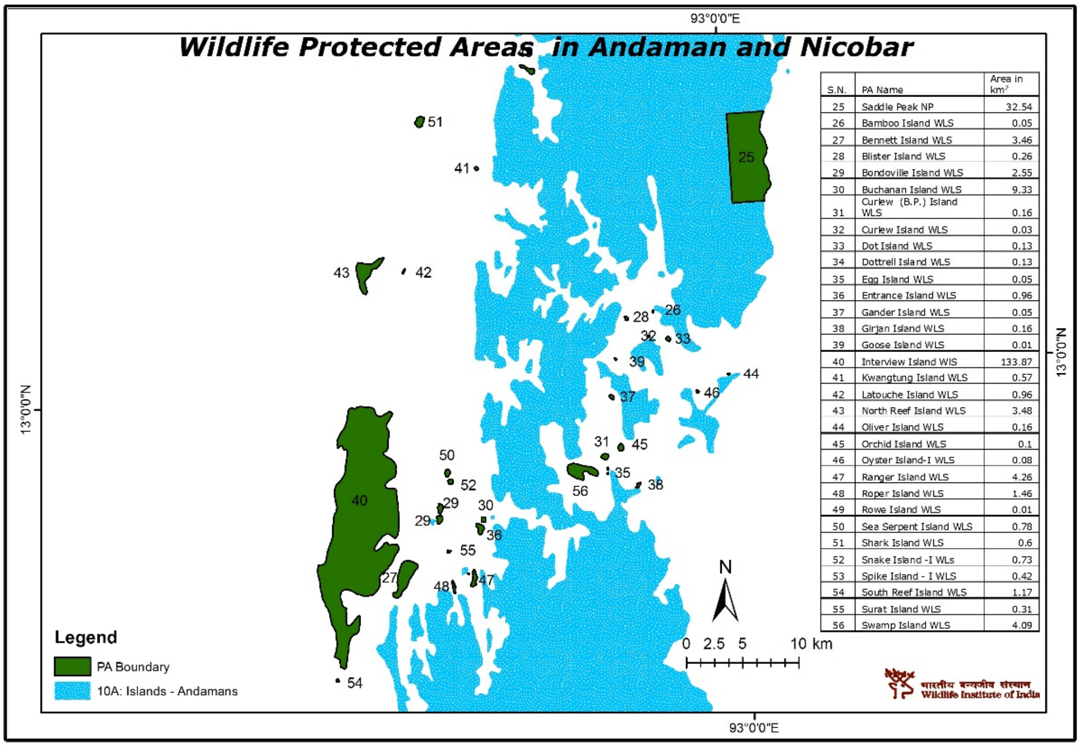
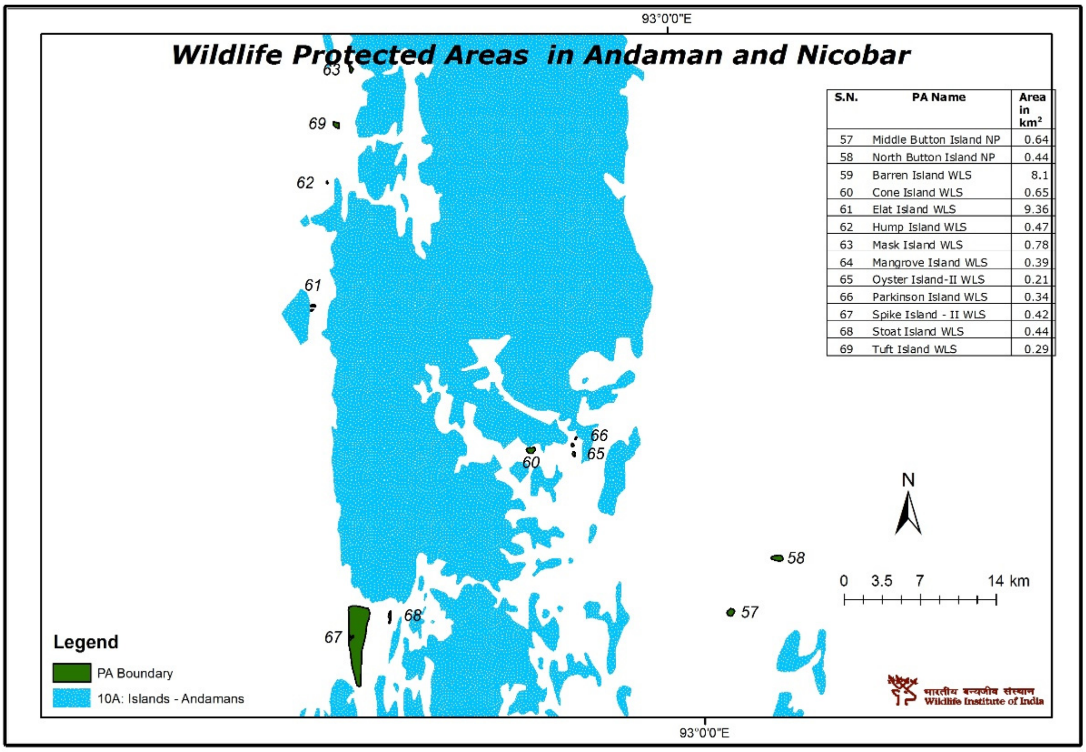
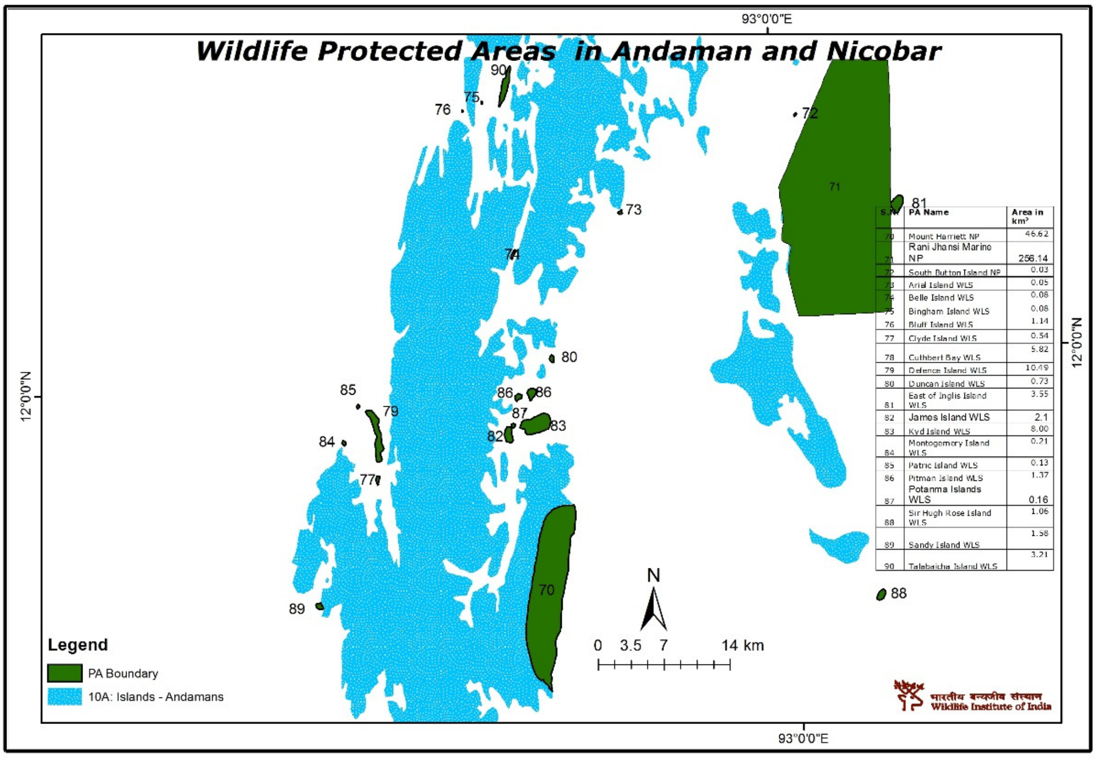


Figure 4.11 Marine protected areas in Andaman and Nicobar Islands Tile 2.



S.N.	PA Name	Area in km²
57	Middle Button Island NP	0.64
58	North Button Island NP	0.44
59	Barren Island WLS	8.1
60	Cone Island WLS	0.65
61	Elat Island WLS	9.36
62	Hump Island WLS	0.47
63	Mask Island WLS	0.78
64	Mangrove Island WLS	0.39
65	Oyster Island-II WLS	0.21
66	Parkinson Island WLS	0.34
67	Spike Island - II WLS	0.42
68	Stoat Island WLS	0.44
69	Tuft Island WLS	0.29

Figure 4.12 Marine protected areas in Andaman and Nicobar Islands Tile 3.



S.N.	PA Name	Area in km²
70	Mount Harriett NP	46.62
71	Rani Jhansi Marine NP	256.14
72	South Button Island NP	0.03
73	Arial Island WLS	0.05
74	Belle Island WLS	0.08
75	Bingham Island WLS	0.08
76	Bluff Island WLS	1.14
77	Clyde Island WLS	0.54
78	Cuthbert Bay WLS	5.82
79	Defence Island WLS	10.49
80	Duncan Island WLS	0.73
81	East of Inglis Island WLS	3.55
82	James Island WLS	2.1
83	Kyd Island WLS	8.00
84	Montogemery Island WLS	0.21
85	Patric Island WLS	0.13
86	Pitman Island WLS	1.37
87	Potanma Islands WLS	0.16
88	Sir Hugh Rose Island WLS	1.06
89	Sandy Island WLS	1.58
90	Talabaicha Island WLS	3.21

Figure 4.13 Marine protected areas in Andaman and Nicobar Islands Tile 4.

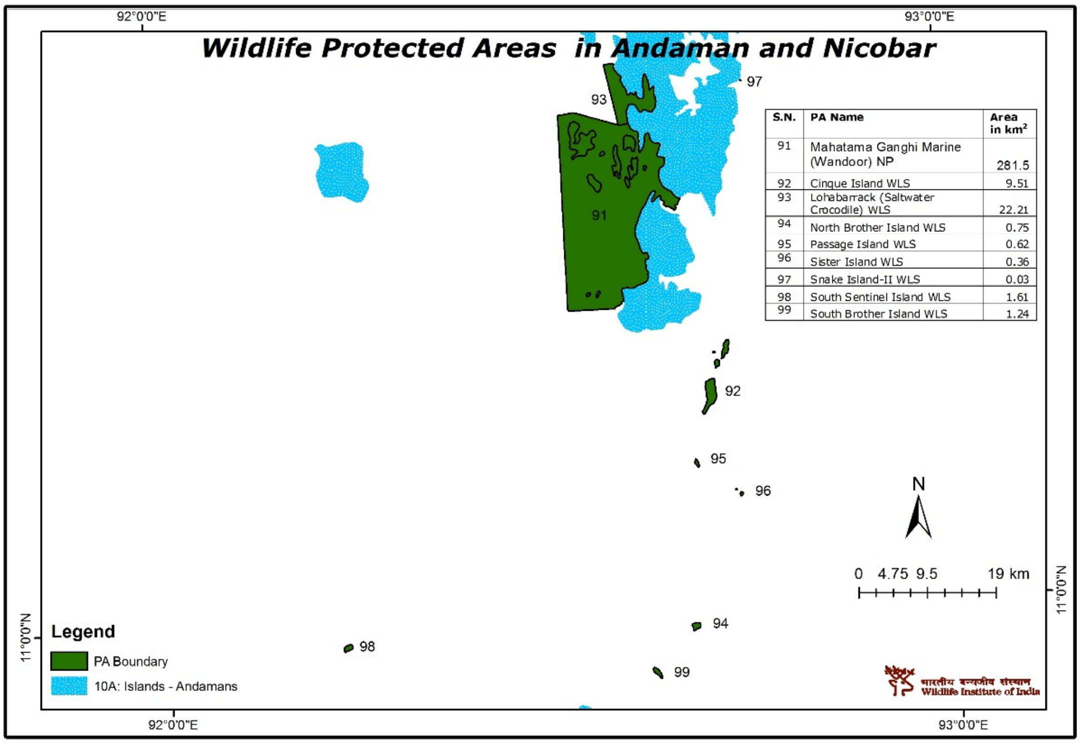


Figure 4.14 Marine protected areas in Andaman and Nicobar Islands Tile 5.

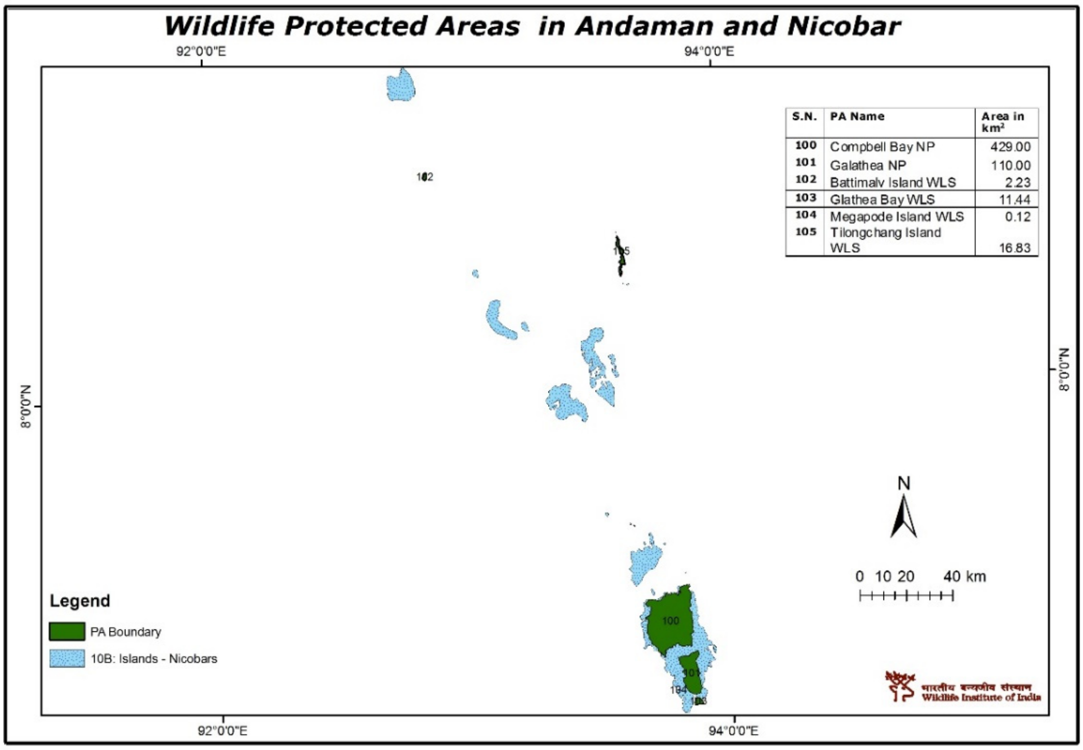


Figure 4.15 Marine protected areas in Andaman and Nicobar Islands Tile 6.

4.3 Distribution of coral reefs in India

India has a coastline of nearly 8,129 km, but the reef formation is restricted to four major centres: Gulf of Kutch, Gulf of Mannar, Lakshadweep, Andaman and the Nicobar Islands. In India, the reefs are distributed along the east and west coasts at restricted places. Fringing reefs are found in the Gulf of Mannar and Palk Bay. Platform reefs are seen along the Gulf of Kachchh. Patchy reefs are present near Ratnagiri and Malvan coasts. Fringing and barrier reefs are found in Andaman and Nicobar Islands. The Lakshadweep is the only atoll formation of our waters. The total area of coral reefs in India is estimated to be 2,375 sq. km (DOD and SAC, 1997). Coral reefs of the Indian Ocean were built up during the tertiary and quaternary periods. Coral reefs are restricted mainly in seven regions of India, such as:

1) Coral reefs in the Gulf of Mannar
2) Coral reefs in Palk Bay,
3) Coral reefs in the Gulf of Kutch,
4) Coral reefs in Andaman and Nicobar islands.
5) Coral reefs in Lakshadweep islands,
6) Coral reefs on the west coast of India (Including Goa and Kerala)

- **Gulf of Mannar**

On the other hand, the Gulf of Mannar reefs are developed around a chain of 21 islands that lie along a 140 km stretch between Tuticorin and Rameswaram (Krishnamurthy, 1987). These islands are located between latitudes 8°47' N and 9°15' N and longitudes 78°12' E and 79°14'E on the southeast coast of India, 21 islands running parallel to a coastline at an average of 8 km from shore. Different types of reef forms, such as shore platforms, patches, coral pinnacles and atoll types, are also observed in the Gulf of Mannar. The islands have fringing coral reefs and patch reefs around them. Narrow fringing reefs are located mostly at a distance of 50 to 100 m from the islands. On the other hand, patch reefs arise from depths of 2 to 9 m and extend to 1 to 2 km in length with a width of as much as 50 m. The reef flat is extensive in almost all the reefs in the Gulf of Mannar. Reef vegetation is richly distributed on these reefs. The total area occupied by the reef and its associated features is 94.3 sq. km. Reef flat and reef vegetation, including algae, occupy 64.9 and 13.7 sq. km, respectively (DOD and SAC, 1997). Visibility is affected by monsoons, coral mining and high sedimentation load. The reefs are more luxuriant and richer than the reefs of Palk bay.

- **Palk Bay**

Coral reefs on the Tamil Nadu coast are located in Palk Bay near Rameswaram and in the Gulf of Mannar. Palk Bay is separated from the Gulf of Mannar by the Mandapam peninsula and Rameswaram Island. The reef is centred on 9°17'N and 79°15'E. There is only one fringing reef in Palk Bay, which lies in an east-west direction along the mainland from the Pamban channel at the Pamban end of the bridge to Rameshwaram Island. This reef is 25-30 km long and generally less than 200 m wide. Visibility is poor, around 1 meter, and it is badly affected by the northeast monsoon. The reef flat is relatively broad from the Pamban channel to the southern end near Ramnad and narrow from Pamban to the south of Rameshwaram. The present-day reef growth is poor and not pristine since it was quarried in the sixties (Pillai, 1996). Satellite data shows that the reef flat is barren, followed by a sandy beach on the landward side and a small patch of reef fringes at the Dhanushkodi tip (Bahuguna and Nayak, 1994).

- **Gulf of Kutch**

The Gulf of Kutch, located at 22°15'-23°40' N Latitude and 68°20'-70°40' East Longitude, is one of the indentations found on the northern side of the Saurashtra Peninsula. The beaches are sandy or muddy, with occasional large sandstone formations. There are about 40 islands with patchy coral formations, of which the largest is Pirotan Island. Corals are found in patches on sandstone substrates. The coral fauna of the Gulf of Kutch is comparatively less diverse compared to other parts of India (Pillai, 1996). The total area of Reefs in the Gulf of Kutch is about 352.5 sq. km. (Jayaprakas and Radhakrishnan, 2014).

- **Andaman and Nicobar Islands**

The Andaman and Nicobar group of Islands are located in the SE of the Bay of Bengal, between 6°-14°N latitude and 91°- 94°E longitude. They consist of 350 islands.

Almost all the islands of the Andaman and Nicobar groups exhibit narrow, linear and extensively well-developed fringing reefs (Vineeta Hoon, 1997). A total of 135 species divided among 59 genera is known to both the Andaman and Nicobar Islands (Pillai 1983). The total area occupied by the reef is 1021.46 sq.km (SAC, 2010). There is not enough recent information about the reefs around North Andaman and the Nicobar islands to provide a true picture of the current status of the reefs.

- **The Lakshadweep Islands**

The Lakshadweep islands lie scattered in the Arabian Sea, about 225 to 450 km from the Kerala coast. Geographically, the islands lie between 8°N – 12°3'N latitude and 71°E- 74°E longitude. The islands consist of coral formations built upon the Laccadive-Chagos submarine ridge, rising steeply from a depth of about 1500 m to 4000 m off the west coast of India. The U.T. of Lakshadweep, along with the Maldives and the Chagos Archipelagoes, form an interrupted chain of coral atolls and reefs on a contiguous submarine bank covering a distance of over 2,000 km. This ridge is supposed to be a continuation of the Arravali Mountains, and the islands are believed to be remnants of the submerged mountain cliffs (James et al.1986). There are 36 tiny islands, 12 atolls, 3 reefs and 5 submerged banks, covering an area of 32 km2, with lagoons occupying about 4,200 km^2. Only 11 of the 36 islands are inhabited (Vineeta Hoon, 1997). The island's coral reefs are mainly atolls, except for one platform reef at Androth. The total area occupied by the reef is 933.7 sq. km, including a lagoon area of 510 sq. km (SAC, 2010).

- **West Coast of India**

The west coast of India between Bombay and Goa is reported to have submerged banks with isolated coral formations (Nair and Qasim, 1978). Coral patches have been recorded in the intertidal regions of Ratnagiri, Malvan and Redi, south of Bombay (Qasim and Wafer, 1979) and at the Gaveshani Bank, 100 Km west of Mangalore (Nair and Qasim, 1978). Ponies, Coscinarares, Turbinaria, some favids and Pseudosiderastrea are reported. Down south from Quilon along the Kerala coast to Enayam in TamilNadu, hermatypic corals are reported along the shore. Pocilipora spp is the most common genus in this area. Acropora is represented by three species. Pseudosiderastrea and

Ponies spp are also found. A recent investigation has shown that 29 species in 17 genera of scleractinians occur in this area (Pillai, 1996).

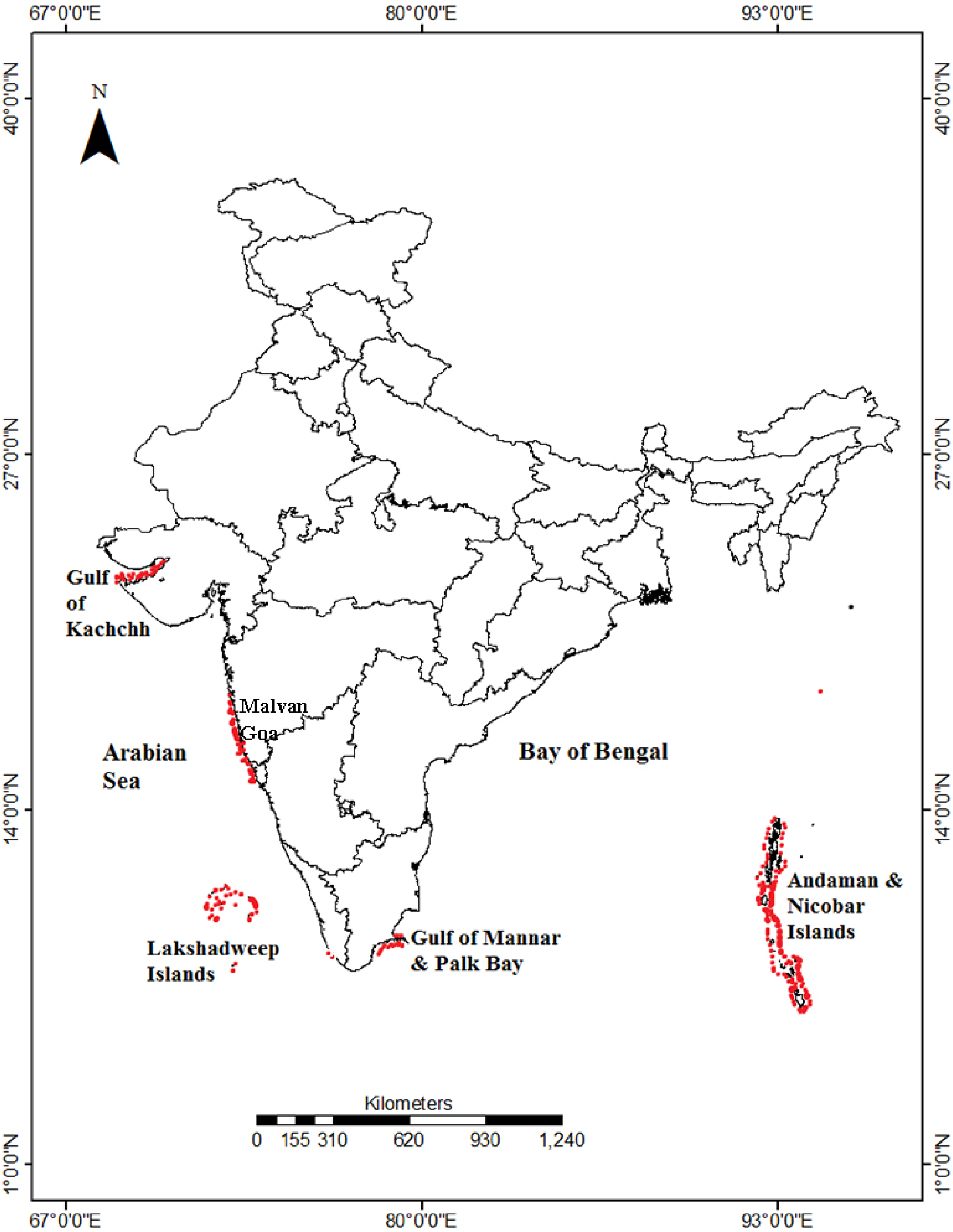


Figure 4.16 Major Coral areas in India.

Table 4.19 Area Estimates of Coral Reefs in the Country (km^2)

Category	Gujrat	Tamilnadu (Pak bay, Gulf of Mannar and Tuticorin)	Lakshadweep islands	A&N Islands
Reef flat	148.4	64.9	136.5	795.7
Sand over reef	11.8	12.0	7.3	73.3
Mud over reef	117.1	-	-	8.4
Coraline shelf	-	-	230.9	45.0
Coral heads	-	-	6.8	17.5
Live coral platform	-	-	43.3	-
Algae	53.8	0.4	0.4	-
Seaweeds	-	-	0.7	-
Seagrass	-	-	10.9	-
Reef vegetation	112.1	13.3	-	8.9
Vegetation over sand	17.0	3.6	0.4	10.5
Lagoon	-	0.1	322.8	-
Sandy substrate	-	-	(67.4)	-
Reef patch	-	-	(13.4)	-
Deep	-	-	(98.5)	-
Uncertain	-	-	(143.5)	-
Total	460.2	94.3	816.1	959.3

Table 4.20 Diversity of hermatypic corals in the Indian Ocean

Locality	Genera	Species
Gulf of KUTCh*	24	37
West Coast Patches*	17	29
Lakshadweep Islands	37	103
Palk bay and Gulf of Mannar	36	96
Tuticorin	19	21
Andaman Islands	31	82
Nicobar Islands	43	103
Total for India*	37	199

4.4 Ecologically sensitive areas in the coastal regions of India

Ecologically Sensitive Areas (ESA's) have been identified and notified by the Indian Ministry of Environment, Forest and Climate Change (MoEFCC) since 1989. Notifications declaring areas as ESA's are issued under Section 5 clauses i,v, vi, viii of the Environment (Protection) Act, 1986. Pranob Sen Committee Report (2000), defined Ecological Sensitivity as the imminent possibility of a) Permanent and irreplaceable loss of extant life forms and b) Significant damage to ecological processes affecting natural evolution and specialization. ESA's as a concept emerged from people's concern to promote habitat protection with sustainable development. It has a wider scope for protecting critical geo-morphological features. To protect the fragile marine and marginal marine ecosystem comprising coral reefs, wetlands, including mangroves, which are endowed with floral and faunal diversity, the Government of India has declared such areas under the Environment (Protection) Act, 1986, banning their exploitation, followed by Coastal Regulation Zone (CRZ) Notification 1991, which prohibits development and disposal of wastes in the region with mangroves and coral reefs. Based on the recommendations of a National Committee, areas were identified as National Parks and sanctuaries and are declared as Marine Protected Areas (MPA's). These MPA's are classified into three categories with mangroves, coral reefs, algal beds, estuaries, lagoons, and intertidal areas falling in Category – I and the protected areas in Andaman and Nicobar and Lakshadweep Islands grouped under Category – II. According to the notifications, there are 32 Marine Protected Areas and sanctuaries, of which 19 belong to Category – I and 13 areas come under Category – II. Of the 19 areas in Category – I, 6 are National Parks, and 13 are sanctuaries. Among the 13 areas classified under category – II, 3 are National Parks, and 10 are sanctuaries. Other ecologically sensitive habitats include Pearl Oyster culture areas, abundant seagrass areas, turtle net breeding and coastal dunes.

Major services of coastal and marine ecosystems

- Life in the sea produces a third of the oxygen that we breathe.
- The ocean absorbs approximately 30% of CO_2 emitted by human activities since the 'Industrial Revolution'; this has helped limit the overall extent of global warming substantially.

- Fisheries directly employ almost 200 million people and provide over 15% of the dietary intake of animal protein.
- Marine bio-products are raw materials for manufacturing industries, such as paints, fertilizers, skin lotions, toothpaste and medicines.
- The divergent chemical deposits in the marine environment are an asset and might even yield new anti-cancer drugs.
- The shore provides for marine transportation, recreation, tourism and salt production.
- Mangroves can protect the coastal aquifers from seawater intrusion and safeguard the coastal communities from natural calamities like cyclones and tsunamis.
- Coastal wetlands play an important role in water quality regulation by capturing and filtering sediment and organic waste transits inland.

CHAPTER 5

IMPACT OF CLIMATE CHANGE ON COASTAL & OFFSHORE OIL AND GAS INDUSTRY AND ITS MITIGATION MEASURES

5.1 Impact of climate change on the oil and gas industry

The oil and gas sector is deeply intertwined with the climate change narrative, as it remains one of the largest sources of greenhouse gas emissions. Oil and gas extraction, refinement, transportation, and consumption have historically powered global economic growth, but at a significant environmental cost. Burning petroleum products for electricity generation, transportation, and industrial processes releases large quantities of CO_2 into the atmosphere, contributing to the greenhouse effect and global warming. Despite the push for cleaner and more sustainable energy sources, oil and gas still account for a significant portion of the world's energy supply.

Even though the oil and gas industry is a major contributor to climate change, it is highly susceptible to its effects. As climate change accelerates, the risks to oil infrastructure become more pronounced. The industry's infrastructure, which comprises extraction sites, pipelines, refineries, and storage facilities, is built to withstand certain environmental conditions, but climate change is introducing new and more severe challenges. Extreme weather events such as hurricanes, typhoons, flooding, and storm surges are becoming more frequent and intense, threatening the integrity of oil rigs, refineries, and pipelines. Rising temperatures can also cause operational challenges, including equipment failures, increased wear and tear, and higher maintenance costs. In some regions, rising sea levels threaten coastal oil and gas infrastructure, increasing the risk of spills and accidents.

Significant factors that severely affect the Oil and Gas industry are as follows:

- Air and water temperature
- Precipitation patterns
- Rate of sea level rise and shoreline erosion
- Storm intensity and wave regime
- Damage to infrastructure leading to oil spills and the release of hazardous contaminants.
- Changes in carbon dioxide levels and ocean acidification

Increases in temperatures, changing precipitation patterns, more frequent and intense storms, and rising sea levels increase the risk of operational disruptions, structural damage, oil spills, etc., which will result in

- Decreased material integrity and increased corrosion risk.
- Decreased efficiency of cooling systems.
- Increased operational and maintenance challenges

5.2 Warming of the atmosphere and ocean

Past air temperatures in the Northern Indian Ocean (the Arabian Sea and Bay of Bengal) were relatively stable during the pre-industrial period but gradually increased by 1.2°C by 2023, with slight fluctuations from 25°C to 26.2°C (Fig. 5.1). Future projections under different SSP scenarios indicate a significant increase in temperatures. In the northern Indian Ocean, under the SSP1-2.6 scenario, temperatures are projected to stay below 27°C by 2100, while SSP2-4.5 shows a rise to around 28.0°C, SSP3-7.0 projects an increase to approximately 29.0°C, and SSP5-8.5 sees temperatures potentially exceeding 30.0°C. The shaded areas in the projections represent the uncertainty range (10^{th} to 90^{th} quantiles), indicating variability in the potential outcomes. Thus, we can anticipate an increase of 1.2°C in the low carbon emission scenario and 3.8°C in the high carbon emission scenario.

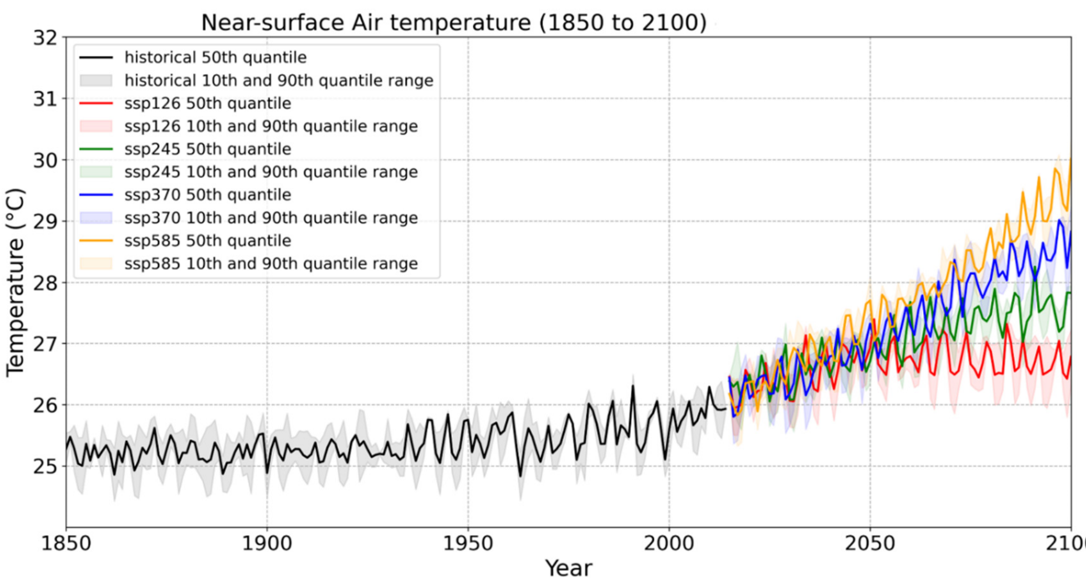


Figure 5.1 Near-surface air temperature under various SSPs from 1850 – 2100.

Sea surface temperature in the Northern Indian Ocean increased by 1.0°C and reached 26.0°C by 2023 (Fig. 5.2). Future projections from 2023 to 2100 under various SSP scenarios indicate a significant increase in sea surface temperature, particularly under SSP3-7.0 and SSP5-8.5, which show the highest increases. In the northern Indian Ocean, SSP1-2.6 projects a gradual rise and fall of about 26.0°C by 2100, SSP2-4.5 shows a more pronounced increase to around 28.0°C, SSP3-7.0 projects temperatures reaching 28.5°C, and SSP5-8.5 indicates the highest rise, approaching 29.0°C by 2100. However, these projections are accompanied by uncertainty ranges, indicating the variability in future outcomes across different emissions pathways. The warming of the ocean is controlled in the low carbon emission scenario, but alarmingly increased by 3.0°C by 2100 in a high carbon emission scenario.

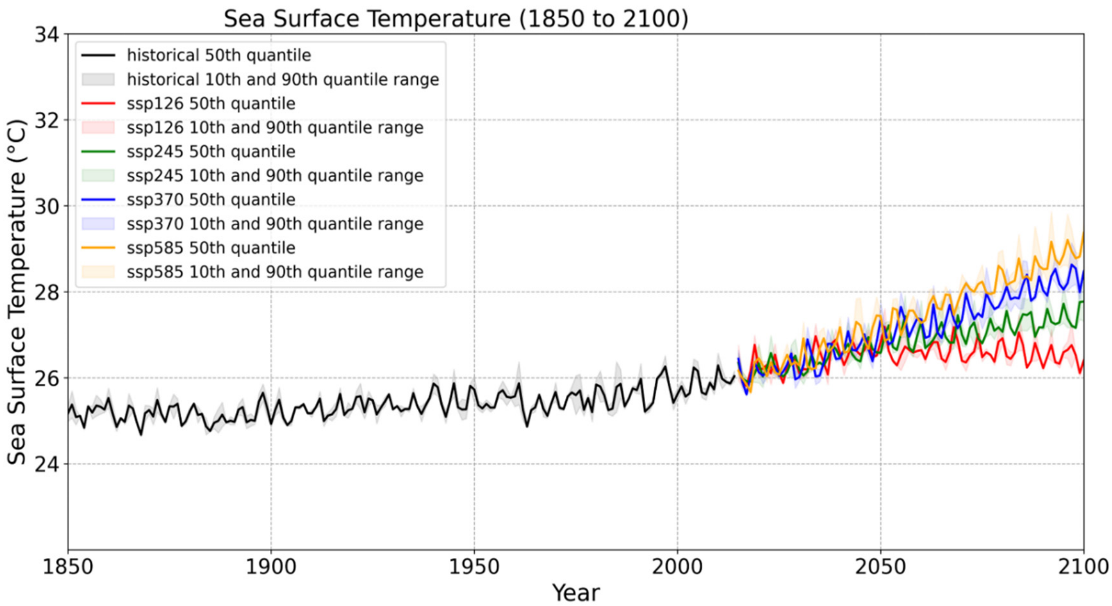


Figure 5.2 Sea surface temperature under various SSPs from 1850 – 2100.

Past records of SST data depict an increasing temperature of 1.6°C in the AS and 1.1°C in the BoB. This indicates that AS is alarmingly warming compared to BoB (Fig. 5.3).

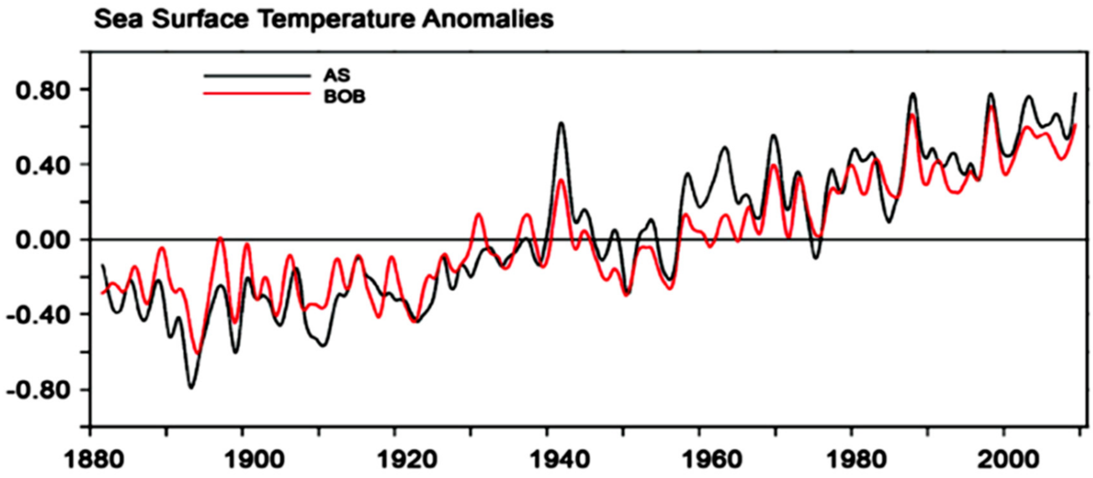
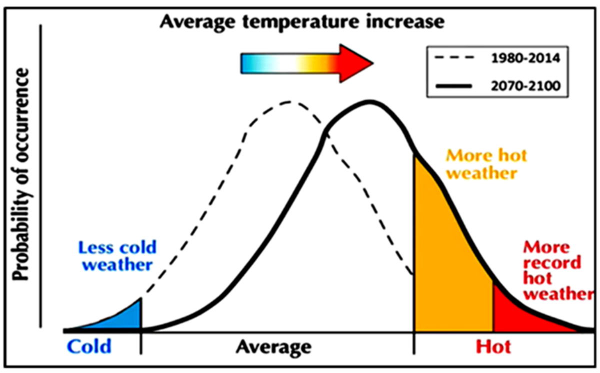


Figure 5.3 Sea surface temperature anomalies of AS and BoB

5.2.1 Impact of warming of the atmosphere and ocean on the coastal and offshore oil and gas exploration activities

Due to the warming of the atmosphere, the average temperature increased by 0.8°C and is expected to rise by 1.1 - 6.4°C by 2100. This warming in the average temperature (Fig. 5.4) will shift the weather to the hotter side, and the impacts will be severe.



Impacts

- Changes in weather patterns
- Extreme weather events
  - severe cyclones,
  - heat waves,
  - droughts,
  - localised heavy rainfalls,
- Changes in crops,
- Affecting human health
- Large socioeconomic impacts.

Figure 5.4 Prediction of the shifting in average temperature to the hotter side.

5.2.2 Operational challenges

1. **Increased storm intensity**:

   - **Damage to infrastructure**: More frequent and severe storms can damage offshore platforms, pipelines, and other infrastructure, leading to costly repairs and downtime.

- **Operational disruptions**: Extreme weather conditions can halt drilling and production activities, affecting overall productivity.

2. **Rising sea levels**:
   - **Flooding of coastal facilities:** Higher sea levels increase the risk of flooding for coastal refineries, storage facilities, and other infrastructure.
   - **Erosion and land loss:** Coastal erosion can undermine the stability of onshore facilities and reduce available land for operations.

3. **Temperature-related issues**:
   - **Equipment performance:** Higher temperatures can affect the performance and lifespan of equipment, leading to increased maintenance costs.
   - **Worker safety:** Elevated temperatures pose health risks to workers, necessitating additional safety measures and potentially reducing work hours.

5.2.3 Mitigation measures

We may adopt the following strategy to mitigate the impacts of air and ocean temperatures in the climate change scenario on humans and infrastructure in the coastal and offshore oil and gas industry.

1. **Human safety and health**
   - **Heat stress management**: Implement protocols to monitor and manage heat exposure, including regular breaks, hydration stations, and cooling areas.
   - **Flexible work hours**: Schedule high-risk tasks during cooler parts of the day to minimise heat exposure for workers.
   - **Protective gear**: Provide breathable, heat-resistant personal protective equipment (PPE) to ensure comfort and safety.
   - **Remote monitoring**: Utilise remote operations and monitoring technologies to reduce the need for on-site personnel in extreme conditions.
   - **Training programs**: Conduct training on recognising signs of heat-related illnesses and emergency response procedures.

2. Infrastructure and machinery adaptation

- **Heat-resistant materials and design**: Use materials that can withstand higher temperatures, prevent corrosion, and withstand high wave action.
- **Elevated platforms**: Design offshore platforms to be elevated to minimise flood risks from rising sea levels and storm surges.
- **Cooling systems**: Upgrade machinery with enhanced cooling systems to prevent overheating during operation.
- **Ventilation improvements**: Ensure adequate ventilation in work areas to mitigate heat buildup, especially in enclosed spaces.
- **Automated shutdown systems**: Implement automated systems that can shut down machinery safely if temperatures exceed safe operating limits.
- **Regular inspections**: Increase the frequency of inspections and maintenance on machinery to identify heat-related wear and tear.
- **Real-time monitoring**: Use sensors to monitor equipment performance and environmental conditions, allowing for proactive maintenance.

3. Environment monitoring systems

- **Real-time data collection**: Implement sensors and monitoring systems for ocean temperatures, weather patterns, and structural integrity to anticipate and respond to changes.
- **Predictive analytics**: Utilise data modelling to forecast operational impacts and optimise response strategies.

4. Sustainable practices

- **Reduce greenhouse gas emissions**: Optimise energy efficiency and integrate renewable energy sources into operations.
- **Carbon management**: Explore carbon capture and storage (CCS) technologies to mitigate emissions.

5. **Research and development**

- **Innovative technologies**: Invest in R&D for new technologies that enhance the safety and efficiency of offshore operations under changing climate conditions.
- **Adaptive design**: Encourage designs that allow for modularity and adaptability to various temperature and environmental scenarios.

6. **Regulatory compliance and collaboration**

- **Stay updated on regulations**: Keep abreast of changing climate and environmental protection regulations, ensuring compliance.
- **Collaborative research initiatives**: Partner with research institutions and regulatory bodies to share knowledge and improve industry practices.

By implementing these measures, the coastal and offshore oil and gas industry can better adapt to the challenges posed by rising air and ocean temperatures while minimising environmental impacts.

5.3 Extreme weather events -Tropical cyclones and associated wave regimes

Tropical cyclones are intense storm systems characterised by strong winds, heavy rainfall, and low atmospheric pressure. Tropical cyclones typically develop when warm, moist air rises over the ocean, creating a low-pressure system. As the air rises, it cools, and water vapour condenses into clouds, releasing latent heat that fuels the storm. For a cyclone to form and strengthen, the sea surface temperature must usually be greater than 26.0°C. Thus, TCs form over warm ocean waters in tropical regions, leading to severe weather events, including high winds, waves, storm surges, and coastal flooding.

Table 5.1 Classification: Cyclones are classified based on their maximum sustained winds:

Tropical depression	Wind Speed: Less than 17 m/s (~ 39 mph or 63 km/h)
Tropical storm	Wind Speed: 17 to 32 m/s (~ 39 to 73 mph or 63 to 118 km/h)
Category 1 TC	Wind Speed: 33 to 42 m/s (~ 74 to 95 mph or 119 to 153 km/h)
Category 2 TC	Wind Speed: 43 to 49 m/s (~ 96 to 110 mph or 154 to 177 km/h)
Category 3 TC	Wind Speed: 50 to 58 m/s (~ 111 to 129 mph or 178 to 208 km/h)
Category 4 TC	Wind Speed: 59 to 69 m/s (~ 130 to 156 mph or 209 to 251 km/h)
Category 5 TC	Wind Speed: 70 m/s or greater (>157 mph or greater, or > 252 km/h)

Tropical cyclones can cause significant damage to coastal areas, including:

- Storm surges: Rapidly rising sea levels due to the cyclone's winds, leading to coastal flooding.
- Heavy rainfall: Results in flash flooding and landslides.
- High Winds: Causing structural damage to buildings, trees, and infrastructure.
- High waves: Damage to offshore structures, ships, and shoreline erosion

Table 5.2 Damage capacity of cyclones on Saffir–Simpson scale

Cyclone category	Wind speed in km/h	Damage capacity
1	120-150	Minimal
2	150-180	Moderate
3	180-210	Extensive
4	210-250	Extreme
5	250 and above	Catastrophic

The frequency of tropical cyclones (TCs) in the BoB is higher relative to that over the AS (Fig 5.5). However, more TCs have been formed in the AS than in the BoB in recent years. During the study period (1982–2019), a significant increase in the intensity, frequency, and duration of cyclonic storms (CS) and very severe CS (VSCS) was observed over the AS. There has been a 52% increase in the frequency of CS during the recent epoch (2001–2019) in the AS, while there has been a decrease of 8% in the BoB. Over the AS, the increment in CS duration is 80%, and VSCS is almost threefold in the recent epoch as compared to the past epoch (1982–2000). The increase in TC duration over the AS is prominent during May, June, and October, and a decrease over the BoB is noted during November (Deshpande eta al., 2021). Data collected from the Indian Meteorological Department, New Delhi, also verified the increase in intense cyclones, especially in the last decade in the Northern Indian Ocean. The increase in the duration of TCs in the AS is associated with increased sea surface temperatures and tropical cyclone heat potential in the basin.

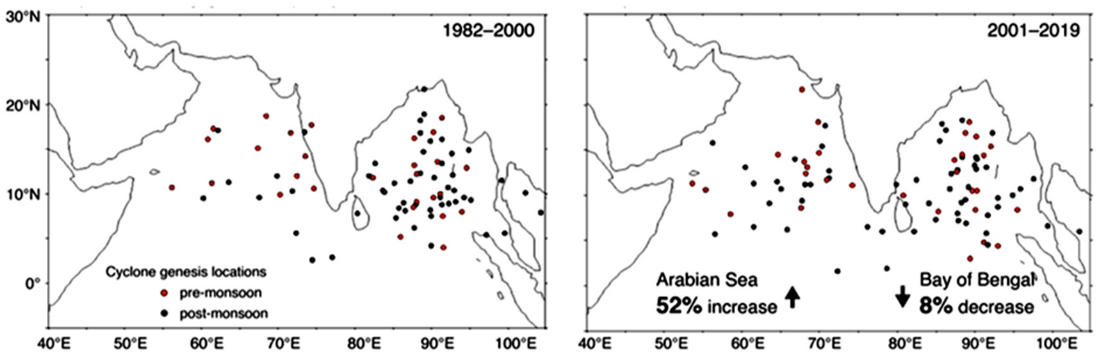


Figure 5.5 Cyclone genesis locations in the AS and BoB (*Source: Deshpande et al., 2021)*

Table 5.3 shows the decadal variation of Depression, Cyclonic storms, and Severe Cyclonic storms in the Northern Indian Ocean.

Decade	*D*		*CS*		*SCS*		*Total*		*CS + SCS*	
	pre	post	pre	post	pre	post	pre	post	pre	*post*
1890–1900	1	6	4	6	3	8	8	20	7	*14*
1900–1910	2	8	0	13	4	7	6	28	4	*20*
1910–1920	0	10	1	14	4	4	5	28	5	*18*
1920–1930	4	16	8	15	6	12	18	43	14	*27*
1930–1940	4	16	4	14	5	9	13	39	9	*23*
1940–1950	11	21	0	15	2	7	13	45	2	*22*
1950–1960	3	23	4	5	3	9	10	37	7	*14*
1960–1970	3	15	3	8	9	21	15	44	12	*29*
1970–1980	1	15	2	10	6	17	9	42	8	*27*
1980–1990	0	14	0	8	5	16	5	38	5	*24*
1990–2000	5	14	3	4	2	14	10	32	5	*18*

Climate change-induced warming of the atmosphere and oceans significantly impacts cyclone formation and behaviour in various ways. Cyclones gain energy from warm ocean waters, and an increase in SST due to climate change enhances the potential for cyclone development and its intensification. As seen in Figure 5.6, a warming of

1.3°C is assessed under the SSP5 scenario by 2070, which will be further warmed by 3°C by 2100. Such warming of Oceans will be more favourable for cyclone formation and expansion of the cyclogenesis region. Climate-induced warming is assessed up to 300 - 600 m in oceanic waters, with maximum at surface layers and minimum at bottom layers. The amount of heat stored in the upper layers of the ocean can be accessed by tropical cyclones. It considers the water's temperature and the warm layer's depth, typically focusing on the top 100 m of the ocean. Cyclones rely on warm ocean water for energy. A sharp increase in oceanic heat potential (OHP) was noticed from 1990, reaching 320 Zetta joules by 2020 Figure 5.7. The climate scale under SSP2-4.5 assessed an increase of 11×10^{21} Jules/decade, which is alarmingly high compared to past decades (Fig. 5.8). Thus, a higher OHP indicates a larger warm water reservoir, providing more energy for potential storm development. Intensifying storms can further warm the ocean surface through mixing, potentially increasing OHP in the vicinity of the cyclone, which may lead to even more intense cyclones. Areas with high OHP can lead to stronger cyclones. As storms move over regions of higher heat content, they can intensify more rapidly, leading to greater wind speeds and rainfall. Ocean Heat Potential is a vital determinant of cyclogenesis, providing the necessary energy for cyclone formation and intensification. Understanding OHP, especially in the context of climate change, is crucial for predicting cyclone behaviour and assessing risks to vulnerable areas.

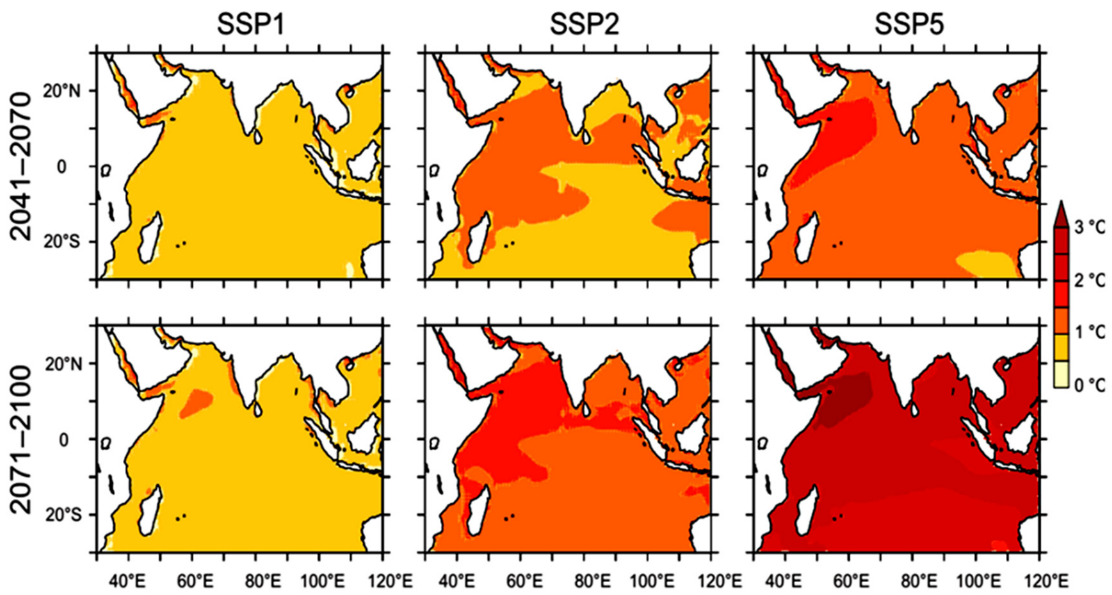


Figure 5.6 SST of Indian Ocean basin under various SSPs (Roxy et al., 2024)

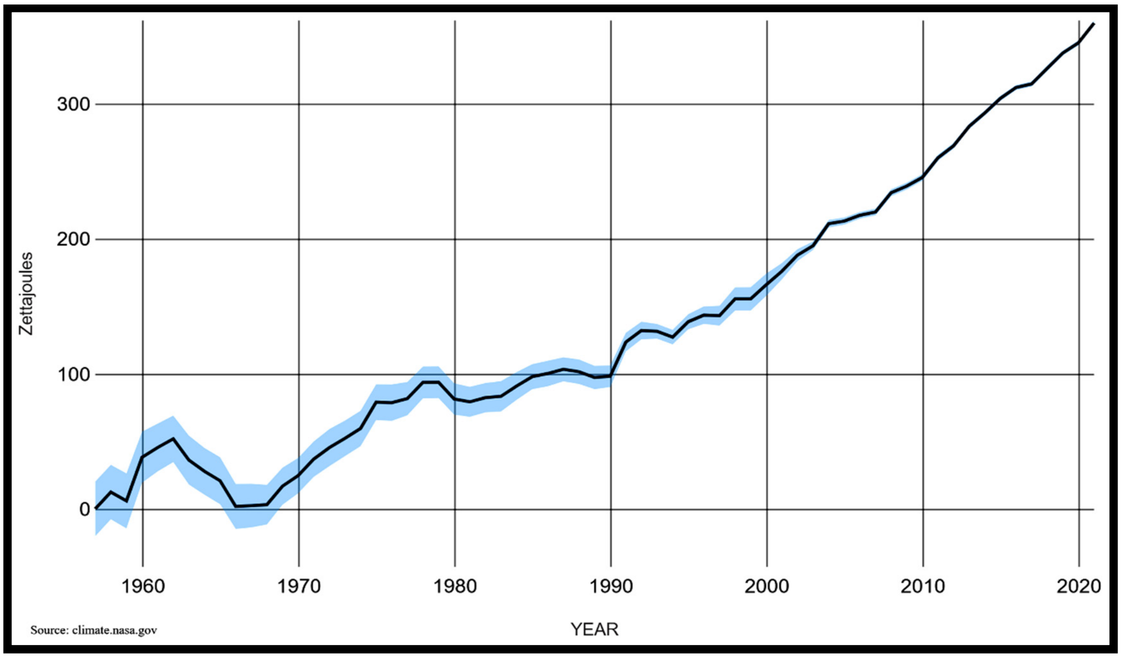


Figure 5.7 Oceanic Heat Potential in the last six decades. (Source: climate.nasa.gov)

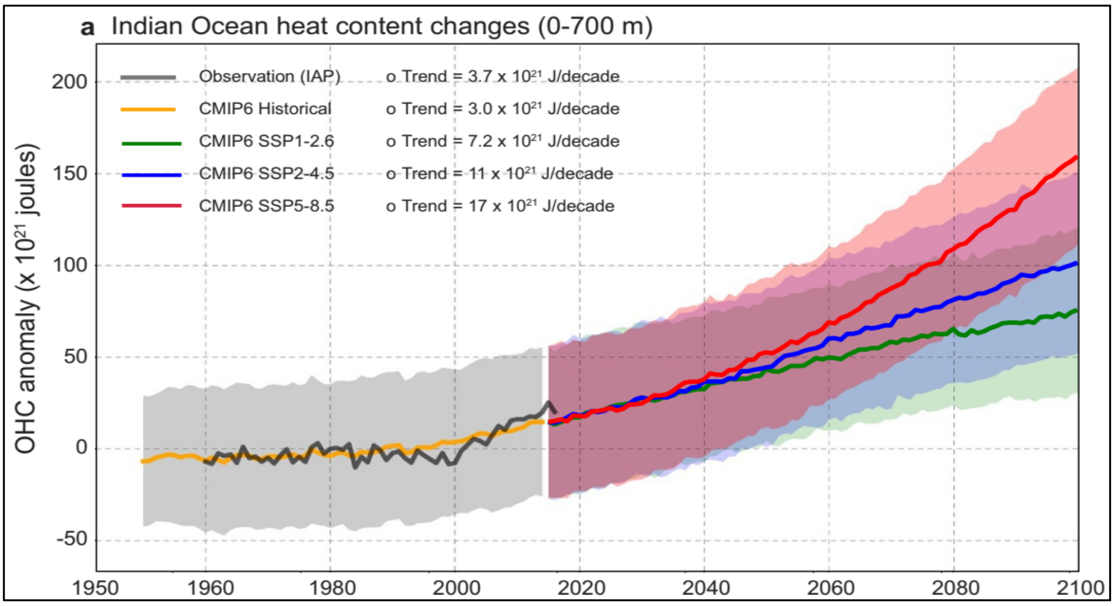


Figure 5.8 Heat content variation and its future projections in the Indian Ocean. (Source: IPCC)

Similarly, a warmer atmosphere can hold more moisture, increasing humidity levels. This added moisture supports stronger convection, which is critical for cyclone development. Furthermore, higher humidity levels can result in more intense rainfall associated with cyclones, leading to greater flooding risks. Another factor related to cyclone formation is vertical wind shear. Climate change may alter wind patterns, affecting the stability of the atmosphere and influencing cyclone formation regions. Changes in atmospheric circulation patterns may lead to alterations in the typical tracks and behaviour of cyclones. Studies indicate that while the overall number of cyclones may not drastically increase, the proportion of Category 4 and 5 storms is likely to rise, driven by warmer ocean temperatures and atmospheric conditions.

The annual frequency of TCs and major hurricanes in 1986–2005, 2016–35, and 2081–2100 HiFLOR simulations (Bhatia, Kieran, et al.). Histograms are plotted for the global frequency of each basin (Fig. 5.9). The study indicates that the future climate will likely have more TCs, which will be a more robust signal that involves the trend in major hurricanes. Both globally and in individual basins, there are significantly more major hurricanes in the HiFLOR late simulation than in the HiFLOR CTL simulation. HiFLOR even suggests that there will be a significant increase in major cyclones by the early part of the twenty-first century. Figures 5.6 and 5.7 also communicate that there will be more TCs in a warmer climate, and the strongest storms will occur more frequently than what was observed at the end of the twentieth century. In the northern Indian Ocean, 30 per cent of storms forming will be category 5 as per the Saffir-Simpson scale. HiFLOR climate change experiments signal that TCs will more routinely reach wind speeds that are well above the category 5 threshold (137 kt), hinting that the Saffir–Simpson scale might need to be extended to include higher categories in the early twenty-first century.

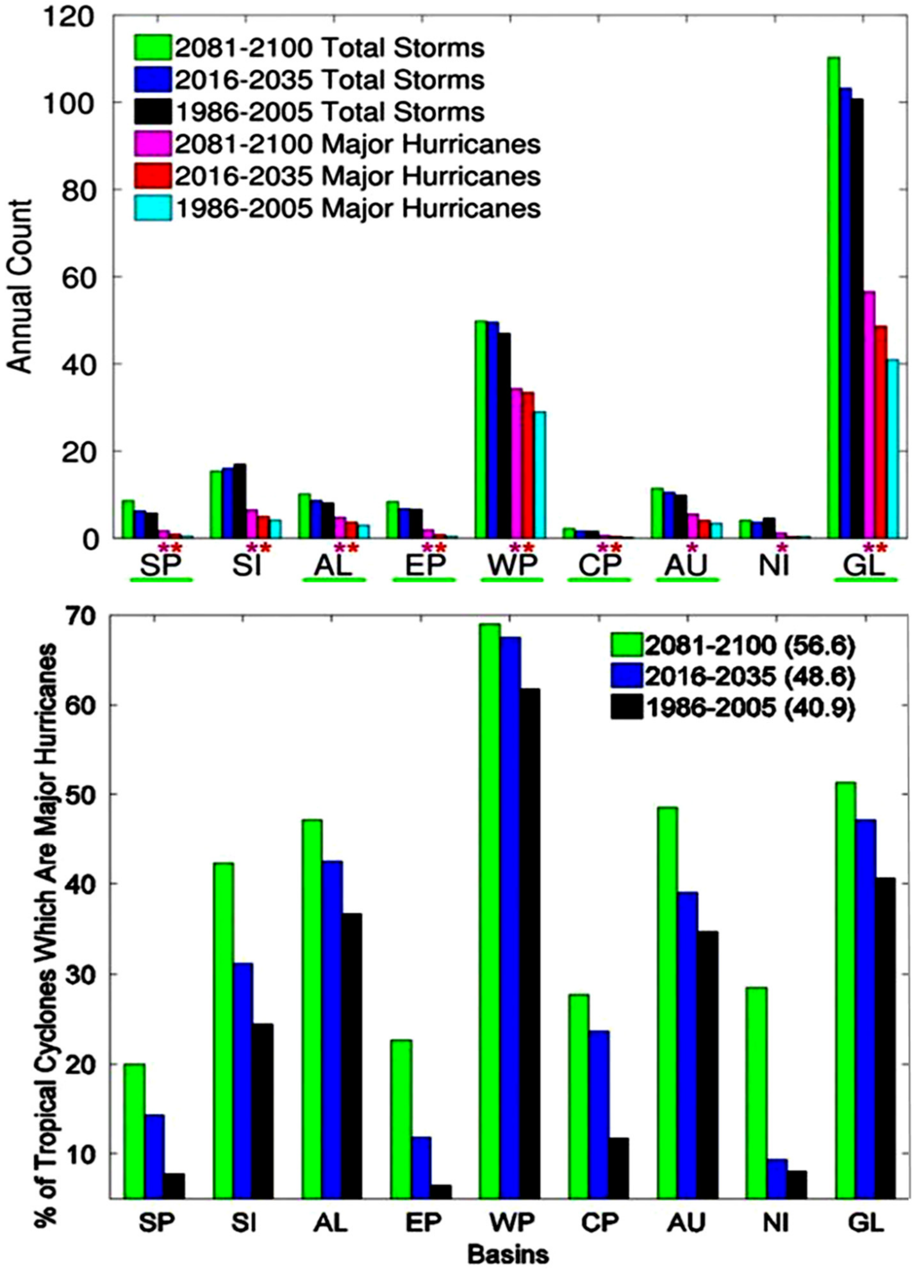


Figure 5.9 Projected response of tropical cyclone intensity and intensification in world ocean basins (*Source: Bhatia, Kieran, et al. "Projected response of tropical cyclone intensity and intensification in a global climate model." Journal of Climate 31.20 (2018): 8281-8303.)*

As the storm intensifies, wind speeds can exceed 74 mph (119 km/h), leading to destructive impacts in the sea and coastal areas. The wind field of a cyclone is typically asymmetric, with the strongest winds occurring in the right front quadrant relative to the storm's motion. Wind speeds can vary greatly, with the eye experiencing calm conditions surrounded by intense winds. Cyclones generate powerful winds that create large waves, often reaching heights of 30 feet (9 meters) or more, especially in the storm's vicinity. A Category 5 cyclone is the most intense classification on the Saffir-Simpson cyclone wind scale, characterised by sustained wind speeds of 157 mph (252 km/h) or higher. Such storms can generate extraordinarily high waves and cause severe damage. Here's a closer look at wave heights and damage potential associated with Category 5 cyclones that can produce wave heights exceeding 10 meters (Figure 5.10).

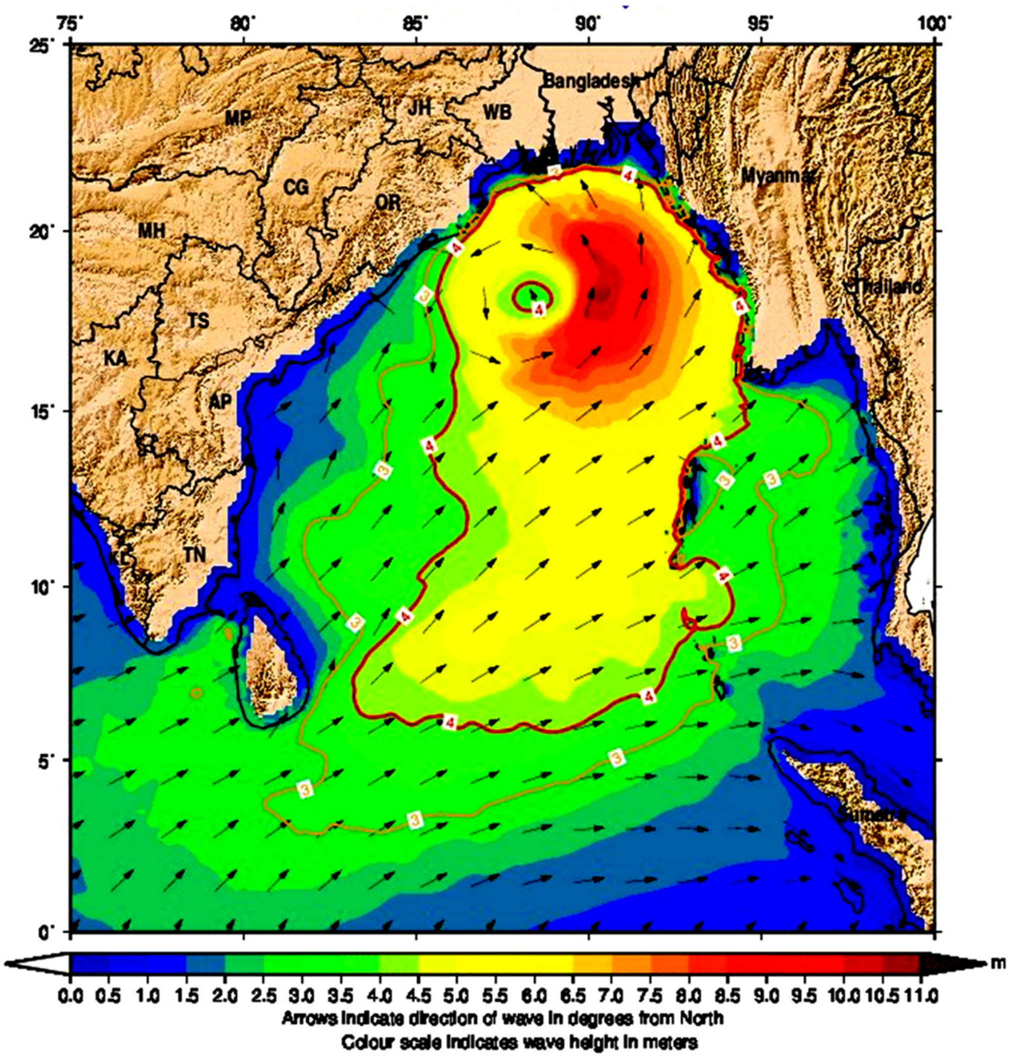


Figure 5.10 shows the significant wave height observed during the passage of a cyclone in the northern BoB.

- **Storm surge**: One of the most devastating impacts of a Category 5 cyclone is the storm surge, which is the rise in sea level caused by strong winds and low pressure. Storm surges can exceed 6 meters in height, inundating coastal areas, leading to widespread flooding, and causing severe shoreline erosion.
- **Flooding**: The combination of high waves, storm surges, and heavy rainfall can lead to extensive flooding, damaging coastal infrastructures.
- **Debris impact**: High winds and waves can turn debris into projectiles, further increasing damage to the infrastructure.

Thus, warming of the atmosphere and oceans due to climate change will likely lead to more intense cyclones with greater rainfall, altered tracks, and potentially changed frequencies. These impacts pose significant risks to coastal regions, ecosystems, and human communities, highlighting the need for continued research and preparedness strategies.

5.3.1 Severe cyclones in the NIO during the recent past

1) ***Cyclone Phailin (2013):*** Eastern coast of India, particularly affecting Odisha and Andhra Pradesh. Several vessels and cargo were significantly damaged. Some ships experienced engine failures and structural damage, leading to emergency responses and salvage operations.

2) ***Cyclone Hudhud (2014):*** Hudhud also caused severe disruptions, leading to accidents and damage.

3) ***Cyclone Vardah (2016):*** This cyclone affected Chennai Ports and shipping activities.

4) ***Cyclone Ockhi (2017):*** Cyclone Ockhi was particularly devastating, with several maritime accidents, including the loss of fishing boats and damage to larger commercial vessels.

5) ***Cyclone Tauktae (2021):*** One of the most intense cyclones in recent years. Ships faced severe conditions, with reports of some vessels losing their way, encountering engine failures, or suffering structural damage.

5.3.2 Cyclones in the climate change scenario

1. **Increased intensity:**

   - *Stronger cyclones:* Warmer SSTs provide more energy to tropical cyclones.
   - *More extreme rainfall:* Increased moisture in the atmosphere due to higher SSTs induces intense rainfall, leading to severe flooding.

2. **Changes in cyclone frequency:**

   - *Variability:* In some seasons or regions, there are more cyclones, while other areas might experience fewer cyclones.
   - *Seasonal shifts:* Changes in temperatures and atmospheric conditions alter the timing and duration of the cyclone season.

3. **Changes in cyclone tracks:**

   - *Altered pathways:* Climate change can influence the steering currents and atmospheric patterns that determine cyclone tracks.
   - *Longer tracks:* Warmer waters might allow cyclones to persist longer and travel further from their origin points.

4. **Increased sea level rise:**

   - *Storm surge:* Higher sea levels can exacerbate the impacts of storm surges associated with cyclones. More extensive coastal flooding and damage.
   - *Coastal erosion:* Higher sea levels, combined with intense cyclones, can lead to increased coastal erosion and damage to infrastructure.

5. **Impact on cyclone formation:**

   - *Formation conditions:* Changes in ocean temperatures and atmospheric stability might alter the conditions necessary for cyclone formation. Warmer waters might increase the likelihood of cyclone formation; changes in wind shear and atmospheric patterns could counteract this effect.

6. **Regional variations:**

- *North Indian Ocean vs. South Indian Ocean:* The impacts of climate change differ between the Northwest Indian Ocean and the Northeast Indian Ocean. Ie, AS and BoB experience different cyclone frequency and intensity.

5.3.3 Regional cyclonic activities

1 **Tropical cyclones (TCs)**

- Increasing intensity metrics regionally.
- US: Increased hurricane damage, decreased TC translation speed.
- Australia: Decrease in TC landfall frequency.
- North Indian Ocean: Decreased overall frequency, increased intensity.

2 **Extratropical cyclones (ETCs)**

- Increase in deep cyclones (core pressure < 980 hPa) over the past five decades.

3 **Severe convective storms**

- Regional variability: Decrease in China, increase in Australia, Europe, and USA.
- Increased short-duration convective event intensity globally, except in eastern China.

4 **Increased storm activities and their impacts**

- Approximately 100 tropical disturbances - Atlantic Ocean annually, leading to about 10 tropical storms.
- Approximately 100 tropical disturbances, leading to about 10 tropical storms.
- Anthropogenic warming is expected to intensify tropical cyclones, increasing wind speeds and rainfall.
- Past hurricanes like Harvey, Katrina, and Rita have severely impacted coastal and offshore petroleum infrastructure.
- Hurricane Harvey in 2017 damaged the release of toxic chemicals and fossil fuels to chemical and petrochemical facilities.
- Hurricane Harvey in 2017 - damage to chemical and petrochemical facilities, release of toxic chemicals and fossil fuels.

- Hurricanes Katrina and Rita destroyed 113 platforms, damaged 19 rigs, and caused 19 mobile offshore drilling to be adrift.
- Increased wave heights during storms contribute to erosion and submergence of coastal infrastructure.
- Offshore pipelines are vulnerable, with statistics showing that hurricanes like Andrew, Ivan, Katrina, and Rita damaged over 1105 pipelines and flowlines.
- Surface damage during hurricanes can disrupt operations of gasoline supply, affecting pumping stations and canopy integrity.

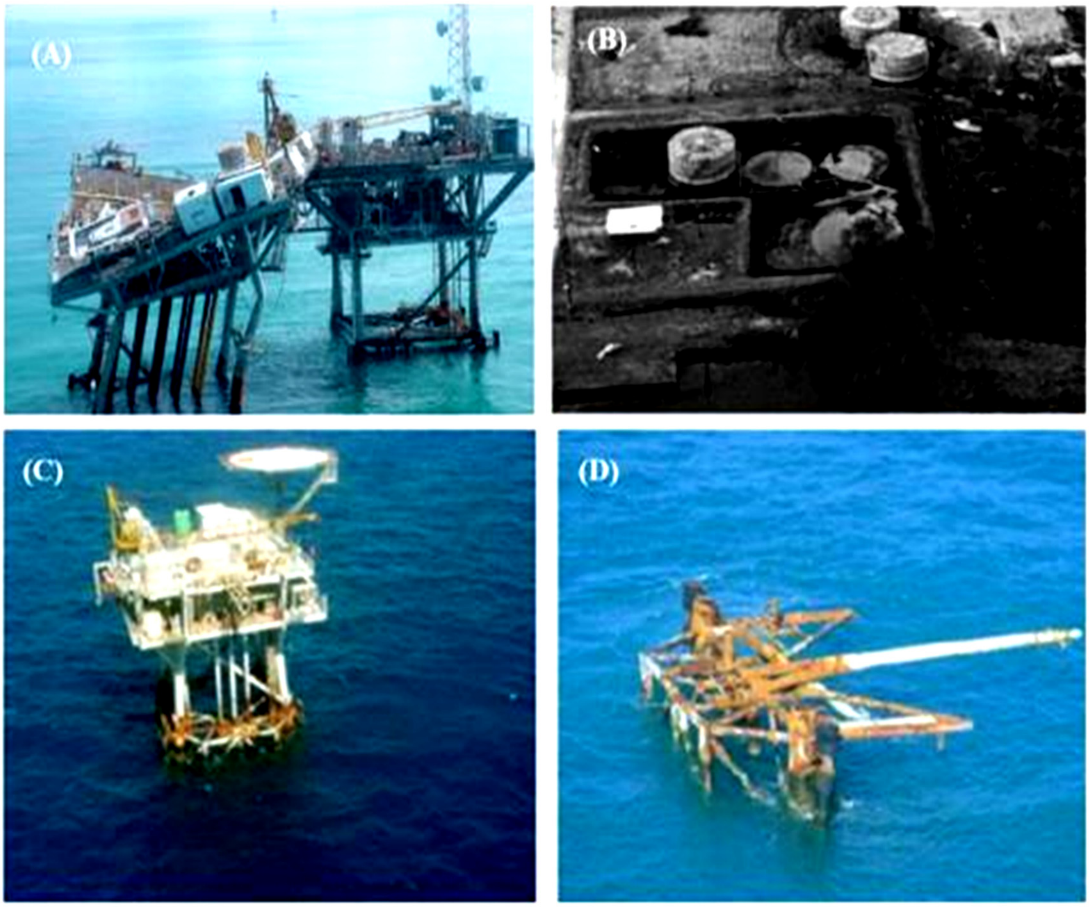


Figure 5.11 Examples of extreme storm impacts on coastal and offshore petroleum infrastructure: (A) offshore platforms were damaged during a hurricane off of Louisiana; (B) oil tanks were carried away by the storm surge that caused over 1,750,000 L of oil release; (C, D) before and after the operating platform was destroyed during the 2005 hurricane season. *(Source: Dong, J., Asif, Z., Shi, Y., Zhu, Y., & Chen, Z. (2022). Climate change impacts on coastal and offshore petroleum infrastructure and the associated oil spill risk: A review. Journal of Marine Science and Engineering, 10(7), 849.)*

5.3.4 Impact of extreme storm events on coastal and offshore infrastructure

- Physical damage to infrastructure.
- Increased risk of oil spills and operational disruptions.
- Need for enhanced resilience and preparedness.
- The energy imposed towards offshore structures due to cyclonic activity

Table 5.4 Equations used for the computations carried out for the analysis

Shallow water waves	$\frac{d}{\lambda} \leq 0.05,\ \lambda_S = \sqrt{gd}$
Intermediate waves	$0.05 < \frac{d}{\lambda} < 0.5\ ,\ \lambda = \lambda_d\ tan(kd)$
Deep water waves	$\frac{d}{\lambda} \geq 0 \cdot 5\ ,\ \lambda_d = \frac{gT^2}{2\pi}$
Total Force	$F = \sqrt{\left(0 \cdot 5\rho C_D A_p v^2\right)^2 + \left(C_m \rho \dot{v} v_{v_0 l}\right)^2 + (0.5\rho C_D A_P v_c^2)^2}$
Acceleration	$a_{max} = \omega \cdot u_{max}\ ,\ (\ \omega = \frac{2\pi}{T})$
Surface Current Speed v/s Wind Speed	$v_0 = \frac{0.0127}{\sqrt{\sin\phi}} \cdot U$
Ekman Depth	$D_E = \frac{7 \cdot 6U}{\sqrt{\sin\phi}}$

Where d = depth,

λ = wavelength,

T = wave period,

C_D = drag coefficient,

C_m = wave force coefficient,

U = wind speed;

v_c = water velocity,

v_{vo} = wave orbital velocity,

l = characteristic length of the object

ω = angular velocity of wave

D_E = Ekman depth, to which wind is influencing the water velocity.

Φ = Latitude

Table 5.5 shows the various wind speeds during the cyclone and associated wave parameters (Gray colour denotes cyclonic storm, yellow indicates category 3 cyclones, and orange indicates category 4 cyclones).

Assumptions for the computations are listed below

Duration = 6 hours,
Fetch = 100 km,
Water depth = 1000 m,
Diameter of the pillar = 0.3 m

Wind Speed(m/s)	Wind Speed (knots)	Significant Wave Height (m)	Peak Wave Period (s)	Mean Wave Length (m)	Wave Celerity (m/s)	Group Celerity (m/s)	Max. Horizontal Velocity (m/s)	Max. Horizontal Acceleration (m/s^2)
10	19.44	1.28	4.82	26.83	6.47	3.24	0.69	0.90
20	38.88	3.84	7.85	71.16	10.54	5.27	1.26	1.01
30	58.32	7.28	10.21	120.38	13.71	6.85	1.84	1.13
40	77.75	10.72	11.52	153.25	15.47	7.73	2.40	1.31
50	97.19	14.10	12.64	184.49	16.97	8.49	2.88	1.43
60	116.63	17.65	13.65	215.15	18.33	9.16	3.34	1.54
70	136.07	21.33	14.55	244.46	19.54	9.77	3.78	1.65
80	155.51	25.14	15.39	273.50	20.66	10.33	4.21	1.75
90	174.95	29.06	16.17	301.93	21.71	10.86	4.64	1.85
100	194.38	33.08	16.90	329.81	22.69	11.35	5.05	1.95

Table 5.6 Variation of wavelength during its transition from deepwater to shallow water

Wind Speed(m/s)	Shallow Depth (m)	Intermediate Depth (m)	Deep Depth (m)	Shallow wavelength (m)	Intermediate wavelength (m)	Deep Wavelength (m)
10	1.34	1.34-13.42	13.42	17.49	32.36	36.27
20	3.56	3.56-35.58	35.58	46.38	85.84	96.21
30	6.02	6.02-60.19	60.19	78.45	145.20	162.76
40	7.66	7.66-76.58	76.58	99.85	184.83	207.20
50	9.20	9.20-92.05	92.05	120.11	222.43	249.45
60	10.70	10.70-106.98	106.98	139.83	259.18	290.91
70	12.09	12.09-120.89	120.89	158.45	294.08	330.53
80	13.42	13.42-134.24	134.24	176.61	328.40	369.80
90	14.68	14.68-146.83	146.83	194.07	361.69	408.23
100	15.87	15.87-158.73	158.73	210.89	394.03	445.93

Table 5.7 Shows net force acting on a pillar installed at intermediate depth region

Wind Speed (m/s)	Ekman Depth (m)	Surface current speed (m/s)	Current Force(N)	Wave Force (N)	Total Force (N)	Total Force (kN)
10	94.25	0.16	42.34	115.73	1309.96	1.31
20	188.49	0.31	338.73	1023.16	1817.57	1.82
30	282.74	0.47	1143.20	3691.10	4196.71	4.20
40	376.98	0.63	2709.81	7989.77	8647.71	8.65
50	471.23	0.79	5292.60	13829.45	14951.90	14.95
60	565.47	0.94	9145.61	21746.46	23696.63	23.70
70	659.72	1.10	14522.89	31953.13	35180.01	35.18
80	753.96	1.26	21678.48	44749.97	49789.03	49.79
90	848.21	1.42	30866.43	60512.88	67983.32	67.98
100	942.46	1.57	42340.78	79245.37	89891.90	89.89

Table 5.8 Shows the net force acting on a pillar installed a shallow depth region

Wind Speed(m/s)	Ekman Depth (m)	Surface current speed (m/s)	Current Force(N)	Wave Force (N)	Total Force (N)	Total Force (kN)
10	94.25	0.16	42.34	11.56	1304.89	1.30
20	188.49	0.31	338.73	102.37	1505.72	1.51
30	282.74	0.47	1143.20	369.17	2030.86	2.03
40	376.98	0.63	2709.81	799.19	3403.70	3.40
50	471.23	0.79	5292.60	1382.19	5849.43	5.85
60	565.47	0.94	9145.61	2175.05	9661.93	9.66
70	659.72	1.10	14522.89	3195.58	15061.29	15.06
80	753.96	1.26	21678.48	4473.66	22280.05	22.28
90	848.21	1.42	30866.43	6050.05	31567.80	31.57
100	942.46	1.57	42340.78	7923.04	43168.28	43.17

Tables 5.5 to 5.8 provide a comprehensive dataset of the effects of wind-generated waves on offshore structures, particularly regarding the forces exerted by both waves and currents. The orange highlighted and the further downward portion of the tables show the projected cyclone scenario the oil industry will experience during severe and catastrophic cyclonic events.

1 Wind speed and wave characteristics

The wave parameters, such as significant wave height, peak wave period, wavelength, and wave celerity, are directly correlated with wind speed. The future scenario calculations predict wave heights of 14.10 – 17.65 m.

For instance, as wind speed increases from 10 m/s to 100 m/s (extreme scenario):

- Significant Wave Height increases from 1.28 m to 54.47 m.
- The Peak Wave Period increases from 4.82 s to 20.02 s.
- Mean Wavelength increases from 26.83 m to 462.82 m.
- Wave Celerity also rises from 6.47 m/s to 26.88 m/s.

This is consistent with general wave theory, where higher wind speeds result in larger, longer-period waves and longer wavelengths. Hence, offshore structures must be designed to withstand greater forces at higher wind speeds due to these increasingly energetic wave conditions.

2 Wave forces vs. Current forces

The total forces acting on a structure (like a pillar) due to waves and currents are calculated by integrating over various depths (shallow and intermediate). These forces show an exponential increase in wind speed:

- At 10 m/s wind speed, the total force integrated to intermediate depth is 1.31 kN, while at 60 m/s, the force reaches 23.7 kN.
- For shallow depths, the total force starts at 1.30 kN at 10 m/s and increases to 9.66 kN at 60 m/s.

The exponential rise in force with increasing wind speed implies that even moderate increases in wind speed could dramatically increase the structural load on offshore systems. This highlights the critical need for accurate wind speed forecasting in offshore engineering to design for extreme conditions.

3 Ekman current and surface speed

The Ekman current and surface current speed calculations show that the wind speed and geographic latitude influence the ocean current speeds. For example, at 150 m/s wind speed, the Ekman depth reaches over 1400 m, and the surface current speed approaches 2.36 m/s. This shows that significant current forces could act on the structure in high-wind conditions, especially in deep water, further increasing the total load. These current-induced forces must be considered in offshore design, particularly in high-wind environments such as hurricanes or typhoons.

4 Depth-dependent forces

The table provides different force calculations based on depth ranges (shallow, intermediate, and deep).

- Shallow water wave forces are relatively low because the waves are smaller, shorter, and less powerful.
- Intermediate depth waves and forces become more pronounced as the wavelength and energy transfer increases.

Offshore designs must account for these depth-related force variations. Shallow water structures may face less extreme wave forces, but are not immune to current forces. In contrast, structures in deeper waters must handle substantial wave and current forces, particularly in high-wind conditions.

5 Scaling with wind speed

The trend across all wave-related metrics (height, period, wavelength, force) is clear: forces on structures scale significantly with wind speed, and the forces rise non-linearly as the wind speed approaches extreme values (150 m/s). This analysis highlights the importance of accounting for wave and current forces in offshore engineering, particularly in high-wind regions. Structures must be robust enough to handle the extreme forces generated by large waves and powerful currents, especially when these forces act together. Offshore designs must integrate thorough wave modelling, including force integration over varying depths, especially for wind turbines, oil rigs, or other marine platforms, to ensure stability and safety under severe weather conditions.

5.3.5 Mitigation and adaptation strategies

Mitigating the impact of severe tropical cyclones in the northern Indian Ocean, particularly in the oil and gas industry context, requires a multifaceted approach. Here are several strategies that can be implemented:

1. **Risk assessment and planning**

   - Vulnerability analysis: Conduct detailed assessments of infrastructure and facilities to identify vulnerabilities to cyclones.
   - Scenario planning: Develop response plans for various cyclone scenarios, including worst-case situations.

2. **Infrastructure resilience**

   - Robust design Standards: Design new facilities to withstand extreme weather conditions, incorporating lessons learned from past events and climate forecast scenarios.
   - Retrofitting existing infrastructure: Upgrade existing structures to enhance their resilience, such as reinforcing offshore platforms and onshore facilities.

3. **Early warning systems**

   - Implement Advanced Monitoring: Utilise satellite imagery and meteorological data to predict cyclone development and track their paths.
   - Communication Networks: Establish reliable communication systems to relay timely information to staff and local communities.

4. **Emergency preparedness and response**

   - Training and Drills: Train employees and emergency response teams regularly on cyclone preparedness and evacuation procedures.
   - Stockpiling Resources: Maintain emergency supplies and equipment to quickly address damage or disruptions caused by cyclones.

5. Environmental management

- Oil Spill Contingency Plans: Develop comprehensive plans to address potential spills resulting from cyclone damage, including deployment of response teams and equipment.
- Ecosystem Restoration: Engage in programs that restore coastal ecosystems, which can act as natural barriers against cyclones (e.g., mangroves).

6. Collaboration with local communities and governments

- Community Engagement: Work with local populations to enhance their resilience, sharing knowledge and resources to prepare for cyclones.
- Public-Private Partnerships: Collaborate with governmental bodies on infrastructure projects that improve regional cyclone resilience.

7. Sustainable practices

- Invest in Renewables: Explore opportunities for integrating renewable energy sources, which can reduce dependence on fossil fuels and enhance overall resilience.
- Carbon Management: Implement strategies to reduce greenhouse gas emissions, contributing to broader climate change mitigation efforts.

8. Research and innovation

- Invest in R&D: Support research on cyclone impacts and innovative technologies that can improve resilience and response strategies.
- Adopt New Technologies: Utilise advanced materials and construction techniques that offer better protection against extreme weather.

9. Policy advocacy

- Promote Regulatory Standards: Advocate for policies that establish stricter building codes and safety regulations for offshore and onshore facilities.
- Insurance and Financial Tools: Develop financial instruments, such as disaster insurance, to help manage risks associated with cyclone damage.

10. Monitoring and evaluation

- Regular Assessments: Continuously monitor the effectiveness of implemented strategies and adapt plans based on new data and experiences.

By combining these strategies, the oil and gas industry can significantly mitigate the impacts of severe tropical cyclones, enhance resilience, and contribute to broader climate adaptation efforts in the northern Indian Ocean.

5.3.6 Anticipated impact of cyclones on ship movements and its mitigation measures

Precautionary measures during a cyclone:

- Study the weather report
- Keep away from the centre of the storm
- Check the stability of the vessel
- Use ballast tanks to minimise - free surface effect
- Be careful while changing speed, angle, and direction
- Inform all departments

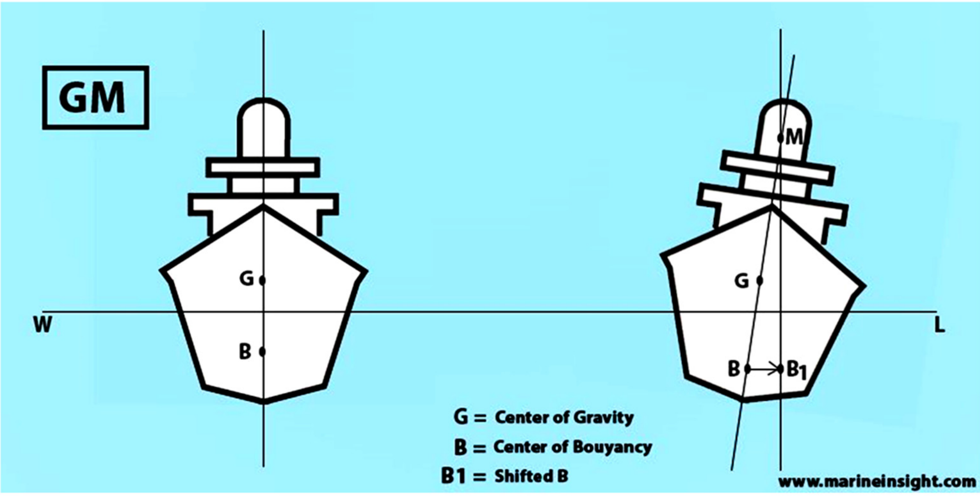


Figure 5.12 A picture depicting the stability of the vessel

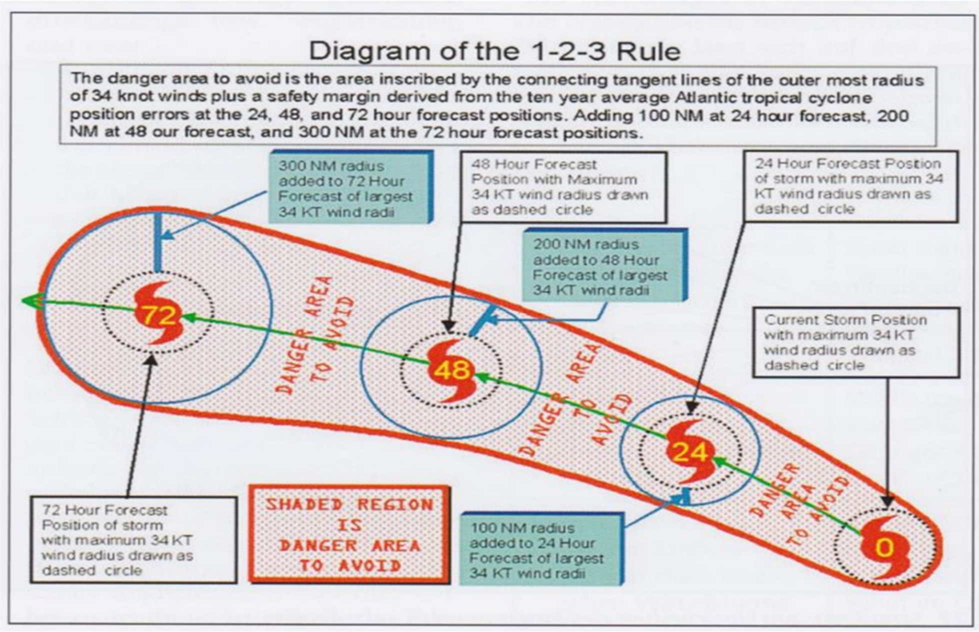


Figure 5.13 Diagram of the 1-2-3 rule

The 1-2-3 rule (Figure 5.13) establishes a minimum recommended distance away from a cyclone. Any ship in the vicinity of a tropical cyclone should make every effort to remain clear of the maximum radius of analysed or forecast 34 kt winds associated with the tropical cyclone. Knowing that the area of 34 kt around tropical cyclones is rarely symmetric but instead varies within semi-circles or quadrants is important.

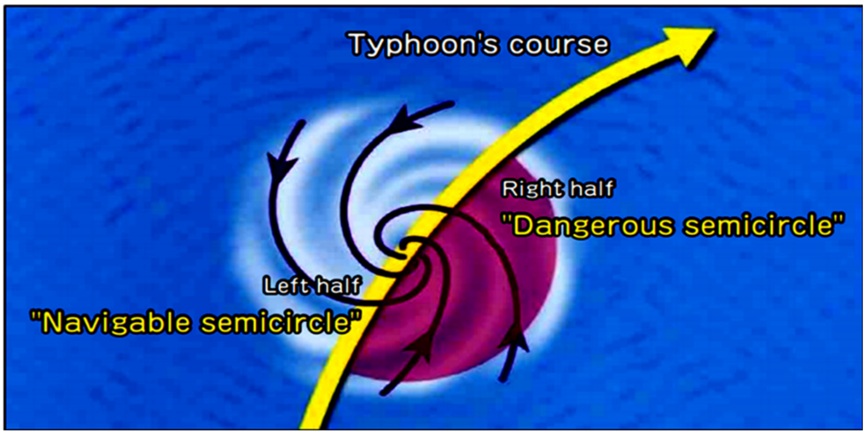


Figure 5.14 Safe pathway during a cyclonic event

A cyclone winds blow counterclockwise into its centre. Wind speed in the right semi-circle is strengthened as the cyclone's migration speed increases. Therefore, wind speed and waves are always higher in the right semi-circle than in the left semi-circle;

the right semi-circle of the typhoon is known as the “dangerous semi-circle”. On the other hand, because a typhoon’s wind speed and blowing wind are reversed, the wind in the left semi-circle is always weaker than in the right semi-circle. Thus, the left semi-circle of the typhoon is known as the “navigable semi-circle” (Figure 5.14).

5.4 Sea-level rise, coastal flooding and shoreline erosion

5.4.1 Sea level rise

In the climate change scenario, the warming of air and water temperatures contributes to the thermal expansion of seawater and the melting of ice caps and glaciers. This increase in sea levels poses severe threats to coastal communities, ecosystems, and infrastructure worldwide. Coastal erosion, increased flooding, and saltwater intrusion into freshwater resources are some of the challenges in the near future (Figure 5.15).

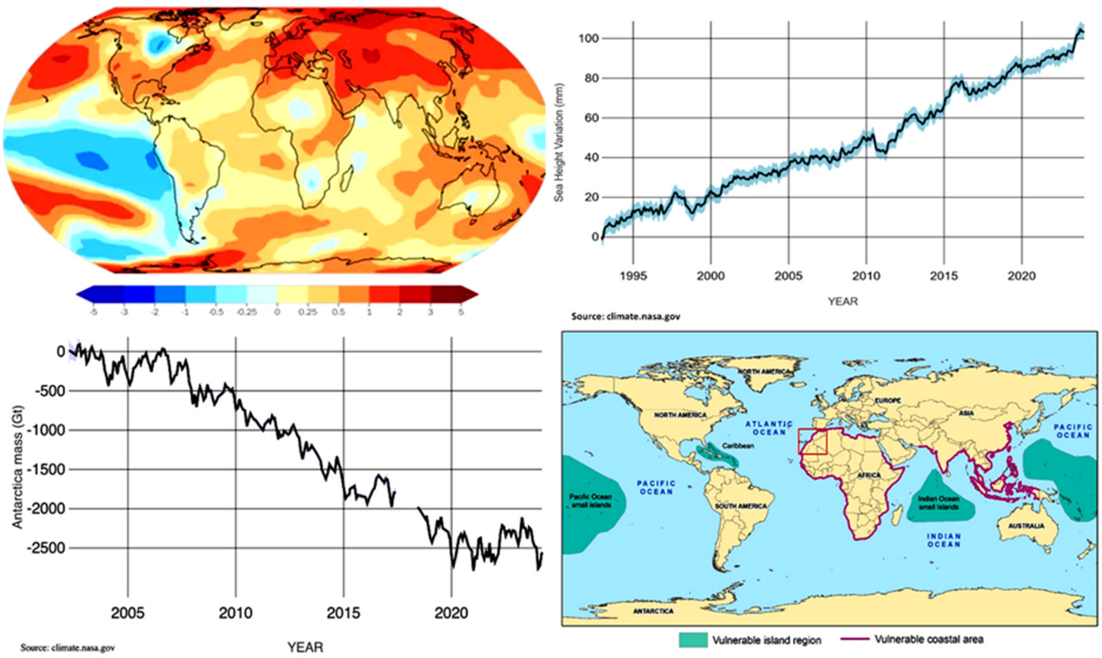


Figure 5.15 The sea level rise causes and impacts. Sea level has risen about 40 cm in the past century and is projected to rise another 60 cm in the next century. Due to global warming, the average rise of sea level is 1.5 to 10 mm per year. It has been observed that a sea level rise of 1 mm per year could cause an inundation of the order of about 0.5 m per year (IPCC report). In the northern Indian Ocean, sea level rise is mainly caused by thermal expansion, which increases by 12-13 mm/decade. *(Source Collin et al., IPCC SROCC 2019; Beal et al., BAMS 2019)*

Understanding the intricate relationship between global warming and sea level rise is crucial for developing effective strategies to mitigate their impacts and protect vulnerable populations and coastal infrastructure. The primary impacts in coastal areas are likely to result from sea level rise, coupled with waves during storms and storm surges, which may lead to increased coastal erosion, tidal inundation and coastal flooding.

SL has risen about 40 cm in the past century and is expected to rise another 60 cm in the next century. Due to global warming, a rising sea level is expected to be 1.5 to 10 mm/year, and a rise of every 1 mm /year could cause inundation of water towards land by 0.5 m /year. The sea-level projection of IPCC showed an increase in sea level between 0.44 m and 0.81 m by 2100, following the temperature projection from 1.5°C to 5°C, respectively (Figure 5.6). Similarly, under various SSPs, sea level variation is estimated to vary between 0.38 m and 0.77 m by 2100 (Figure 5.16).

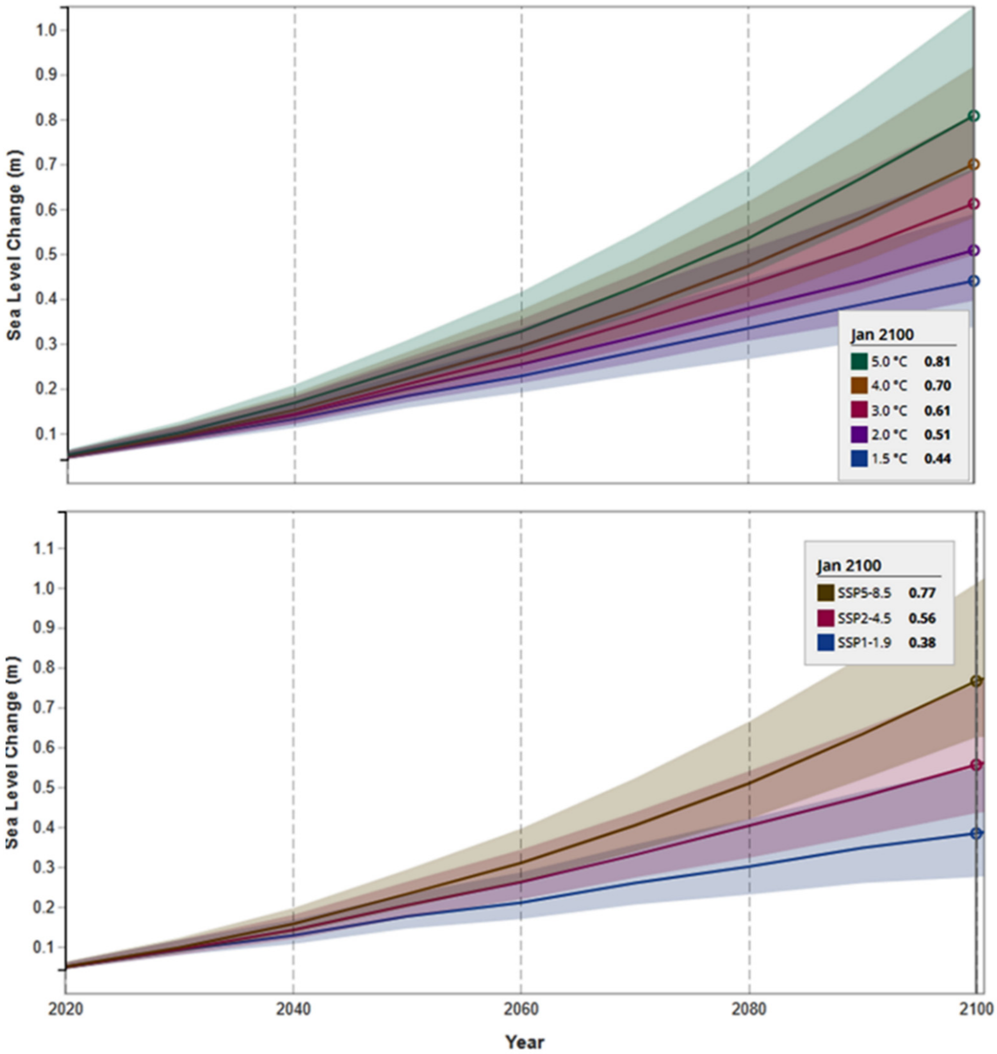


Figure 5.16 Shows the sea-level variation under warming temperatures and various SSP scenarios. *(Source: https://sealevel.nasa.gov/task-force-scenario-tool)*

The Indian coastline is one of the world's most vulnerable regions to the impacts of sea level rise, driven largely by global warming. As temperatures increase, the Indian Ocean experiences thermal expansion of seawater and significant melting of glaciers and ice sheets in surrounding regions, particularly in the Himalayas and the polar ice caps. The annual increase of sea level along the Indian coastline is not similar, according to the rate of change of thermal expansion of each region, shoreline slope, and water level changes, which is listed in Table 5.9. All the records show an increasing trend and show that Indian coastlines are vulnerable to sea level rise and climate change.

Table 5.9 Rate of sea level rise (mm/year) along the Indian coastline

Kandala:	2.41
Goa:	3.07
Kochi:	1.78
Chennai:	0.41
Visakhapatnam:	1.46
Paradip:	2.24

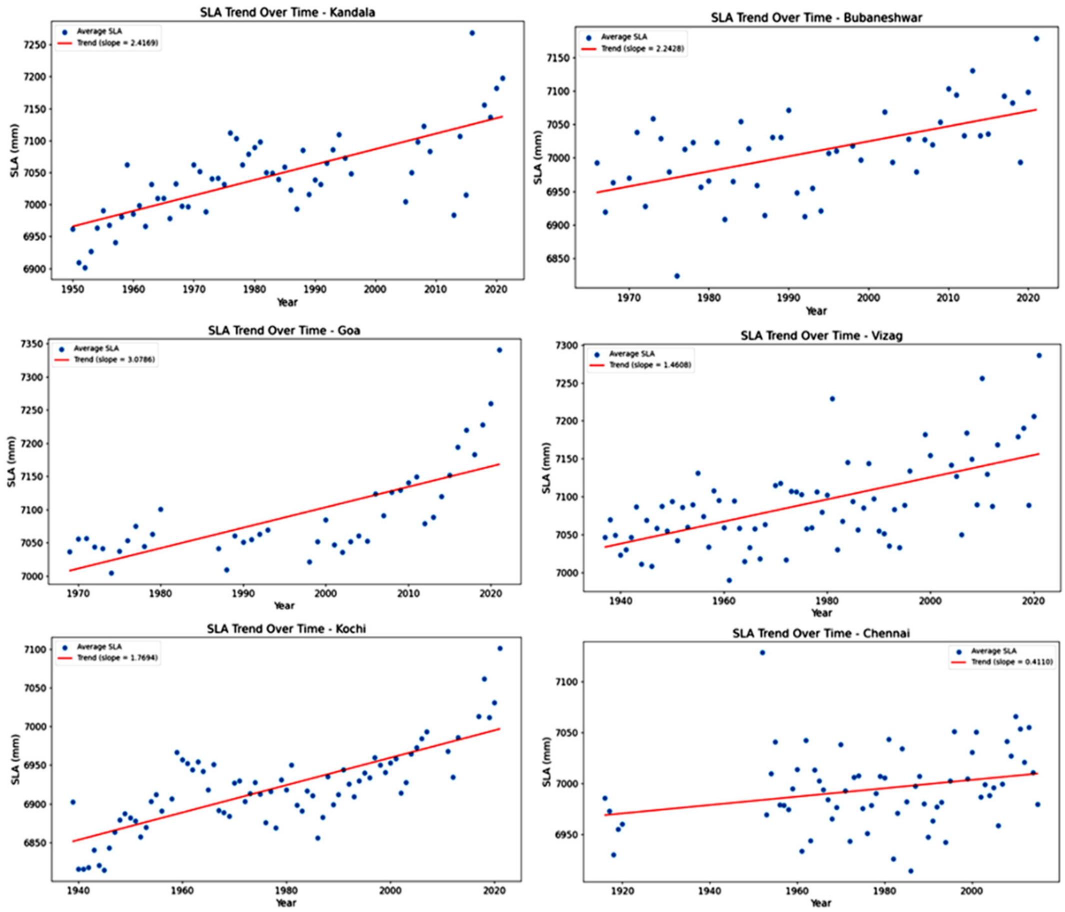


Figure 5.17 The rising trend of sea level along the Indian coastline.

5.4.2 Coastal flooding

To investigate the effect of wave-current-cyclone interactions on wave height and wave propagation, one inundation model experiment has been conducted by changing the projected sea level and wave parameters along the major coastal city of India, Mumbai (Figure 5.18). The vulnerable coastal regions have been demarcated through inundation mapping due to the cyclones, tsunamis, in a climate change scenario, etc. During cyclonic events, the coastal regions, especially at elevations less than 3 m, are severely affected and will be continuously inundated up to a distance of 100 m from shore. This study shows that coastal cities like Mumbai are highly vulnerable to sea level rise and storm surges during cyclone periods. The coastal regions, with the presence of mangrove forests, protected the coast from immediate inundation.

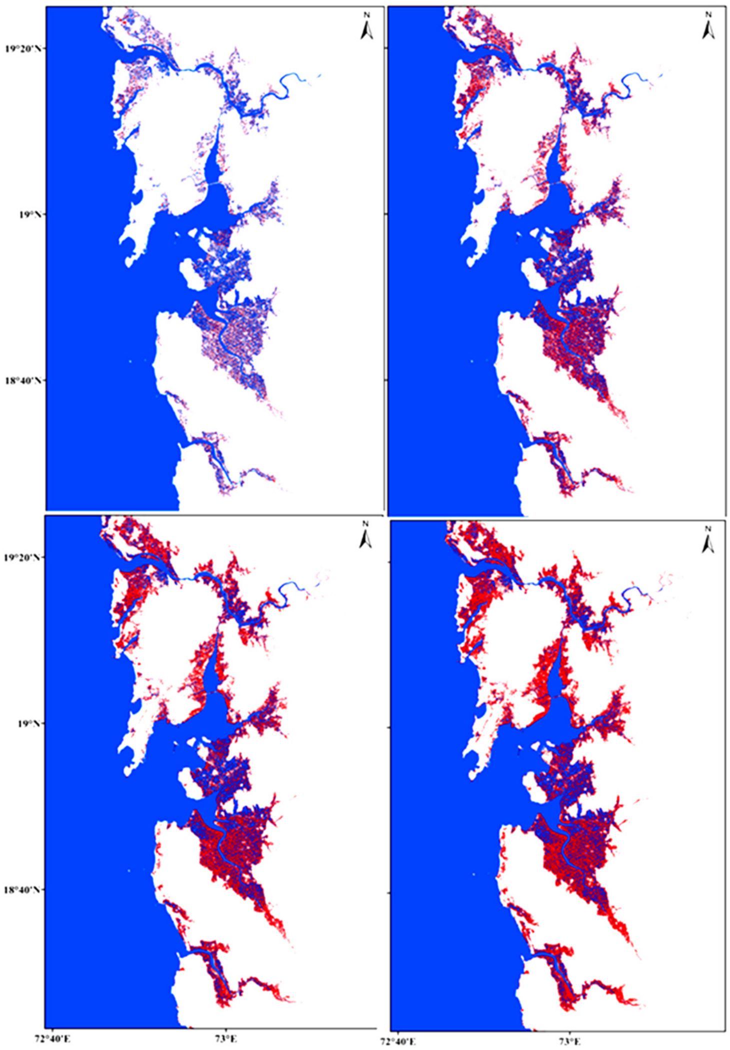


Figure 5.18 The inundation of waters during the storm surge in a climate change scenario

5.4.3 Shoreline Erosion

India has a vast coastline stretching over 7,500 kilometres, comprising various coastal states along the AS and BoB. These coastal regions are vital for their biodiversity, economic activities, and cultural heritage. However, they are increasingly facing the challenge of shoreline erosion due to various factors, including climate change, human activities, and natural processes.

Anthropogenic activities such as urbanisation, sand mining, and coastal constructions disrupt natural sediment transport processes. This is further augmented by natural processes, including severe wave action during monsoon season, tides, and currents, contributing to the' erosion dynamics of coastlines. Climate change induced a rise in sea level and increased the frequency of storms and associated surges along the coast. Finally, deforestation and Land Use Changes resulted in the loss of mangroves and coastal vegetation, reducing natural barriers against erosion.

Shoreline erosion is a significant concern for many of these states (Table 5.10), with trends varying based on local conditions:

1. **Gujarat**:
   - Certain areas, particularly around the Gulf of Khambhat, are experiencing rapid erosion due to both natural processes and human interventions, such as coastal development and dredging.
2. **Maharashtra**:
   - The coastline, particularly in Mumbai and Konkan regions, faces erosion due to construction, increased wave energy, and rising sea levels. Coastal defences are being implemented in vulnerable areas.
3. **Goa**:
   - The beaches are undergoing erosion due to tourism-related activities and changes in coastal land use. The government is working on beach nourishment and management strategies.

4. **Karnataka**:

- Areas like Udupi and Mangalore have reported significant erosion, primarily due to urbanisation and natural factors. Efforts are underway to implement coastal protection measures.

5. **Kerala**:

- The state faces severe beach erosion, influenced by monsoon patterns, rising sea levels, and sand mining. Measures like artificial reefs and beach nourishment are being explored.

6. **Tamil Nadu**:

- The eastern coastline, particularly around Chennai, is prone to erosion exacerbated by urban development and climate change. Studies are focusing on sustainable coastal management.

7. **Andhra Pradesh**:

- The coastline experiences erosion and accretion due to natural sediment dynamics, with some areas losing land rapidly. Integrated coastal zone management is being emphasised.

8. **Odisha**:

- The state faces significant erosion, especially in the Balasore district, which is influenced by cyclones and rising sea levels. Strategies include afforestation and constructing embankments.

9. **West Bengal**:

- The Sundarbans region is particularly vulnerable to erosion due to tidal influences and rising sea levels. Sustainable practices and restoration efforts are being implemented.

Impact of sea level rise, shoreline erosion, coastal flooding and storm surges on oil and gas infrastructure

Coastal structures, particularly in the oil and gas industry, are increasingly vulnerable to the impacts of storm surge, coastal flooding, sea level rise, and shoreline erosion. Here's a breakdown of these effects:

1. Storm surge and coastal flooding

- **Infrastructure damage**: Storm surges can inundate oil and gas facilities, leading to physical damage to equipment and infrastructure, including refineries, pipelines, and storage facilities.
- **Operational disruption:** Flooding can halt operations, delay production, and cause financial losses. Recovery and clean-up efforts can be costly and time-consuming.
- **Environmental risks:** Flooded facilities may release hazardous materials into the environment, leading to potential spills and contamination of water sources and ecosystems.

2. Sea level rise

- **Increased vulnerability**: As sea levels rise, coastal facilities are at a greater risk of flooding during regular high tides and storm events, necessitating costly adaptations or relocations.
- **Erosion of coastal infrastructure**: Rising seas contribute to shoreline erosion, which can undermine the foundations of coastal structures, increasing maintenance costs and the risk of structural failure.
- **Regulatory challenges**: Companies may face stricter regulations and increased scrutiny regarding their environmental impact, pushing for more sustainable practices and infrastructure designs.

3. Shoreline erosion

- **Loss of access**: Erosion can compromise access roads and transportation routes critical for the oil and gas industry, impacting supply chains and logistics.

- **Increased maintenance costs**: Continuous erosion requires ongoing investment in protective measures like seawalls and beach nourishment, which can strain budgets.
- **Long-term viability**: The sustainability of coastal operations is called into question as erosion and flooding increase, potentially leading to relocations or closure of facilities.

4. **Economic implications**

- **Investment in resilience**: The need for adaptive infrastructure, such as raised platforms and better drainage systems, increases operational costs. Companies must balance these investments against their overall financial health.
- **Insurance and liability issues**: With rising risks, insurance premiums may increase, and liability for environmental damages can lead to significant financial repercussions.

5. **Operational challenges**

- **Access issues:** Rising sea levels and coastal erosion can make access to offshore platforms more difficult, complicating logistics and increasing costs for transportation and maintenance.
- **Increased storm intensity:** Climate change is linked to more frequent and severe storms, which can disrupt operations, delay production, and increase the risk of accidents. Severe weather events can damage equipment and infrastructure, leading to costly repairs and downtime.

6. **Future considerations**

- **Technological innovations**: The industry may invest in new technologies and materials that can withstand extreme weather and flooding events.
- **Collaborative efforts**: Engaging with government and environmental organisations can lead to better planning and investment in coastal resilience, benefiting industry and communities.

Challenges

- Climate change induced a rise in sea level and an increasing frequency of extreme events on India's west and east coasts.
- Need for adaptation strategies and resilient infrastructure design.
- Maintenance of existing structures & unavailability of large-sized armour stones.
- The environmental impact of hard solutions-transferring the problems to the down drift direction.
- Absence of site-specific nearshore wave dynamics and morphology.

Table 5.10 Showing shoreline erosion accretion station of coastal states of India

Sl No	States		Shoreline used for mapping (in km)*	Status of the coast					
				Erosion		Stable		Accretion	
				km	%	km	%	km	%
1	West Coast	Gujarat, Daman & Diu	1701.78	524.84	31	741.98	43	434.96	26
2		Maharashtra	739.57	178.26	24	472.67	64	88.64	12
3		Goa	139.64	16.82	12	95.58	68	27.24	20
4		Karnataka	313.02	70.02	22	151.16	48	91.84	30
5		Kerala	592.96	263.04	45	201.52	34	128.40	21
6	East Coast	Tamil Nadu	991.47	407.05	41	353.56	36	230.86	23
7		Pondicherry	41.66	23.80	57	14.63	35	3.23	8
8		Andhra Pradesh	1027.58	272.34	27	320.98	31	434.26	42
9		Odisha	549.50	153.80	28	113.52	21	282.18	51
10		West Bengal	534.35	336.52	63	68.78	13	129.05	24
Total			6631.53	2246.49		2534.38		1850.66	
%				34		38		28	

* Length of shoreline estimated from imageries(1:25000 scale) excluding river /creak mouths etc.

Source: NCCR Chennai Shoreline Assessment Report

5.4.4 Mitigation measures to sea level rise, shoreline erosion, storm surge and coastal flooding

1. Soft and hard methods

The rise of sea levels in the Indian Ocean is a multifaceted issue that poses significant challenges to coastal communities and ecosystems. As the impacts of global warming continue to unfold, proactive measures are crucial to mitigate risks and build resilience in the face of changing environmental conditions. Through collaborative efforts and innovative solutions, it is possible to address the challenges of rising sea levels and shoreline erosion and protect the livelihoods of millions in the Indian Ocean region.

- Soft coastal solutions are those that do not damage or grossly interfere with the beach and allow the natural flow of sand along the beaches.
- Hard coastal solutions disrupt the beach, natural sediment movement and environment.

To combat climate change, the primary design goal of all coastal works is to rotate the beaches onto a more neutral orientation.

Soft Solution

Soft solutions to prevent shoreline change focus on natural processes and materials to manage erosion and protect coastal areas. These approaches are often more sustainable and environmentally friendly than hard engineering solutions. One of the most suitable methods is to preserve the coastal beaches, sand dunes, beach nourishments, preservation and afforestation of mangroves (Figure 5.19), and protect natural barriers such as coral reefs and coastal islands.

Mangroves

- Effective bio-shields.
- Salt-tolerant plants of tropical and subtropical intertidal regions.
- Roots trap silt in the water & form a skeletal biological mesh under the ground.
- Porous root-textile mesh facilitates the accumulation of debris.
- Does not yield easily to the tidal waves associated with natural disasters.

Figure 5.19: Mangrove protection

Hard Solution

This solution involves structural interventions to protect the coast from erosion and other coastal processes. These solutions are typically engineered to withstand the forces of waves and currents, providing immediate protection but often requiring significant investment and maintenance. These solutions include the construction of seawalls, breakwaters, revetements, paving of groynes structures, sandbags and temporary barriers along the coast (Figure 5.20). This method is only suggested where soft solutions cannot practically trap sediment, and the regions have severe shoreline erosion.

Figure 5.20: Groynes, breakwaters and tetrapods

Table 5.11 Shoreline protection method from bottom to top, where shoreline erosion has to be mitigated by soft/ hard solutions

Title	Methodology	Env. Impact	Category
Steep seawalls	A longshore wall is built to protect the land with front slope gradient >1:15.	12	Hard
Low gradient seawalls	A long shore wall is built to protect the land with front slope gradient <1:15.	11	Hard
Headland groynes	Groynes/headlands longer than 300 m with high crest	10	Hard
Long, high-crested groynes	Groynes longer than 100-300 m with crest above high tide	9	Hard
Short, high-crested groynes	Groynes with crest above high tide, but less than 100 m long	8	Hard
Low-crested groynes	Series of groynes with crests lower than high tide, and less than 100 m long	7	Moderate
Nearshore reef	A reef is built close to shore or on the inter-tidal beach.	6	Moderate
Off. islands/ breakwater	Emerged offshore structure	5	Moderate
Offshore reefs	Reef is built offshore, normally in 3-8 m depth	4	Moderate
Nourishment	Major sand replenishment. Sand source is offshore or external	3	Soft
Dune restoration	Sand replacement from the beach or surf zone	2	Soft
Dune care	Replanting, fencing, walkways on dunes	1	Soft

2. Infrastructure design and upgrades

- **Drilling platforms and rigs**: Offshore platforms are often located near coastlines, making them susceptible to rising sea levels and increased wave action. Infrastructure designed to withstand certain environmental conditions may face heightened risks, potentially leading to structural damage or failure.

- **Pipeline integrity:** Subsea pipelines can be exposed to increased sedimentation and erosion, leading to vulnerabilities. Erosion of the seabed can expose pipelines, risking leaks and spills, which can have devastating environmental consequences.
- **Elevated structures**: Building facilities on raised platforms can help protect against sea level rise, flooding and storm surge.
- **Flood-resistant materials**: Using materials designed to withstand flooding and corrosion can extend the lifespan of the structures.
- **Flexible and modular designs**: Creating modular facilities that can be relocated or adapted as conditions change enhances resilience.

3. Natural barriers and coastal restoration

- **Beach nourishment**: Adding sand to eroded beaches to restore their natural shape and width.
- **Dune restoration**: Rebuilding sand dunes can provide a first line of defence against storm surges and erosion.
- **Living shorelines**: Implementing living shorelines that use natural materials and vegetation can stabilise shorelines and reduce erosion.
- **Wetland restoration**: Restoring coastal wetlands can absorb storm surges and reduce flooding, acting as natural barriers.

4. Engineering solutions

- **Seawalls and flood barriers**: Constructing seawalls and flood barriers can protect critical infrastructure from storm surges and high tides.
- **Tidal gates and surge barriers**: Installing tidal gates can control water flow and reduce flooding in low-lying areas.
- **Revetments and breakwaters**: These structures can absorb wave energy and protect shorelines from erosion.

5. **Monitoring and early warning systems**

- **Real-time monitoring**: Implementing advanced monitoring systems for weather patterns, sea levels, and storm surges allows for timely responses.
- **Early warning systems**: Establishing robust early warning systems can help prepare and protect infrastructure ahead of storms.

6. **Land use planning and zoning**

- **Strategic site selection**: Avoiding construction in the most vulnerable areas can reduce risk.
- **Regulatory compliance**: Adhering to updated building codes and environmental regulations ensures that new developments consider future risks.

7. **Emergency preparedness and response plans**

- **Crisis management planning**: Developing and regularly updating emergency response plans can minimise damage and facilitate recovery during extreme weather events.
- **Training and drills**: Regular training for staff on emergency procedures and evacuation plans helps ensure preparedness.

8. **Research and development**

- **Investment in R&D**: Funding research into innovative technologies and practices can yield new solutions for mitigating the impacts of climate change.
- **Data collection and analysis**: Continuous collection of environmental data supports informed decision-making and adaptive management.

9. **Policy and regulatory framework**

- **Integrated Coastal Zone Management (ICZM):** Implementing a comprehensive approach to managing coastal resources sustainably.
- **Compliance challenges:** As governments respond to climate change, regulations around environmental protection are likely to tighten. The oil and gas industry may face increased scrutiny and stricter regulations related to emissions and environmental impact, complicating operational compliance.

5.5 Oil spills in a climate change scenario

The major causes of oil spills in the coastal and offshore waters are accidents involving ships, barges, tankers, pipelines, platforms, and facilities, exacerbated by equipment failures and natural disasters like hurricanes and storm surges. Once an oil spill occurs in the environment, it will poison fish, birds, and other wildlife. The oil can coat feathers and fur, leading to loss of insulation and buoyancy and disrupting reproductive and feeding behaviours. Further disruption in coastal and marine habitats, such as mangroves, coral reefs, and salt marshes, can severely affect them. Thus, it damages fishing grounds and affects the livelihoods of local fishermen. Contaminated seafood can pose health risks and lead to market closures, which also affect coastal areas and may experience a decline in tourism, impacting local economies.

➢ **Risks associated with an oil spill in a climate change scenario**

- *Sea level rise:* Raises the likelihood of erosion, disruption, and damage to oil and gas platforms, refineries, and pipelines.
- *Flooding:* Extreme rainfall and floods can damage onshore and offshore pipelines and infrastructure, as seen in incidents like the low flatland area flood in Japan in 2019.
- *Oil spills:* From 1991-1995 to 2016-2021, spills from pipelines and wells/ platforms significantly increased globally.
- *Impact of extreme storms:* Hurricanes like Katrina and Ida have caused substantial oil spill events, highlighting increased infrastructure vulnerability during extreme weather.
- *Shoreline exposure:* Global warming can lead to larger oil spill areas and increased shoreline exposure.
- *Overall risk increase:* While the direct influence of climate change on oil spill frequency is not fully clear, climate change intensifies risks in coastal and offshore areas.
- *Management needs:* Urgent development of decision support systems to optimise oil spill management, considering climate change dynamics, is crucial.

- **Oil spills occurrence -worldwide**

  Total Incidents: From 1991 to 2021, 2182 oil spill incidents were recorded in coastal and offshore areas of the USA, of which 380 had unknown sources. (*Source https://doi.org/10.3390/jmse10070849*).

  - Primary Sources (excluding mystery spills):
    1) Shipping vessels (60.6%): Includes military, fishing vessels, bulk carriers, and pleasure crafts.
    2) Pipelines (10.7%)
    3) Tanks/ facilities (10.0%)
    4) Tankers/ barges (9.9%)
    5) Wells/ platforms (8.8%)

  - Trends: Despite declines from 2011 to 2015, spills from shipping vessels, pipelines, tanks/ facilities, and wells/ platforms have shown an increasing trend over the last three decades.

Recent oil spill accident in Indian waters

1. **MV Pavit Oil Spill (2011)**
   - On July 31, 2011, the MV Pavit, a cargo vessel carrying crude oil, sank off the coast of Mumbai due to rough seas.
2. **MV Mega Sun Oil Spill (2015)**
   - On January 28, 2015, the MV Mega Sun, a Liberian-flagged tanker, experienced a collision with another vessel in the Arabian Sea, leading to an oil spill.
3. **Sagar Nidhi Oil Spill (2011)**
   - Incident: In September 2011, the Indian research vessel Sagar Nidhi suffered an oil spill while conducting operations off the coast of Chennai.

The Statutory Agency is responsible for the institution of prosecutions and the recovery of clean-up costs on behalf of all participating agencies. The Statutory Agencies for oil spills are appended in Table 5.12.

Table 5.12 Statutory agencies for oil spills

Source/ Location	Statutory agency
From ships	The relevant designated authority under the Merchant Shipping Act, 1958
From offshore installations and upstream pipelines	The relevant designated authority under the Petroleum Act, 1934
From shore terminals, refineries and downstream pipelines	The relevant designated authority under the Petroleum and Natural Gas Regulatory Board Act, 2006
In major ports	The relevant port authority under the Major Ports Act
In non-major ports	The relevant designated authority in the coastal State, or union territory

5.5.1 Details of different types of oil spills clean-up methods

The Coast Guard District or Regional Commander decides on actions to contain, disperse, or neutralise pollution and remove potential pollutants from the scene. These decisions include the different response methods: assessment and monitoring, dispersant spraying operations, mechanical recovery operations, and cargo transfer operations. Any clean-up operation aims to minimise the damage (environmental, ecological, and financial loss) that the spill would cause. Once the oil has been spilt, urgent decisions need to be made about the options available for clean-up to keep environmental and socioeconomic impacts to a minimum.

Different methodologies can be adopted to clean up oil spills. Some of the few important and commonly used methods can be explained as follows:

1. **Using oil booms**

   Containment booms are used to control the spread of oil, reduce the possibility of polluting shorelines and other resources, and concentrate oil in thicker surface layers, making recovery easier. In addition, booms may be used to divert and channel oil slicks along desired paths, making them easier to remove from the surface of the water.

2. Using skimmers

Once the oil has been confined by using oil booms, skimmers or oil scoops can be deployed onto boats to remove the contaminants from the water surface. Skimmers are machines specially designed to suck up the oil from the water surface like a vacuum cleaner. Skimmers are used to physically separate the oil from the water, which is further processed for reuse.

3. Using sorbents

Sorbents are materials that soak up liquids. They can be used to recover oil through absorption, adsorption, or both. Absorbents allow oil to penetrate into pore spaces in the material they are made of, while adsorbents attract oil to their surfaces but do not allow it to penetrate into the material.

4. Using dispersants

When the spilt oil cannot be contained by using booms, the only option left is to accelerate the disintegration of the oil. Dispersal agents, such as Corexit 9500, are chemicals sprayed upon the spill with the help of aircraft and boats, aiding the natural breakdown of oil components.

5. Hot water and high-pressure washing

This procedure is mainly used when the oil is inaccessible to mechanical removal methods such as booms and skimmers. It is used to dislodge the trapped and weathered oil from generally inaccessible locations to machinery.

6. Using manual labour

It involves using manual means like hands, rakes, shovels, etc., to clean the surface oil and oily debris and place them in special containers to be removed from the shoreline.

7. Biological agents

Biological agents are nutrients, enzymes, or microorganisms that increase the rate at which natural biodegradation occurs. Biodegradation is a process by which microorganisms such as bacteria, fungi, and yeasts break down complex compounds into simpler products to obtain energy and nutrients. Biodegradation of oil is a natural process that slowly, over the course of weeks, months, or years, removes oil from the environment.

8. Chemical Stabilisation of oil by elastomisers

Experts have recently been using compounds like 'Elastol', which is basically polyisobutylene (PIB) in a white powdered form, to confine oil spills. The compound gelatinises or solidifies the oil on the water surface, thus preventing it from spreading or escaping.

9. Natural Recovery

The simplest method of dealing with the oil spill clean-up operation is to use the vagaries of nature, like the sun, the wind, the weather, tides, or naturally occurring microbes.

The treatments follow a general rule: (All distances measured from the shoreline)

Table 5.13 Distance from the shore and treatments

Distance from shore	Treatment methods
200 nautical miles and beyond	No treatment is used unless the case is very severe
Between 20 and 200 nautical miles	Booms and skimmers may be used
Between 20 and 10 nautical miles	Dispersants are used
For areas very close to the shoreline	Biological agents are used

5.5.2 Contingency plan with GIS, remote sensing, and numerical modelling.

Remote sensing and GIS (Geographic Information System)

The ability to remotely detect and monitor oil spills at sea is becoming increasingly important due to the constant threat posed to marine wildlife and the ecosystem. It can allow for early detection of slicks, provide size estimates, and help predict the slick's movement and possibly the oil's nature. This information will be valuable in aiding clean-up operations and will not only help save wildlife and maintain the balance of the local ecosystem but will also provide damage assessment and help to identify the polluters. Contingency planners and other response organisations are now using GIS to make contingency plans easier. GIS makes electronic maps that can focus on the locations of things important to planners and oil spill responders. Oil spill models are numerical tools capable of (a) forecasting the trajectory of a spill, (b) estimating the time needed for the spill to reach specific areas of interest, and (c) assessing its state when it arrives at the modelled locations.

5.5.3 Response and mitigation measures

1. **Emergency Response:**
   - **Oil spill response teams:** The Indian Coast Guard and other specialised agencies are equipped with spill response equipment, including oil booms, skimmers, and dispersants.
   - **Clean-up operations:** Clean-up operations involve containment of the spill, recovery of oil from the water surface, and shoreline clean-up. Chemical dispersants are also employed to break down the oil and accelerate natural degradation.
2. **Legislation and regulations:**
   - **National Oil Spill Disaster Contingency Plan (NOSDCP):** India has developed the NOSDCP.
   - **Environmental protection laws:** The Environment Protection Act, 1986, and the Merchant Shipping Act, 1958.
3. **Prevention and preparedness:**
   - **Risk Assessment:** Risk assessments for shipping routes and offshore operations to mitigate potential hazards.
   - **Training and drills:** Regular training and exercises for response teams to ensure preparedness for oil spill incidents.
   - **Monitoring and surveillance:** Enhancing monitoring and surveillance capabilities to detect and respond to spills.

4. **International cooperation:**

   - **Regional collaboration:** India collaborates with neighbouring countries for transboundary oil spill risks.
   - **Global agreements:** India is a signatory to international conventions such as the International Convention on Oil Pollution Preparedness, Response, and Cooperation (OPRC), which promotes global cooperation in oil spill response.

5. **Oil spill modelling:**

   - Used globally to simulate oil spill fate and transport, crucial for assessing environmental, economic, and health impacts.
   - Models like CDOG, OSCAR, and MEDSLIK-II predict oil spill trajectories and sensitive areas.
   - Some models like COZOIL and OILMAP focus on shoreline oil transport prediction.

6. **Decision support approaches:**

   - Utilise Geographical Information Systems (GIS) to create spatial decision support systems.
   - Includes models like Fuzzy logic-based, multi-criteria analysis, and scenario analysis for oil risk assessment.
   - Novel approaches like SAPSO integrate oil transport simulation, clean-up response, and optimisation.
   - Focus on enhancing the resilience of offshore structures and coastal facilities against storm surges, cyclones, and shoreline erosion.
   - Strategies include upgrading design thresholds, safe protection, and relocation of critical components, waterproofing, and emergency response.
   - Emphasis on improving infrastructure resilience and recovery capabilities in the face of climate change impacts.

5.6 Ocean acidification and biofouling

Ocean acidification implies high atmospheric carbon dioxide concentrations and subsequent absorption by oceanic systems. It threatens life on Earth by disturbing the trophodynamics of the oceanic ecosystem. The ocean has taken up approximately 40% of anthropogenic carbon dioxide (Sabine et al., 2004; IPCC 2021), which alters the composition of seawater chemistry. The elevated carbon dioxide partial pressure (pCO2) decreases the seawater pH and $CaCO_3$ saturation state (Feely et al., 2004). The pCO2 value is predicted to reach 420 and 940 µatm by 2100, leading to a projected pH decrease of 0.13-0.42 units depending on the climate change scenario (Rhein et al., 2013). The pH of the seawater has decreased from 8.17 in pre-industrial times (Key et al., 2004) to the current value of 8.06 units (Rhein et al., 2013), suggesting a 34.91% increase in acidity.

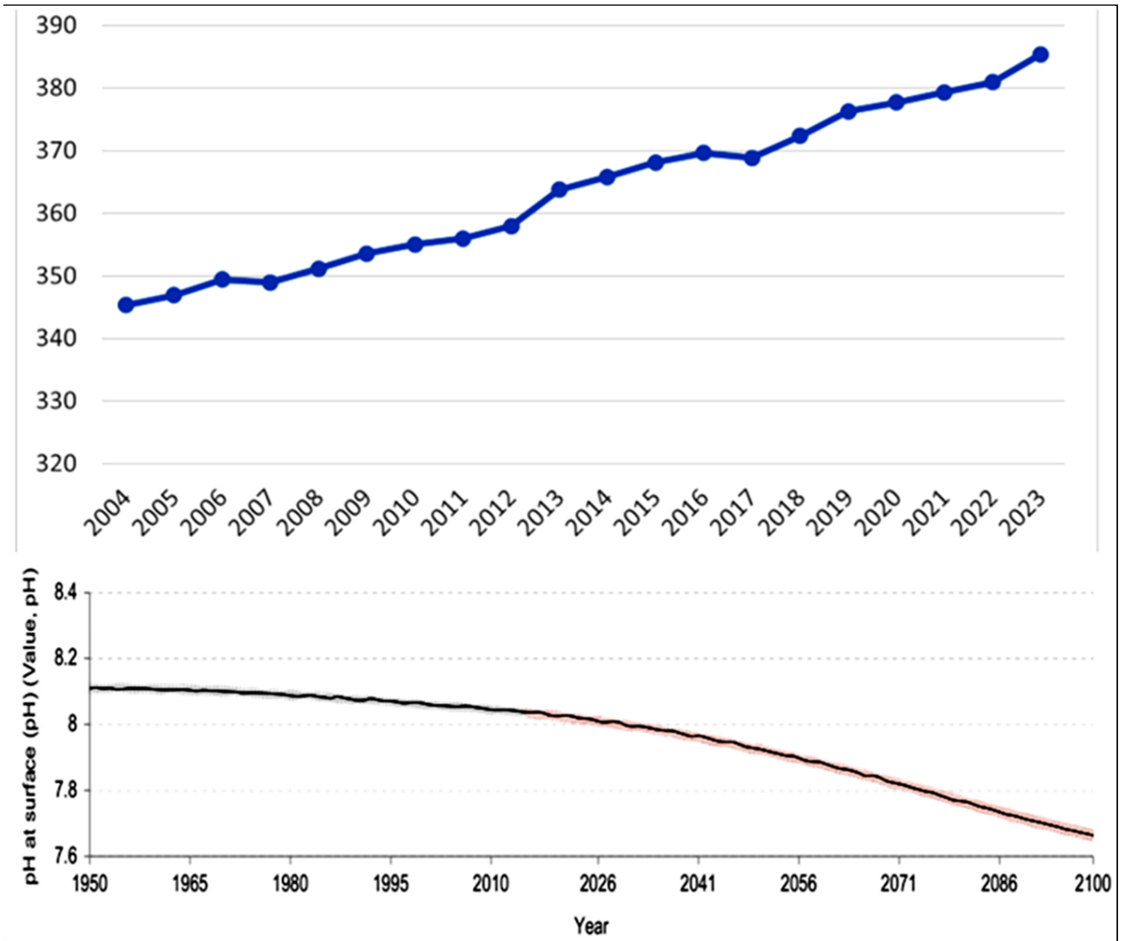


Figure 5.21 Shows recent trends in the atmospheric CO_2 concentration and pH variations.

The marine carbonate system is critical in controlling seawater pH and maintaining chemical equilibrium in the ocean (Fig. 5.21). The carbonic acid (H_2CO_3) is formed due to the dissolved CO_2 in the seawater, which dissociates into a hydrogen ion (H^+) and bicarbonate ion (HCO_3^-). The net effect of adding CO_2 to seawater is an increase in carbonic acid, hydrogen ions, and bicarbonate ions and a decrease in CO_3^{2-} concentration. This increase in hydrogen ion concentration corresponds to the reduction in pH and a decrease in CO_3^{2-}, reducing the saturation state (Ω) of calcium carbonate, thereby limiting the bioavailability of $CaCO_3$ for carbonate-secreting organisms, especially microfauna such as foraminifera and pteropods to produce their shells. However, as the oceans acidify, causing the dissolution of shells, their capacity to absorb CO_2 decreases (Sabine et al., 2004). The carbon dioxide concentration will be highest in 2023; the lowest value was 371.41 in 2004, and pH is predicted to be 7.64 by 2100 (Figure 5.21).

5.6.1 Physico-chemical effects

Historical evidence for changes in ocean carbonate chemistry and calcification rates has been sought over three basic timescales: the recent past (decades; pre-industrial through present). Over the past 250 years, atmospheric carbon dioxide (CO_2) levels increased by nearly 40%, from pre-industrial levels of approximately 280 ppmv (parts per million volume) to nearly 384 ppmv in 2007 (Solomon et al. 2007). The northern Indian Ocean is indeed a unique environment when it comes to ocean chemistry and acidification. Ocean acidification can be simply commensurated to its pH, which depends on the oceans' carbon chemistry. The atmospheric concentrations of CO_2 now exceed 415 ppmv and are still increasing as compared to the pre-industrial levels of 280 ppmv, which acidifies the seawater by reducing the pH. Several studies have projected a decline of upper ocean pH by 0.3–0.4 units by the end of the 21st century.

- Warming of seawater decreases the solubility of gases (O_2 and CO_2)
- Oceans absorb about ¼ (~2.5 Gt/y) of CO_2 emitted to the atmosphere due to human activities.
- This CO_2 has penetrated the sub-subsurface ocean to various depths.

- Seawater becomes acidic (pH already decreased by 0.1, to decrease further by 0.3 by 2100).

Impact of ocean acidification

- **Infrastructure integrity**
  - **Corrosion of materials**: Increased acidity can accelerate the corrosion of offshore infrastructure, including pipelines, rigs, and platforms. This may necessitate more frequent inspections and maintenance, leading to higher operational costs.
- **Impact on marine ecosystems**
  - **Coral reefs:** Ocean acidification affects the calcification processes of corals, leading to weaker reefs. This can impact biodiversity and the health of marine ecosystems that support oil and gas operations.
  - **Shellfish and marine life:** Many marine organisms, such as molluscs and certain fish species, are sensitive to changes in pH. A decline in these populations can disrupt the food web and impact local fisheries, which are often integral to coastal communities surrounding oil and gas sites.

5.6.2 Mitigation measures

1. **Infrastructure resilience**
   - **Material selection**: The oil and gas industry may need to invest in more resistant materials and coatings to counteract the corrosive effects of acidified seawater.
   - **Corrosion-resistant materials**: Utilising advanced materials and coatings that resist corrosion can extend the lifespan of offshore equipment and infrastructure.
   - **Regular maintenance**: Establishing rigorous inspection and maintenance schedules can help identify and address corrosion issues before they lead to significant failures.

2. **Research and monitoring**

- **Continuous monitoring**: Implementing real-time monitoring systems for ocean pH levels and CO_2 concentrations helps track acidification trends and impacts on marine ecosystems.
- **Ecosystem studies**: Conducting research on the effects of acidification on local marine life can inform best practices and risk assessments.

3. **Sustainable practices**

- **Reduced emissions**: Implementing measures to reduce greenhouse gas emissions from offshore operations can help mitigate the root cause of ocean acidification. This includes optimising energy efficiency and transitioning to cleaner technologies.
- **Carbon Capture and Storage (CCS)**: Investing in CCS technologies can help capture CO_2 emissions from production activities and prevent them from entering the atmosphere and oceans.

4. **Adaptive management**

- **Flexible operations**: Developing adaptable operational strategies that can respond to changing marine conditions and acidification impacts will enhance resilience.
- **Impact assessments**: Regularly conduct environmental impact assessments to understand how acidification may affect operations and adjust practices accordingly.

5. **Regulatory compliance and best practices**

- **Adhering to environmental standards**: Complying with evolving environmental regulations ensures that companies are prepared for stricter standards related to ocean health.
- **Industry guidelines**: Following best practice guidelines developed by industry groups can help standardise responses to ocean acidification.

5.7 Mitigation measures to reduce GHG emissions, especially methane gas

Methane pollution from offshore oil and gas installations can significantly contribute to greenhouse gas emissions, and detecting and mitigating these leaks is crucial for environmental protection. To address this, proactive measures, technologies, and strategies can be implemented to reduce methane emissions.

a) Regular inspection and monitoring

- **Routine inspections**: Regular inspection schedules should be in place to identify potential leaks. Inspections may include visual checks, infrared thermography, and gas detection technologies.
- **Leak detection technologies**:
  - ✓ **Infrared cameras**: Thermal imaging cameras can detect methane leaks as they show temperature differences between the surroundings and gas emissions.
  - ✓ **Laser-based systems (LDAR)**: Laser-based methane detection systems, such as Tunable Diode Laser Absorption Spectroscopy (TDLAS), can quickly identify leaks.
  - ✓ **Acoustic monitoring**: This technology can detect the sound of gas leaks that may not be visible.
  - ✓ **Fixed continuous monitoring systems**: These systems can be placed at various points in the offshore installation to monitor methane concentrations consistently.

b) Advanced detection tools

- **Drones and UAVs**: Drones equipped with methane sensors can be deployed to scan offshore platforms for leaks, especially in areas that are difficult to reach.
- **Helicopter-based monitoring**: Aerial surveys with mounted sensors can be used for large-scale monitoring of offshore installations.

- **Sniffing sensors**: Handheld methane detectors and sniffing sensors can help spot leaks in hard-to-reach or confined spaces.

c) Real-time data collection and analysis

- **Continuous Emissions Monitoring (CEMS)**: Installing real-time sensors for methane emissions at critical points can provide instant data, allowing operators to act quickly.
- **Data analytics and AI**: The use of artificial intelligence (AI) and data analytics can help predict potential leak hotspots based on historical data and operational conditions.

d) Leak repair and mitigation

- **Automated shutoff valves**: Implementing automated shutoff systems that can quickly isolate leaking areas when a methane leak is detected.
- **Leak sealing technologies**: Develop and implement technologies that can seal leaks without requiring platform shutdowns, such as pressure relief valves, elastomeric sealing methods, and bolted repair kits.
- **Flare systems**: In some cases, methane can be flared safely to reduce the impact of leaks until a permanent solution can be applied. However, flaring itself should be minimised to reduce emissions.

e) Regular maintenance and equipment upgrades

- **Corrosion prevention**: Corrosion of equipment can lead to leaks. Implementing regular maintenance schedules, corrosion-resistant materials, and coatings can help reduce the risk of leaks.
- **Equipment upgrades**: Upgrade to more efficient, durable, and leak-proof equipment, such as using high-quality seals and valves.
- **Pipeline integrity management**: Regularly inspect and maintain the pipelines and other infrastructure that transport gas to ensure they remain leak-free.

f) Emergency response plans

- **Incident response protocols**: Develop comprehensive emergency response plans to address leaks and other related incidents. This includes protocols for containing and controlling the leak, evacuations if necessary, and coordinating with environmental protection agencies.
- **Training personnel**: Regularly train all personnel in leak detection, emergency response, and best practices for minimising methane emissions.

g) Regulatory compliance and reporting

- **Regulatory adherence**: Ensure that all leak detection and repair measures comply with local and international regulations, such as those outlined by the International Maritime Organisation (IMO) or the Environmental Protection Agency (EPA).
- **Leak reporting**: Establish procedures for reporting methane leaks as soon as they are detected, ensuring transparency and compliance with regulatory requirements.

h) Zero emissions initiatives

- **Carbon Capture and Storage (CCS)**: For larger offshore operations, consider implementing CCS technology to capture and store methane emissions safely underground.
- **Methane recovery systems**: Recover and reinject methane gas into the reservoir or process it for use rather than letting it escape into the atmosphere.

i) Collaborative industry efforts

- **Industry standards and best practices**: Participate in industry forums and initiatives aimed at reducing methane emissions, such as the Oil and Gas Methane Partnership (OGMP) under the United Nations Environment Programme (UNEP).
- **Collaborate with environmental groups**: Partner with environmental NGOs to develop and implement best practices and technologies for reducing methane leaks.

5.7.1 Energy efficiency

- **Improving processes:** Enhancing the efficiency of extraction, refining, and transportation processes to reduce energy consumption and associated emissions.

5.7.2 Carbon Capture and Storage (CCS):

CCS technologies: Capturing CO_2 emissions from industrial processes and storing them underground to prevent them from entering the atmosphere.

CCUS involves the capture of CO_2, generally from large point sources like power generation or industrial facilities that use either fossil fuels or biomass as fuel. If not used on-site, the captured CO_2 is compressed and transported by pipeline, ship, rail or truck to be used in various applications or injected into deep geological formations such as depleted oil and gas reservoirs or saline aquifers. Offshore petroleum fields are responsible for up to 15% of global CO_2 emissions. The emissions are mainly caused by the combustion of natural gas on-site for power generation. A possible way to minimise greenhouse gas emissions is by lowering operating costs and possibly increasing energy savings in the oil and gas fields. A few measures are (i) decreasing the energy of the process implemented on the platform. (ii) steam cycles are technically feasible and would result in a substantial decrease in CO_2-emission, and (iii) the most effective technique is electrifying the platform by connecting it to the onshore electric grid or offshore wind power facilities. Onshore electrification is claimed to present several technical and operational benefits, such as higher facility availability, lower maintenance costs, and higher system efficiency, at the expense of high investment costs.

Waste heat recovery and CO_2 capture are the different technological options that can be implemented to reduce the CO_2 emissions of the oil and gas plant. CO_2 separation with acid gas (i.e. CO_2 and H_2S) removal is a mature technology and is widely applied in hydrocarbon processing industries such as refineries. It is also a common process for purifying hydrogen after steam reforming processes, such as in integrated gasification combined cycle plants. Heat-to-power technologies are necessary to convert waste heat into power. It is common in onshore applications, but the integration of these technologies offshore was performed only on three facilities and has faced several practical challenges. Different scenarios for the integration of steam networks can be considered, which differ (i) by the selection of the cooling utility (water and air), (ii) by the recovery of waste heat from either one or two gas turbines, (iii) the possible use of an intermediary heating loop.

India is the 3rd largest emitter of CO_2 in the world after China and the US, with estimated annual emissions of about 3.1 gigatonnes per annum (gtpa). The government of India has committed to reducing CO_2 emissions by 50% by 2050 and reaching net zero by 2070. Renewable power capacity growth has been one of the key success stories of the clean energy transition in India. Carbon Capture Utilisation and Storage (CCUS) has an important and critical role to play in decarbonising the E&P sector, which is hard to electrify and hard to abate due to the use of fossil fuels not only as a source of energy but also within the process itself.

5.7.3.1 Brief overview of carbon capture technologies

CO_2 capture technologies separate carbon dioxide from gas streams that are released from industrial processes. Since anthropogenic CO_2 is a by-product of the combustion of fossil fuels, CO_2 capture technologies are generally classified as either pre-combustion or post-combustion systems. In the former, CO_2 is captured before the fuel combustion, while in the latter, CO_2 is removed after the combustion of fuel. A third approach, oxyfuel or oxy-combustion, does not require a CO_2 capture device. This concept is still under development and not yet commercial. Various CO_2-separation technologies are available for absorption, adsorption, cryogenic distillation, and membrane separation. In the absorption technique, two types of absorptions are possible; one is chemical absorption, where CO_2 is bound to an organic solvent, either chemically based on the CO_2-dissociation into hydrogen carbonates (HCO_3), or physically (physical absorption), based on the solubility differences of CO_2 in the feed gas and the liquid solvent. Chemical absorption with alkanoamines such as monoethanolamine is preferred for treating acid gases with low CO_2 partial pressures. Chemical absorption with alkanol amines such as triethanolamine (TEA) or physical absorption with methanol (MeOH- RectisolR) and mixtures of polyethylene glycol esters (DEPG- SelexolR) are preferred for high CO_2 partial pressures (> 7bar). The CO_2-separation process takes place in two main columns: an absorption column, in which the solvent circulates at the counter-current of the feed gas, removing CO2, and a regeneration column, in which CO_2 is recovered at high purity, generally by heating up or depressurising the solvent-CO_2 mixture.

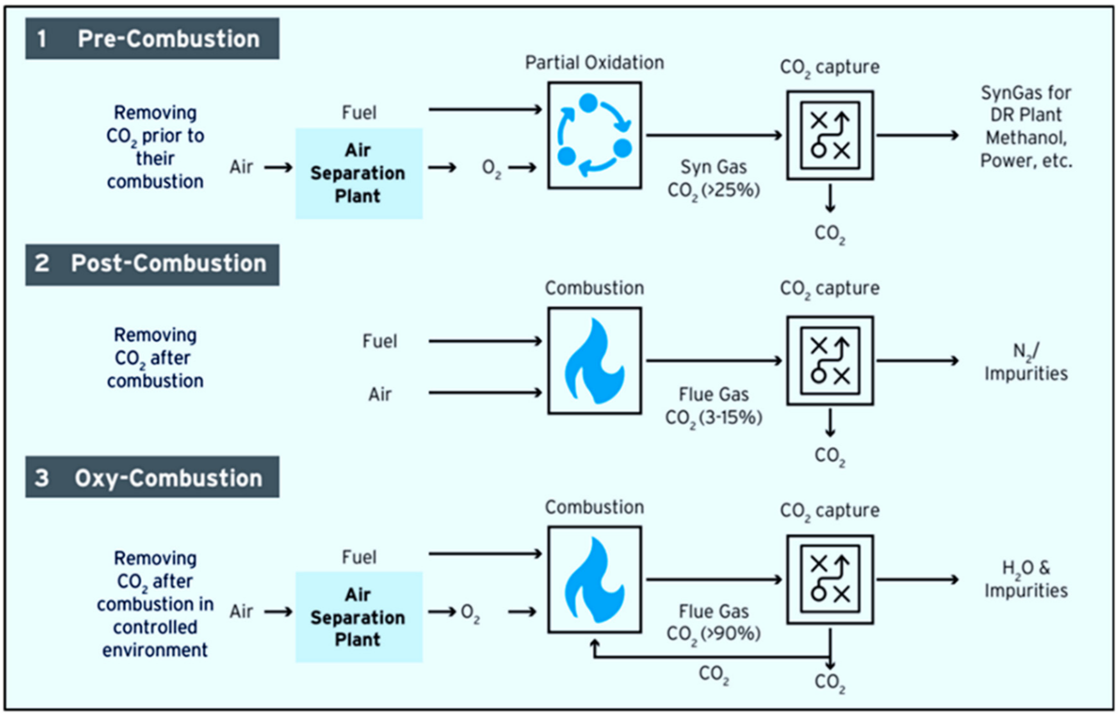


Figure 5.22 Schematic representation of major carbon capture technologies (NITI Ayog Report 2023)

5.7.3.2 Overview of CO_2 utilisation methods

The following are the major CO_2 utilisation methods:

1. **Enhanced Oil Recovery (EOR):** Using CO_2 for EOR has been successfully carried out for decades to produce low-carbon oil from maturing oil fields in North America and other geographies. With Indian oil fields progressing towards their maturity, CO_2 EOR can play an essential role in residual oil extraction that is environmentally sustainable and economically feasible.

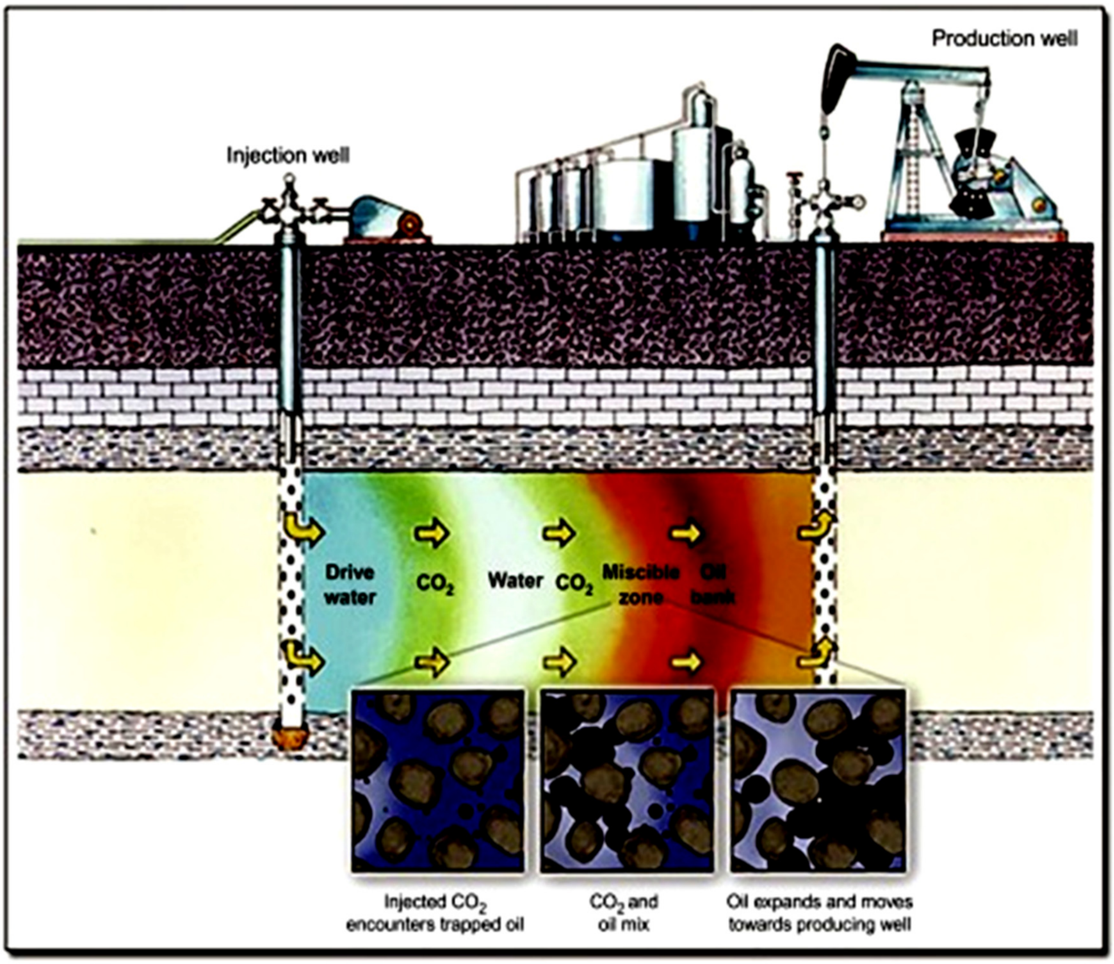


Figure 5.23 Schematic representation of Enhanced Oil Recovery (EOR)

2. **Green urea**: Urea production from green ammonia can utilise a significant part of CO_2. India's current production of ammonia and urea is primarily based on imported LNG. Therefore, renewable energy-based ammonia can replace conventional ammonia production with an increased scale of renewables and a competitive cost of green hydrogen production. While renewable-based hydrogen is still in a nascent stage in India, the new green hydrogen policy will boost electrolysis-based hydrogen production shortly.

3. **Food and beverages applications**: The utilisation of CO_2 in food and beverages is in applications such as carbonated drinks, dry ice, and modified atmosphere packing.

4. **Building material (concrete and aggregates)**: Utilising CO_2 to produce building materials (aggregates and concretes) is one of the feasible options for CO_2 utilisation. A large market for aggregates and concrete is in a developing country like India. CO_2 can be used both during concrete curing and aggregate formation. Since CO_2 is injected in a liquid state without conversion, relatively little energy is consumed.

5. **Chemicals (methanol and ethanol)**: The production of chemicals such as methanol and ethanol from CO_2 has been proven at commercial scales by various companies around the world. Methanol is a low-carbon hydrogen carrier fuel that can support applications like fuel substitution, as well as an intermediate for the production of various speciality chemicals like acetic acid, methyl tert-butyl ether, dimethyl ether, and formaldehyde raw materials for the production of adhesives, foams, plywood subfloors etc.

6. **Polymers (including bioplastics):** The conversion of CO_2 to polymers presents another possible CO_2 utilisation route. Various polymers, such as polyether carbonates, polycarbonates, diphenyl carbonate, cyclic carbonates etc., have been manufactured globally at different scales.

CCUS projects: A global scenario

A total of 21 large-scale CCUS facilities are operating globally with a capacity to capture approximately 40 gtpa CO_2. The first CCUS project was established in Texas in the 1970s-80s to capture CO_2 from natural gas processing plants and supply it to local oil producers to utilise the CO_2 for enhanced oil recovery. CCUS has spread to the USA, Norway, Canada, Australia, Brazil, China, Saudi Arabia and the United Arab Emirates (Table 5.14).

Table 5.14 Large Scale CCUS facilities in operation in 2020 (*Source: Carbon Capture Utilization and Storage (CCUS) – Policy Framework and Deployment Mechanism in India, NITI AYOG Report 2023*)

Country	Operation Start Year	Project	CO_2 Source	CO_2 Capture Capacity (mtpa)	CO_2 Utilisation
USA	1972	Terrell natural gas plants (earlier Val Verde)	Natural gas processing	0.5	EOR
USA	1982	Enid Fertilizer	Fertiliser production	0.7	EOR
USA	2010	Century Plant	Natural gas processing	8.4	EOR
USA	2013	Lost Cabin Gas Plant	Natural gas processing	0.9	EOR
USA	2013	Coffeyville Gasification	Fertiliser production	1.0	EOR
USA	2013	Air Products Steam Methane Reformer	Hydrogen production	1.0	EOR
USA	1986	Shute Creek Gas Processing Facility	Natural gas processing	7.0	EOR
USA	2000	Great Plains Synfuels (Weyburn/Midale)	Synthetic natural gas	3.0	EOR
USA	2017	Petra Nova	Power generation (coal)	1.4	EOR
USA	2017	Illinois Industrial	Ethanol production	1.0	Storage
Norway	1996	Sleipner CO2 Storage Project	Natural gas processing	1.0	Storage
Norway	2008	Snohvit CO2 Storage Project	Natural gas processing	0.7	Storage
Brazil	2013	Petrobras Santos Basin Pre-salt Oilfield CCS	Natural gas processing	3.0	EOR
Saudi Arabia	2015	Uthmaniyah CO2-EOR Demonstration	Natural gas processing	0.8	EOR
Canada	2014	Boundary Dam CCS	Power generation (coal)	1.0	EOR
Canada	2015	Quest	Hydrogen production	1.0	Storage
Canada	2020	ACTL with North West Sturgeon Refinery	Hydrogen production	1.2 - 1.4	EOR
Canada	2020	Alberta Carbon Trunk Line (ACTL) with Agrium	Fertiliser production	0.3 - 0.6	EOR
Australia	2019	Gorgon Carbon Dioxide Injection	Natural gas processing	3.4 - 4.0	Storage
UAE	2016	Abu Dhabi CCS	Iron and steel production	0.8	EOR
China	2018	Jilin oilfield CO2-EOR	Natural gas processing	0.6	EOR

5.7.3.3 Prospects of CCUS in India

As per the NITI AYOG Report 2023, carbon capture in India is confined to certain industries/ applications where carbon capture is part of the process, viz., the manufacture of urea. CO_2 is also captured as part of the gas conditioning process in the gasifiers of Reliance Industries Limited in Jamnagar and JSPL in Angul. However, the CO_2 is primarily released into the atmosphere and is not utilised or stored. While there are few pilot-scale carbon capture projects (viz. IOCL R&D's amine and biological enzyme-based carbon capture plant and Tata Steel Jamshedpur's pilot-scale carbon capture plant for capturing 5 tonnes per day CO_2 from Blast Furnace gases), there are no commercial-scale dedicated CCUS projects in India.

Recently, India has undertaken concerted efforts to scale up renewable energy projects, including solar, wind and tides. However, fossil fuels will continue to play a crucial role in India's energy sector for at least four decades. India is one of the fastest-growing major economies in the world, and it requires sustained energy sources to continue its growth and cater to the aspirations of its vast population. As per the Nationally Determined Contributions (NDC) of the Paris Agreement, India has ratified to decrease its emission intensity of GDP by 33- 35% by 2030 from 2005 level. CCUS offers pathways to reduce atmospheric emissions and promotes various mechanisms of CO_2 utilisation for various industrial applications. The following total carbon storage capacity is theoretically identified, and further, carbon capture and storage initiatives should be undertaken to meet the NDC.

Table 5.15 CO_2 EOR Storage Capacity Estimates Source: Carbon Capture Utilisation and Storage (CCUS) – Policy Framework and Deployment Mechanism in India, NITI AYOG Report 2023

Basin	Storage Capacity (mt CO_2)
Krishna-Godavari	658.69
Mumbai	1597.24
Assam shelf	667.48
Rajasthan	312.52
Cauvery	99.50
Assam-Arakan	67.01
Cambay	657.25
Total	**3402.43**

Table 5.16 CO_2 Storage Capacity Estimation for Deep Saline Aquifers Source: Carbon Capture Utilisation and Storage (CCUS) – Policy Framework and Deployment Mechanism in India, NITI AYOG Report 2023

Basin	Capacity (Gt)
Krishna–Godavari	13.39
Mumbai offshore	9.26
Assam Shelf	14.16
Rajasthan	7.34
Cauvery	16.08
Assam-Arakan fold belt	32.30
Cambay	16.13
Saurashtra	39.74
Kutch	15.60
Vindhyan	11.81
Mahanadi–NEC (North East Coast)	3.25
Andaman–Nicobar	12.35
Kerala–Konkan–Lakshadweep	25.33
Bengal–Purnea	51.58
Ganga–Punjab	-
Pranhita–Godavari	6.14
Satpura–South Rewa–Damodar	1.87
Himalayan Foreland	-
Chhattisgarh	0.11
Narmada	-
Spiti–Zanskar	-
Deccan Syncline	-
Cuddapah	14.24
Karewa	-
Bhima–Kaladgi	0.41
Bastar	-
Total	**291.09**

Chapter 6

SUMMARY AND CONCLUSION

Global warming-induced climate change is a broader term that describes increasing shifts in temperature and associated weather patterns over decades linked to human activities, especially post-1950, due to fossil fuel combustion. From 2011–2020, global temperatures rose by 1.1°C compared to 1850–1900, warming land faster than oceans. CO_2 levels reached 420 ppm in 2023, the highest in 2 million years. Methane and nitrous oxide have also seen unprecedented rises. Fossil fuels contribute 90% of anthropogenic CO_2 emissions, with coal being the most significant source. Oil and Gas sector accounts for ~40% of global energy-related CO_2 emissions, with methane leaks and gas flaring being major contributors. This is where emissions occur across the oil and gas lifecycle, from exploration to end-use consumption. India is the third-largest CO_2 emitter globally, with the energy sector contributing 75–80% of its GHG emissions.

Climate change severely impacts the Oil and Gas Industry, leading to infrastructure damage, increased disaster recovery costs, and economic disruptions. Rising sea levels and extreme weather events significantly challenge coastal and offshore industries. Risks include infrastructure damage, oil spills, operational disruptions, and accelerated infrastructure ageing. Cyclonic storms in the northern Indian Ocean are projected to increase in frequency and intensity, posing severe risks to offshore infrastructure.

Key climate change drivers affecting the oil and gas industry are:

1) Air and water temperature changes.
2) Altered precipitation patterns.
3) Sea level rise and shoreline erosion.
4) Increased storm intensity and wave regimes.
5) Ocean acidification and CO_2 level changes.
6) Infrastructure damage leads to oil spills and contamination.

The inter-governmental Panel for Climate Change assesses global temperatures that could soon exceed 1.5°C above pre-industrial levels. This leads to catastrophic consequences like extreme weather, biodiversity loss, and displacement due to sea-level rise. The Coupled Model Intercomparison Project evaluates climate models globally to inform IPCC assessments and shape climate policies based on the shared socio-economic pathways (SSPs). Based on such studies, the Paris Agreement proposes limiting global warming below 2°C, aiming to cap it at 1.5°C by transitioning to low-carbon energy systems. To achieve this, countries must shift toward low-carbon energy systems and reduce drastically their reliance on fossil fuels.

Climate change profoundly alters marine ecosystems, with rising sea levels, ocean acidification, warming temperatures, and intensified storm systems posing significant threats. Warmer oceans fuel cyclones, increasing the frequency and severity of extreme weather events, while acidification disrupts marine biodiversity, destabilising ecosystems. Higher waves, stronger currents, and storm surges jeopardise the structural integrity of platforms, pipelines, and subsea infrastructure, raising risks of spills, operational downtime, and costly repairs. Rising sea levels can also complicate the design and stability of offshore structures, requiring more resilient engineering solutions. These events can cause damage to infrastructure, hinder production, and increase the costs associated with safety measures and repairs. Furthermore, the shifting ecosystems and biodiversity in affected regions can lead to regulatory changes, pushing companies to comply with stricter environmental standards.

Past air temperatures in the northern Indian Ocean (the Arabian Sea and Bay of Bengal) were relatively stable during the pre-industrial period but gradually increased by 1.2° by 2023 and crossed 1.5°C in 2024, with slight fluctuations from 25°C to 26.2°C. Future projections under different SSP scenarios indicate a significant temperature increase from 27°C to 30°C by 2100. Thus, we can anticipate an increase of 1.2°C in the low carbon emission scenario and 3.8°C in the high carbon emission scenario. The surface of the northern Indian Ocean increased by 1°C and reached 26°C by 2023. Future projections from 2023 to 2100 under various SSP scenarios indicate a significant increase in sea surface temperature, from 26°C to 29°C by 2100. However, these projections are accompanied by uncertainty ranges, indicating the variability in future outcomes across different emissions pathways. The warming of the Ocean is controlled in the low carbon emission scenario but alarmingly increased by 3°C by 2100 in a high carbon emission scenario. Climate change-induced warming of the atmosphere and oceans significantly impacts cyclone formation and behaviour in various ways**.** Climate-induced warming is assessed up to 300 - 600m in oceanic waters, with maximum at surface layers and minimum at bottom layers. The amount of heat stored in the Ocean's upper layers can be used to form intense tropical cyclones. Thus, warming of the atmosphere and Ocean can breed intense tropical cyclones characterised by strong winds and heavy rainfall, leading to high winds, waves, storm surges, and flooding. Data collected from the Indian Meteorological Department, New Delhi, also verified the increase in intense cyclones, especially in the last decade in the northern Indian Ocean.

The annual frequency of major cyclones was studied from 1986–2005, 2016–35, and 2081–2100 using HiFLOR simulations. In the northern Indian Ocean, 30% of storms forming will be category 5 (137 kt) as per the Saffir-Simpson scale. As the storm intensifies, wind speeds can exceed 74 mph (119 km/h), leading to destructive impacts in the sea and coastal areas. Such storms can generate extraordinarily high waves and cause severe damage to the infrastructure. In such scenarios, the force acting on the offshore infrastructure will be 5 times higher than the category 1 cyclone.

Mitigation measures to address the impact of climate change on offshore oil and gas operations are critical to maintaining safety and minimising environmental harm. Companies are investing in advanced technology to improve the durability and resilience of offshore platforms. This includes innovations in platform design, such as floating structures that can withstand higher waves and more intense storms by elevating platforms, reinforcing subsea equipment, and using corrosion-resistant materials. Advanced monitoring systems enhance preparedness for extreme events, including accurate weather forecasting and real-time oceanographic data collection and interpretation, allowing companies to adjust operations proactively. Companies are integrating renewable energy, like offshore wind or solar, to power operations, reducing carbon footprints. Carbon capture, utilisation, and storage (CCUS) technologies are being deployed to mitigate emissions. Another crucial aspect of mitigation is ensuring that environmental protection standards are met to prevent oil spills and habitat destruction, thereby preserving marine life and adhering to regulatory requirements.

The impact of climate change on the coastal & offshore oil and gas industry in the Indian EEZ has been assessed, and its mitigation measures were suggested**.** The section details the challenges of rising air and sea temperatures, extreme weather events, sea-level rise, and ocean acidification. It outlines operational disruptions, infrastructure vulnerabilities, and environmental risks. Key points include:

1. **Impact of climate change**: Rising temperatures, severe storms, and sea-level rise threaten oil infrastructure, increasing risks of oil spills, operational challenges, and maintenance costs.

2. **Mitigation measures**:

   - **Human safety**: Heat management, protective gear, and remote monitoring.
   - **Infrastructure adaptation**: Use of heat-resistant materials, elevated platforms, and automated systems.
   - **Environmental monitoring**: Real-time systems for tracking weather and ocean conditions.
   - **Sustainable practices**: Energy efficiency, carbon capture, and collaboration on climate initiatives.

3. **Extreme weather and cyclones**:

   - Analysis of cyclone intensities, impacts, and potential risks to offshore platforms and shipping.
   - Mitigation strategies include advanced warning systems, infrastructure resilience, and collaborative efforts.

4. **Sea-level rise and shoreline erosion**:

   - Threats to coastal infrastructure, operational disruptions, and increased maintenance needs.
   - Use of soft (mangroves, beach nourishment) and hard solutions (seawalls, breakwaters) for mitigation.

5. **Oil spills**:

   - Causes, impacts, and cleanup methods, emphasising prevention and rapid response systems.
   - Integrating GIS, remote sensing, and predictive modelling for better spill management.

6. **Ocean acidification**:

- Impacts on marine ecosystems and infrastructure corrosion.
- Strategies to reduce emissions, monitor ecosystems, and improve material resilience.

7. **Mitigation measures to reduce GHG emissions, especially methane gas**

Methane pollution from offshore oil and gas installations can significantly contribute to greenhouse gas emissions, and detecting and mitigating these leaks is crucial for environmental protection.

- The proactive measures, technologies, and strategies that can be implemented to reduce methane emissions are regular inspection and monitoring, leak detection systems, advanced detection systems, real-time data collection and analysis, leak repair and its mitigation, regular maintenance and upgradation of equipment and finally emergency response plans.
- **Methane recovery systems**: Recover and reinject methane gas into the reservoir or process it for use rather than letting it escape into the atmosphere.

8. **Zero emissions initiatives: Carbon Capture and Storage (CCS)**: For larger offshore operations, consider implementing CCS technology to capture methane or CO_2 emissions and store them safely underground to prevent them from entering the atmosphere. A possible way to minimise greenhouse gas emissions is by lowering operating costs and possibly increasing energy savings in the oil and gas fields. The major CO_2 utilisation methods based on CCS technology are Enhanced Oil Recovery (EOR), green urea, food and beverages applications, building material (concrete and aggregates), chemicals (methanol and ethanol and polymers (including bioplastics).

Despite climate challenges, offshore exploration remains vital to meet energy demands during the transition to renewables. Responsible E&P activities and robust environmental practices demonstrate that energy security and sustainability can coexist. For instance, repurposing ageing platforms for carbon storage or hybrid energy systems showcases industry adaptability. Proactive measures like minimising flaring and investing in ecosystem resilience reduce environmental risks and enhance operational efficiency and stakeholder trust. The synergy between sound environmental practices and successful oil and gas operations underscores a critical truth: innovation and ecological responsibility are not mutually exclusive. By prioritising this balance, the industry can safeguard marine ecosystems while ensuring reliable energy supplies, paving the way for a sustainable future.

STANDARD OPERATING PROCEDURE

Standard Operating Procedures (SOPs)

Mitigation of the impact of climate change-induced natural hazards on the oil and gas industry in Indian waters

The last decade (2011–2020) recorded 1.1°C warmer temperatures with a peak of 1.5°C in 2014 compared to 1850–1900, where CO_2 levels reached 420 ppm in 2024, which is found to be the highest in the last 2 million years. Methane and nitrous oxide have also seen unprecedented rises during this period. Fossil fuels contribute 90% of anthropogenic CO_2 emissions, with coal being the most significant source. Oil and Gas sector accounts for ~40% of global energy-related CO_2 emissions, with methane leaks and gas flaring being major contributors. India has become the third-largest CO_2 emitter globally, with the energy sector contributing 75–80% of its GHG emissions. Climate change severely impacts the Oil and Gas Industry, leading to infrastructure damage, increased disaster recovery costs, and economic disruptions. Rising sea levels and extreme weather events significantly challenge coastal and offshore industries. Risks include infrastructure damage, oil spills, operational disruptions, and accelerated infrastructure ageing. Cyclonic storms in the northern Indian Ocean are projected to increase in frequency and intensity, posing severe risks to offshore infrastructure. Since India has a long coastline of ~ 7500 km and depends on its EEZ for resources like fisheries, Oil and minerals, it is essential to prepare a SOP to mitigate the impact of Climate change in a possible manner.

All the activities mentioned in the guidelines have to be implemented and monitored through the following divisions.

- **Operations Manager/ Health, Safety, and Environment (HSE) Manager**: Ensure compliance with this SOP and allocate resources for implementation. Coordinates pre-event preparations, real-time response, and post-event recovery. Monitor risks and ensure training and readiness.

- **Environmental manager and response team**: Monitor and report environmental performance metrics. Lead spill response operations and coordinate with authorities.
- **Platform supervisor/ incident commander**: Oversees the implementation of this SOP and coordinates emergency responses. Executes on-site preparation, monitoring, and evacuation procedures.
- **Maintenance team**: Secures infrastructure and conducts post-event inspections.
- **All staff and contractors**: Adhere to the outlined procedures and report non-compliance. Follow evacuation plans, participate in drills, and report hazards.

A Guidelines and best practices for minimising the environmental and climate-related impacts on offshore oil and gas operations.

The oil and gas sector contributes approximately 25-30% of India's total GHG emissions, primarily through carbon dioxide (CO_2) from combustion and methane (CH_4) from fugitive emissions.

1. Objectives

- Reduce GHG emissions across all stages of operations.
- Minimise environmental risks to marine ecosystems.
- Enhance energy efficiency and promote low-carbon technologies.
- Comply with international and local environmental regulations.

2. Procedures

2.1 Emissions reduction

1. Implement flaring and venting reduction strategies:
   - Use flare gas recovery systems.
   - Eliminate routine flaring by adopting advanced process controls.
2. Upgrade equipment to minimise methane leaks:
   - Regular maintenance of valves, seals, and pipelines.
   - Deploy leak detection and repair (LDAR) technologies.
3. Utilise carbon capture and storage (CCS) technologies.

2.2 Energy efficiency

1. Optimise energy consumption:
   - Use energy-efficient pumps, compressors, and lighting systems.
   - Conduct energy audits periodically.
2. Transition to renewable energy for power supply where feasible.
   - Incorporate offshore wind or solar power systems.

2.3 Waste management

1. Develop a waste management plan:
   - Segregate, recycle, and responsibly dispose of hazardous and non-hazardous waste.

- Avoid discharges of harmful substances into the marine environment.

2. Promote the reuse of water and materials.

2.4 Monitoring and reporting

1. Conduct regular environmental impact assessments (EIAs).
2. Monitor GHG emissions and marine ecosystem health using appropriate technologies.
3. Submit periodic reports to regulatory authorities and stakeholders.

2.5 Emergency response

1. Maintain an updated spill response plan.
2. Train staff on emergency preparedness for oil spills and equipment failures.

2.6 Collaboration and innovation

1. Partner with research organisations to develop and implement low-carbon technologies.
2. Participate in industry initiatives to reduce the impact of climate change.

3. Training and awareness

- Conduct regular training sessions on this SOP for all personnel.
- Raise awareness about the importance of sustainability and climate change mitigation.

4. Compliance and audits

- Ensure compliance with local and international regulations (UNFCC, MARPOL, IMO, PNG and OISD guidelines).
- Conduct internal and external audits to evaluate adherence to the SOP.

5. Review and continuous improvement

- Update this SOP based on advancements in technology, regulations, and lessons learned from audits.
- Set measurable goals for continuous improvement.

B Guidelines and best practices mitigate oil spills in offshore oil and gas operations in a climate change scenario.

1. Objectives

1. Prevent oil spills through robust risk management and operational practices.
2. Mitigate environmental and social impacts in the event of a spill.
3. Enhance resilience to climate-related risks, such as storms, high seas, and equipment degradation.

2. Procedures

2.1 Spill prevention

1. **Infrastructure resilience**:
   - Design and maintain facilities to withstand extreme weather events (e.g., hurricanes, rising sea levels).
   - Use corrosion-resistant materials and reinforce critical equipment.
2. **Operational controls:**
   - Conduct regular inspections of pipelines, valves, and storage tanks.
   - Install automated shutoff systems and real-time monitoring technologies.
3. **Risk assessments**:
   - Update risk assessments to account for climate-related changes.
   - Model spill scenarios under extreme weather conditions.
4. **Personnel training**:
   - Provide spill prevention training tailored to climate risks.
   - Conduct regular drills for spill containment during adverse conditions.

2.2 Spill response preparedness

1. **Emergency Response Plan (ERP)**:
   - Maintain a comprehensive, climate-resilient ERP.

- Incorporate alternative response strategies for scenarios involving high seas or limited access.

2. **Equipment and supplies**:
   - Ensure availability of spill response equipment (e.g., booms, skimmers, dispersants).
   - Store emergency supplies at accessible, climate-resilient locations.

3. **Monitoring systems**:
   - Deploy advanced sensors and drones for real-time spill detection.
   - Use satellite imagery to track oil spill movement.

2.3 Spill mitigation and management

1. **Containment**:
   - Deploy booms immediately to contain spills, considering wave dynamics under climate-induced conditions.
   - Use absorbents and barriers suitable for rough seas.

2. **Recovery**:
   - Deploy skimmers and pumps designed for high-flow conditions.
   - Collect spilt oil promptly to minimise environmental exposure.

3. **Dispersal and bioremediation**:
   - Apply dispersants in compliance with environmental guidelines.
   - Use climate-optimised bioremediation techniques to accelerate natural degradation.

4. **Marine life protection**:
   - Create exclusion zones around spill areas to protect marine ecosystems.
   - Monitor wildlife for oil exposure and provide rehabilitation support.

2.4 Collaboration and communication

1. **Stakeholder Engagement**:
   - Coordinate with regulatory bodies, local authorities, and NGOs.

- Establish partnerships with research organisations to improve spill response techniques.

2. **Community outreach**:
   - Inform nearby communities about risks and response actions.
   - Provide training for local stakeholders to assist in emergency responses.
3. **Reporting**:
   - Follow mandatory reporting protocols for spills and responses.
   - Submit post-incident reviews and lessons learned to authorities.

3. Monitoring and continuous improvement

1 Conduct regular audits of spill prevention and response systems.

2 Update this SOP based on new climate models, technological advancements, and regulatory changes.

3 Implement feedback loops from drills and incident reviews to improve practices.

4. Training and awareness

1 Train all personnel on spill prevention, response protocols, and the impact of climate change on operations.

2 Conduct joint exercises with external response teams and regulators.

5. Compliance and references

1 Adhere to international standards, including:

- MARPOL Annex I (Prevention of Pollution by Oil).
- IMO OPRC (Oil Pollution Preparedness, Response and Cooperation).
- Follow the National Oil Spill Disaster Contingency Plan (NOSDCP) and the Local Oil Spill Disaster Contingency Plan.

C Guidelines and best practices for safeguarding offshore platforms, personnel, and the environment from the increased frequency and intensity of extreme weather events due to climate change.

1. Objectives

1. Strengthen offshore platform resilience to extreme weather.
2. Ensure the safety of personnel and secure equipment and infrastructure.
3. Mitigate environmental impacts and enable rapid recovery post-event.

2. Procedures

2.1 Pre-event planning and preparation

1. **Risk assessments**:
   - Conduct regular climate risk assessments for offshore platforms.
   - Model platform vulnerability to high winds, waves, and storm surges.
2. **Platform resilience measures**:
   - Design and upgrade platforms to withstand extreme weather conditions (e.g., elevated decks, reinforced structures).
   - Install storm shutters, secured helipads, and backup power systems.
3. **Emergency Response Plans (ERP)**:
   - Develop and update ERPs for weather-related emergencies.
   - Include evacuation protocols, communication plans, and equipment safeguarding measures.
4. **Monitoring and forecasting**:
   - Use real-time weather monitoring systems to track extreme weather events.
   - Establish thresholds for initiating emergency protocols based on weather conditions.

2.2 Pre-event actions

1. **Securing infrastructure and equipment**:
   - Anchor floating structures and secure loose equipment.

- Depressurise pipelines and shut down non-essential operations.
- Protect critical systems (e.g., electrical, communication) from flooding.

2. **Evacuation preparations**:
   - Identify essential personnel to remain on-site and provide shelter-in-place protocols.
   - Evacuate non-essential personnel at least 48 hours before the anticipated weather event.
   - Arrange for transportation to safe zones, including helicopters and support vessels.
3. **Emergency drills**:
   - Conduct drills for evacuation and shelter-in-place scenarios, ensuring readiness.
4. **Stock emergency supplies**:
   - Ensure adequate stocks of food, water, medical supplies, and emergency equipment for personnel remaining on-site.

2.3 During the event

1. **Monitoring and communication**:
   - Maintain continuous monitoring of weather conditions and platform status.
   - Keep open lines of communication between the platform and onshore emergency teams.
2. **Safety protocols**:
   - Ensure personnel in shelter-in-place areas follow safety measures (e.g., use of personal protective equipment).
   - Regularly check emergency systems, such as backup power and fire suppression.

2.4 Post-event recovery

1. **Damage assessment**:
   - Conduct a thorough inspection of platform infrastructure and equipment.

- Identify and prioritise repairs for critical systems.

2. **Environmental protection**:

   - Deploy spill containment measures if oil or chemical leaks are detected.
   - Monitor surrounding marine environments for pollution or habitat damage.

3. **Operational restart**:

   - Resume operations gradually after ensuring structural integrity and safety.
   - Test all critical systems before restarting full-scale operations.

4. **Incident reporting**:

   - Document the impact of the event, response actions, and lessons learned.
   - Submit required reports to regulatory authorities and stakeholders.

3. Training and awareness

1 Conduct regular training sessions for all personnel on extreme weather preparedness and response.

2 Simulate extreme weather scenarios during emergency drills.

3 Raise awareness about climate change risks and their implications for offshore platforms.

4. Compliance and collaboration

1. **Regulatory compliance**:

   - Adhere to international standards (e.g., IMO, MARPOL, API standards) and local regulations.
   - Ensure platforms meet design and operational requirements for extreme weather resilience.

2. **Collaboration**:

   - Partner with meteorological agencies for early warning systems.

- Coordinate with local authorities, emergency services, and NGOs for disaster response and recovery.

5. Continuous improvement

1. **Review and updates**:
    - Regularly review and update the SOP based on technological advancements, regulatory changes, and past incidents.
2. **Audits and assessments**:
    - Conduct periodic audits of emergency preparedness and platform resilience measures.
3. **Innovation**:
    - Invest in research and development for climate-resilient technologies and systems.

D Guidelines and best practices for minimising the impacts of ocean acidification on offshore oil and gas infrastructure, operations, and the surrounding marine environment.

1. Objectives

1. Assess and mitigate the impact of ocean acidification on infrastructure and equipment.
2. Reduce operational contributions to ocean acidification.
3. Protect marine ecosystems in proximity to offshore installations.

2. Procedures

2.1 Assessment and monitoring

1. **Water quality monitoring**:
   - Regularly measure pH levels, dissolved CO_2, and carbonate ion concentrations in surrounding waters.
   - Use advanced sensors and autonomous underwater vehicles (AUVs) for continuous monitoring.
2. **Risk assessments**:
   - Conduct vulnerability assessments of equipment and infrastructure to acidic conditions.
   - Assess potential impacts on marine biodiversity near operations.
3. **Baseline studies**:
   - Establish baseline conditions for pH and marine life health prior to starting operations.

2.2 Mitigating operational contributions

1. **Reducing CO_2 emissions**:
   - Implement carbon capture and storage (CCS) technologies in offshore operations.

- Transition to low-carbon energy sources for powering platforms (e.g., wind, solar, or hybrid systems).

2. **Minimising chemical discharges**:
   - Avoid the discharge of chemicals that exacerbate ocean acidification or harm marine ecosystems.
   - Treat wastewater and other effluents to neutralise their impact on ocean acidity.

2.3 Infrastructure and equipment resilience

1. **Corrosion-resistant materials**:
   - Use materials like duplex stainless steel, titanium, or protective coatings for equipment and structures exposed to seawater.
   - Regularly inspect and replace vulnerable components.
2. **Maintenance protocols**:
   - Increase the frequency of maintenance checks for underwater structures.
   - Implement cathodic protection systems to prevent corrosion.

2.4 Marine ecosystem protection

1. **Marine habitat preservation**:
   - Avoid placing infrastructure near sensitive marine habitats (e.g., coral reefs).
   - Use environmental impact assessments (EIAs) to identify and mitigate potential risks to marine biodiversity.
2. **Artificial reef development**:
   - Where appropriate, design decommissioned platforms to serve as artificial reefs, fostering marine life in acidifying waters.
3. **Monitoring biodiversity**:
   - Regularly assess the health of marine species and habitats near operations.

- Partner with marine biologists and research institutions to study acidification impacts.

2.5 Emergency response

1. **Contingency plans**:
   - Develop protocols for responding to unexpected acidification-related damage to equipment or environmental harm.
2. **Rapid mitigation measures**:
   - Deploy neutralising agents to localised areas if operations cause acute changes in acidity.

3. Training and awareness

1 Train personnel on the effects of ocean acidification and the importance of mitigation strategies.

2 Conduct drills and workshops to improve preparedness for acidification-related challenges.

3 Raise awareness among stakeholders about operational measures to reduce CO_2 emissions and protect marine ecosystems.

4. Compliance and collaboration

1. **Regulatory compliance**:
   - Adhere to international conventions, such as MARPOL, and local environmental regulations.
   - Report water quality data and acidification mitigation efforts to relevant authorities.
2. **Collaborative efforts**:
   - Partner with NGOs, research organisations, and governmental bodies to address ocean acidification.
   - Support initiatives aimed at reducing global CO_2 emissions and promoting ocean health.

3. **Performance audits**:
   - Conduct regular audits to assess the effectiveness of mitigation measures.
   - Adjust strategies based on audit findings and emerging technologies.
4. **Innovation**:
   - Invest in research to develop new materials, technologies, and methods to address acidification challenges.

E Guidelines and best practices for minimising rising sea temperatures' operational, structural, and environmental impacts on offshore oil and gas activities.

1. Objectives

1. Adapt offshore operations to cope with the challenges posed by elevated sea temperatures.
2. Protect equipment and infrastructure from temperature-induced stress.
3. Preserve marine ecosystems impacted by warm water discharges and other operational factors.

2. Procedures

2.1 Assessment and monitoring

1. **Water temperature monitoring**:
    - Use sensors to continuously monitor sea surface temperatures and subsurface thermal gradients.
    - Track anomalies and long-term trends in water temperatures near offshore installations.
2. **Impact assessments**:
    - Conduct regular assessments of the effects of warm waters on equipment, marine biodiversity, and operational efficiency.
    - Evaluate the risks of thermal stress on pipelines, cooling systems, and processing equipment.
3. **Baseline studies**:
    - Establish baseline data for water temperatures and associated ecological conditions.

2.2 Mitigating operational challenges

1. **Equipment adaptation**:
    - Install heat-resistant materials in critical systems, such as pipelines, heat exchangers, and storage tanks.

- Upgrade cooling systems to manage higher ambient water temperatures effectively.

2. **Maintenance protocols**:
   - Increase the frequency of inspections and cleaning to address accelerated wear and tear caused by warm waters.
   - Implement anti-biofouling measures, such as coatings and ultrasonic cleaning systems, to prevent marine growth.
3. **Operational adjustments**:
   - Optimise production processes to account for changes in thermal efficiency.
   - Adjust operational schedules during peak temperature periods to minimise equipment strain.

2.3 Mitigating environmental impacts

1. **Thermal discharge management**:
   - Use diffusers or cooling systems to reduce the temperature of discharged water.
   - Ensure compliance with regulatory limits on thermal pollution.
2. **Marine ecosystem protection**:
   - Conduct environmental impact assessments (EIAs) to evaluate the effects of warm waters and thermal discharges on local ecosystems.
   - Establish marine protected areas around sensitive habitats to shield them from operational impacts.
3. **Monitoring biodiversity**:
   - Regularly monitor marine species composition and abundance near installations.
   - Partner with marine biologists and research institutions to study the impacts of warm waters on biodiversity.

2.4 Emergency preparedness

1. **Contingency plans**:
   - Develop response plans for incidents linked to warm water impacts, such as equipment failures or sudden ecological disruptions.

2. **Emergency Systems**:
   - Maintain backup cooling and processing systems to handle unexpected spikes in water temperature.

3. Training and awareness

1 Train personnel on the challenges associated with warm waters and the mitigation measures outlined in this SOP.

2 Conduct drills to prepare staff for responding to temperature-related emergencies.

3 Raise awareness of the ecological impacts of warm waters and promote sustainable operational practices.

4. Compliance and collaboration

1. **Regulatory compliance**:
   - Adhere to international and local regulations regarding thermal discharges, water quality, and marine biodiversity protection.
   - Submit regular reports on warm water impacts and mitigation measures to regulatory authorities.

2. **Collaborative efforts**:
   - Partner with environmental organisations and research institutions to monitor and mitigate the effects of warm waters.
   - Support initiatives aimed at reducing global greenhouse gas emissions and promoting ocean health.

3. **Review and updates**:
   - Periodically review the SOP to incorporate technological advances and environmental changes.

4. **Performance audits**:
   - Conduct audits to evaluate the effectiveness of mitigation measures and identify areas for improvement.

5. **Innovation**:
   - Invest in research to develop advanced materials, cooling technologies, and ecological monitoring tools.

F Guidelines and best practices for the risks posed by sea-level rise and shoreline erosion to offshore oil and gas operations, infrastructure, and associated coastal facilities.

1. Objectives

1. Adapt offshore and coastal infrastructure to withstand sea-level rise and shoreline erosion.
2. Reduce the vulnerability of pipelines, platforms, and coastal facilities to flooding and erosion.
3. Minimise the environmental impact of climate-driven changes.

2. Procedures

2.1 Assessment and monitoring

1. **Sea-level monitoring**:
   - Use tide gauges, satellite altimetry, and real-time sensors to track sea-level changes near offshore and coastal facilities.
   - Monitor the rate of shoreline erosion using geospatial tools and aerial imagery.
2. **Risk assessments**:
   - Conduct vulnerability assessments for offshore platforms, coastal facilities, and subsea pipelines.
   - Evaluate the potential for storm surges and flooding during extreme weather events.
3. **Baseline studies**:
   - Establish baseline data for coastal morphology, erosion rates, and water levels near facilities.

2.2 Infrastructure resilience measures

1. **Platform design and retrofitting**:
   - Elevate platforms above projected future sea levels.

- Strengthen foundation designs to account for erosion and shifting seabed conditions.
- Use corrosion-resistant materials for infrastructure exposed to prolonged immersion.

2. **Shoreline protection**:
   - Install natural or engineered barriers (e.g., mangroves, dunes, seawalls, or revetments) to reduce erosion near coastal facilities.
   - Use breakwaters and artificial reefs to minimise wave energy reaching the shore.
3. **Pipeline protection**:
   - Bury pipelines deeper below the seabed to protect against erosion and exposure.
   - Use flexible pipeline designs to accommodate shifting seabed conditions.

2.3 Operational adjustments

1. **Flood risk management**:
   - Install water-tight seals, elevated platforms, and pump systems at coastal facilities to prevent flood damage.
   - Develop contingency plans for temporary shutdowns during extreme weather events.
2. **Emergency response plans**:
   - Prepare evacuation protocols and backup systems to maintain safety during severe flooding.
   - Stock emergency supplies and ensure the readiness of transportation systems for personnel evacuation.
3. **Environmental safeguards**:
   - Design operations to minimise sediment disruption and preserve coastal ecosystems.

- Avoid construction in areas with high erosion risks unless mitigation measures are in place.

2.4 Collaboration and community engagement

1. **Stakeholder engagement**:
   - Collaborate with local authorities, coastal engineers, and environmental agencies to address shared risks.
   - Support community-led initiatives to restore and protect natural coastal defences (e.g., mangrove reforestation).
2. **Regulatory compliance**:
   - Adhere to international and local regulations governing coastal development, erosion control, and environmental protection.
   - Submit monitoring reports on erosion and flood mitigation measures to regulatory bodies.

3. Training and awareness

- Train personnel on the risks posed by sea-level rise and shoreline erosion and the measures outlined in this SOP.
- Conduct regular drills to prepare for flood scenarios and structural failures.
- Raise awareness of the importance of preserving natural coastal defences.

4. Continuous improvement

1. **Audits and reviews**:
   - Conduct regular audits of infrastructure resilience and operational readiness.
   - Review and update this SOP based on technological advancements and new data on sea-level rise.

2. **Innovation and investment**:
   - Invest in R&D for erosion-resistant materials, innovative coastal defences, and resilient platform designs.
   - Explore renewable energy sources to reduce greenhouse gas emissions contributing to climate change.
3. **Lessons learned**:
   - Document and share experiences from past events to improve future preparedness.

REFERENCES

Aboobacker, V.M., Vethamony, P., Samiksha, S.V., Rashmi, R. and Jyoti, K., 2013. Wave transformation and attenuation along the west coast of India: Measurements and numerical simulations. Coastal Engineering Journal, 55(1), pp.1350001-1.

Ahlawat, S.P.S., Roy, S.D., Soundarajan, R., Mandal, A.B., Chatterjee, R.N., Singh, D.B., Shiva, K.N., Madhu, K., Sheeja, T.E., KUMARI, V. and Sharma, T.V.R.S., 2002. Flora and fauna of Andaman and Nicobar Islands.

Anandakumar, S., Subramani, T. and Elango, L., 2008. Spatial variation and seasonal behaviour of rainfall pattern in Lower Bhavani River basin, Tamil Nadu, India. The Ecoscan, 2(1), pp.17-24.

Anandavelu, I., Robin, R.S., Purvaja, R., Ganguly, D., Hariharan, G., Raghuraman, R., Prasad, M.H.K. and Ramesh, R., 2020. Spatial heterogeneity of mesozooplankton along the tropical coastal waters. Continental Shelf Research, 206, p.104193.

Anderson, D.M., Glibert, P.M. and Burkholder, J.M., 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries, 25(4), pp.704-726.

Annamalai, H., Prasanna, V., Hafner, J., Nagothu, U. and Kitterod, N.O., 2011. Modeling the current and future climate over the Cauvery river basin. Sustainable Rice Production in a Warmer Planet, pp.59-81.

Anonymous, 2003. Thailand state pollution report. Pollution Control Departmentp. 28. APHA, 1995. Standard methods for the examination of water and wastewater. 2540 D.

Balakrishnan, M., Srivastava, R.C. and Pokhriyal, M., 2008. Biodiversity of Andaman and Nicobar Islands. Biobytes, 3, pp.9-12.

Balakrishnan, N.P., 1989. Andaman Islands-vegetation and floristics. Andaman, Nicobar and Lakshadweep: An Environmental Impact Assessment. Oxford and IBH Publication, New Delhi, India, p.5561.

Balasubramanian, T., 2012. Heavy metal contamination and risk assessment in the marine environment of Arabian Sea, along the southwest coast of India. Am. J. Chem, 2, pp.191-208.

Begum, A., 2008. Study on the quality of water in some streams of Cauvery River. E-Journal of chemistry, 5(2), pp.377-384.

Bendschneider, K. and Robinson, R.J., 1952. A new spectrophotometric method for the determination of nitrite in sea water.

Bhadja, P. and Kundu, R., 2012. Status of the seawater quality at few industrially important coasts of Gujarat (India) off Arabian Sea.

Bhargava, N., 1983. Ethnobotanical studies of the tribes of Andaman and Nicobar Islands, India. I. Onge. Economic Botany, 37(1), pp.110-119.

Bhatt, N., Murari, M.K., Ukey, V., Prizomwala, S.P. and Singhvi, A.K., 2016. Geological evidences of extreme waves along the Gujarat coast of western India. Natural Hazards, 84(3), pp.1685-1704.

Biksham, G. and Subramanian, V., 1988. Elemental composition of Godavari sediments (central and southern Indian subcontinent). Chemical Geology, 70(3), pp.275-286.

Biksham, G. and Subramanian, V., 1988. Sediment transport of the Godavari River basin and its controlling factors. Journal of Hydrology, 101(1-4), pp.275-290.

Biksham, G., Subramanian, V., Ramanathan, A.L. and Van Grieken, R., 1991. Heavy metal distribution in the Godavari river basin. Environmental Geology and Water Sciences, 17(2), pp.117-126.

Biswas, S.K., 1992. Tectonic frame-work and evolution of graben basins of India.

Brodeur, R.D., Sugisaki, H. and Hunt Jr, G.L., 2002. Increases in jellyfish biomass in the Bering Sea: implications for the ecosystem. Marine Ecology Progress Series, 233, pp.89-103.

Brown, R.M., McClelland, N.I., Deininger, R.A. and Tozer, R.G., 1970. A water quality index-do we dare. Water and sewage works, 117(10).

Buragohain, D. and Ghosh, A., 2021. Seasonal Distribution Trends of Benthic Foraminiferal Assemblages from the Saurashtra Coast, Western India. Journal of the Geological Society of India, 97(1), pp.61-69.

Carruthers, T., Wazniak, C., Wazniak, C.E. and Hall, M.R., 2004. Development of a water quality index for the Maryland coastal bays. Maryland's Coastal Bays: Ecosystem Health Assessment, pp.4-59.

Centre for Environmental Studies, 2014. Water quality of Mahanadi River. ENVIS Newsletter, Vol.38, July-September 2014. CES, Department of Environment, Forest and Climate Change, Government of India.

Chakrapani, G.J. and Subramanian, V., 1990. Preliminary studies on the geochemistry of the Mahanadi river basin, India. Chemical Geology, 81(3), pp.241-253.

Chakrapani, G.J. and Subramanian, V., 1993. Heavy metals distribution and fractionation in sediments of the Mahanadi River basin, India. Environmental Geology, 22(1), pp.80-87.

Chakrapani, G.J. and Subramanian, V., 1993. Rates of erosion and sedimentation in the Mahanadi River basin, India. Journal of hydrology, 149(1-4), pp.39-48.

Coastal Zones of India (Sponsored by Ministry of Environment & Forests, Govt. of India)

COMAPS, 2012. Monitoring of Marine Pollution through Coastal Ocean Monitoring and Prediction System. ICMAM PD, Ministry of Earth Sciences, Govt. of India.

Das, J., Das, S.N. and Sahoo, R.K., 1997. Semidiurnal variation of some physico-chemical parameters in the Mahanadi estuary, east coast of India.

Dash, S.K., Shekhar, M.S. and Singh, G.P., 2006. Simulation of Indian summer monsoon circulation and rainfall using RegCM3. Theoretical and applied climatology, 86(1), pp.161-172.

Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W. and Batiuk, R.A., 1993. Assessing water quality with submersed aquatic vegetation. BioScience, 43(2), pp.86-94.

Desai, I. and Nair, A., Diversity and Ecol Diversity and Ecology of Aquatic Ogy of Aquatic Microfauna Along The Coast Of Saurashtra.

Deshraj, T., Mani Christy, R., Koravangatt, D., Devender, K., Ilya, B., Nagesh R, I. and Rajesh R, N., 2012. Sediment characteristics of tidal deposits at Mandvi, Gulf of Kuchchh, Gujarat, India: geophysical, textural and mineralogical attributes. International Journal of Geosciences, 2012.

Devi, V., Karthikeyan, K., Lekameera, R., Nandhagopal, G., Mehta, P.N. and Thivakaran, G.A., 2014. Water and sediment quality characteristics near an industrial vicinity, Vadinar, Gulf of Kachchh, Gujarat, India. International Journal of Plant, Animal and Environmental Sciences, 4(3), pp.219-226.

Dhage, S.S., Chandorkar, A.A., Kumar, R., Srivastava, A. and Gupta, I., 2006. Marine water quality assessment at Mumbai West Coast. Environment international, 32(2), pp.149-158.

Dineshbabu, A.P., 2013. Trawl fishery of eastern Arabian Sea. In APFIC Regional Expert Workshop on Tropical Trawl Fishery Management, Thailand (Vol. 34).

Diversity of Zooplankton in Coastal Waters of Mumbai (West Coast of India) November 2020 Publisher: LAMBERT PUBLICATIONISBN: ISBN-13: 978-620-3-02450-0, ISBN-10: 6203024503, EAN: 9786203024500

Eastern Offshore Environmental Monitoring of KG-PG Basin, Bay of Bengal (2019 - 20)

Eastern Offshore Environmental Monitoring of Palk bay, Cauvery basin, Bay of Bengal, 2019

Eaton, A.D., Clesceri, L.S., Rice, E.W., Greenberg, A.E. and Franson, M.H., 2005. Total suspended solids dried at 103–105 C. Standard methods for the examination of water and wastewater, pp.2-58.

EIA Report - Offshore Oil & Gas Development and Production from Discovered Small Field of B-9 Cluster Offshore Fields at Mumbai Offshore Basin.

Environment Monitoring Report of Deendayal Port Trust (Annual Report) (March 2020 to February 2021) (Report No - DCPL/DPT(19-22)/AMR/20-21/01)

Environmental Monitoring Around ONGC Installations in the Western Offshore Region for IPSEHM - Oil and Natural Gas Corporation Limited 2019-2020

Farhadian, O. and Pouladi, M., 2014. Seasonal changes in the abundance and biomass of zooplankton from shallow mudflat river-estuarine system in Persian Gulf. Brazilian Journal of Aquatic Science and Technology, 18(2), pp.19-29.

Ganesh, T. and Raman, A.V., 2007. Macrobenthic community structure of the northeast Indian shelf, Bay of Bengal. Marine Ecology Progress Series, 341, pp.59-73.

Gaonkar, C.A., Krishnamurthy, V. and Anil, A.C., 2010. Changes in the abundance and composition of zooplankton from the ports of Mumbai, India. Environmental monitoring and assessment, 168(1), pp.179-194.

Ghani, S.A.A., 2015. Trace metals in seawater, sediments and some fish species from Marsa Matrouh Beaches in north-western Mediterranean coast, Egypt. The Egyptian Journal of Aquatic Research, 41(2), pp.145-154.

Giangrande, A., Licciano, M. and Musco, L., 2005. Polychaetes as environmental indicators revisited. Marine Pollution Bulletin, 50(11), pp.1153-1162.

Gideon, P.W., Menon, P.K.B., Rao, S.R.V. and Jose, K.V., 1957. On the marine fauna of the Gulf of Kutch: A preliminary survey.

Gohel, N.A., Mehta, S.K., Vyas, S.J., Talekar, S.D., Pawar, U.S. and Joshi, A.J., International Journal Of Scientific Research And Education.

Gopal, A., Abdul Jaleel, K.U., Parameswaran, U.V., Sanjeevan, V.N., Saramma, A.V., Vijayan, A., Saravanane, N., Gupta, G.V.M. and Sudhakar, M., 2020. Distinctive community patterns with exceptional diversity of polychaetes around a tectonically active archipelago in the tropical Indian Ocean. Frontiers in Marine Science, 7, p.710.

Gordon, J., Gillespie, D., Potter, J., Frantzis, A., Simmonds, M.P., Swift, R. and Thompson, D., 2003. A review of the effects of seismic surveys on marine mammals. Marine Technology Society Journal, 37(4), pp.16-34.

Gouda, R. and Panigrahy, R.C., 1996. Ecology of phytoplankton in coastal waters off Gopalpur, east coast of India.

Government of India (1956). The Interstate River Dispute Act 1956 (modified in 2002), Retrieved May, 2017, from Ministry of Law, Justice and Company Affairs

Government of India (2012) National Water Policy, Retrieved from, Ministry of Water Resources, GoI:

Government of India (2016). Guidelines for Integrated Water Resources Development and Management. Ministry of Water Resources.

Government of India Central Water Commission Coastal Management Directorate Guidelines for "Protection and Control of Coastal Erosion in India"

Government of India Ministry of Ocean Development Annual Report 2005-06

Grasshoff, K., Kremling, K. and Ehrhardt, M. eds., 2009. Methods of seawater analysis. John Wiley & Sons

Guhathakurta, P. and Revadekar, J., 2017. Observed variability and long-term trends of rainfall over India. In Observed climate variability and change over the Indian region (pp. 1-15). Springer, Singapore.

Guhathakurta, P., Sreejith, O.P. and Menon, P.A., 2011. Impact of climate change on extreme rainfall events and flood risk in India. Journal of earth system science, 120(3), pp.359-373.

Gujarat State Action Plan On Climate Change Government Of Gujarat Climate Change Department Supported By The Energy And Resources Institute New Delhi & Giz 2014

Gupta, A.K., Gupta, S.K. and Patil, R.S., 2003. A comparison of water quality indices for coastal water. Journal of Environmental Science and Health, Part A, 38(11), pp.2711-2725.

Gupta, I., Dhage, S. and Kumar, R., 2009. Study of variations in water quality of Mumbai coast through multivariate analysis techniques.

Hays, G.C., Richardson, A.J. and Robinson, C., 2005. Climate change and marine plankton. Trends in ecology & evolution, 20(6), pp.337-344.

Hussain, J., Dubey, A., Hussain, I., Arif, M. and Shankar, A., 2020. Surface water quality assessment with reference to trace metals in River Mahanadi and its tributaries, India. Applied Water Science, 10(8), pp.1-12.

Ingole, B.S., Gaonkar, U.V., Deshmukh, A., Mukherjee, I., Sivadas, S.K. and Gophane, A., 2014. Macrobenthic community structure of coastal Arabian Sea during the fall intermonsoon.

Jaison, C.A. and Sivanandan, A.V., 2012. Assessment of Water Quality along the Coastal Areas of Kerala: A Study of the Tsunami Impact on Groundwater (Doctoral dissertation, Cochin University of Science and Technology).

Jameel, A.A. and Hussain, A.Z., 2005. Water quality index of Ujjakondan channel of river Cauvery at Tiruchirappalli. Indian Journal of Environmental Protection, 25(10), p.941.

Jarvis, A., Lau, C., Cook, S., Wollenberg, E., Hansen, J., Bonilla, O. and Challinor, A., 2011. An integrated adaptation and mitigation framework for developing agricultural research: synergies and trade-offs. Experimental Agriculture, 47(2), pp.185-203.

Jayaram, K.C., 2000. Kaveri riverine system: An environmental study. The Madras Science Foundation, Chennai, pp.1-6.

Jha, D.K., Devi, M.P., Vidyalakshmi, R., Brindha, B., Vinithkumar, N.V. and Kirubagaran, R., 2015. Water quality assessment using water quality index and geographical information system methods in the coastal waters of Andaman Sea, India. Marine pollution bulletin, 100(1), pp.555-561.

JiyalalRam, M.J., Ram, A., Rokade, M.A., Karangutkar, S.H., Yengal, B., Dalvi, S., Acharya, D., Sharma, S. and Gajbhiye, S.N., 2013. Phytoplankton dynamic responses to oil spill in Mumbai Harbour.

Jose, D.M., Mandla, V.R., Subbarao, S.S., Rao, N.S. and Moses, S.A., 2018. Assessment of coastal water quality along south west coast of India using multile regression analysis on satellite data. Journal of Rural Development, 37(2), pp.269-284.

Joseph, A., Vijaykumar, K., Mehra, P., Unnikrishnan, A.S., Sundar, D. and Desai, R.G.P., 2009. Observed tides at Mumbai High offshore region near the continental shelf break in the eastern Arabian Sea.

Joydas, T.V. and Damodaran, R., 2002. Macrobenthos of the shelf waters of the west coast of India (Doctoral dissertation, School of Marine Sciences).

Joydas, T.V. and Damodaran, R., 2009. Infaunal macrobenthos along the shelf waters of the west coast of India, Arabian Sea.

Jyothibabu, R., Karnan, C., Jagadeesan, L., Arunpandi, N., Pandiarajan, R.S., Muraleedharan, K.R. and Balachandran, K.K., 2017. Trichodesmium blooms and warm-core ocean surface features in the Arabian Sea and the Bay of Bengal. Marine pollution bulletin, 121(1-2), pp.201-215.

Kalavathy, S., Sharma, T.R. and Sureshkumar, P., 2011. Water quality index of river Cauvery in Tiruchirappalli district, Tamilnadu. Arch Environ Sci, 5, pp.55-61.

Kamble, S.R. and Vijay, R., 2011. Assessment of water quality using cluster analysis in coastal region of Mumbai, India. Environmental monitoring and assessment, 178(1), pp.321-332.

Karunakaran, C., 1964. Sedimentary environment of the formation of Andaman flysch, Andaman Islands, India. In International Geological Congress, Report of the Twenty-Second Session (Vol. 15, pp. 226-232).

Karunakaran, C., Ray, K.K. and Saha, S.S., 1964. A new probe into the tectonic history of the Andaman and Nicobar Islands. 22d Internat. Geol. Cong., India, Rept., pp.507-515.

Kasturirangan, L.R., 1963. A Key for the Identification of the More Common Planktonic Copepoda: Of Indian Coastal Waters (No. 2). Council of Scientific & Industrial Research.

Keller, G.H. and Richards, A.F., 1967. Sediments of the Malacca strait, southeast Asia. Journal of Sedimentary Research, 37(1), pp.102-127.

Konhauser, K.O., Powell, M.A., Fyfe, W.S., Longstaffe, F.J. and Tripathy, S., 1997. Trace element geochemistry of river sediment, Orissa State, India. Journal of Hydrology, 193(1-4), pp.258-269.

Krishnankutty, S., Joseph, C.A., Vincent, P.D., Jabir, T., Vishnu, P.S., Saramma, A.V. and Hatha, A.A., 2019. Hydrographic, seasonal diversity, distribution and abundance of phytoplankton in coastal waters off Cochin-south-eastern Arabian Sea.

Kuenen, P.H., 1957. Longitudinal filling of oblong sedimentary basins. Verhandelingen van het Koninklijk Nederlands Geologisch-Mijnbouwkundig Genootschap, Geologische Serie, 18, pp.189-195.

Kumar, K.N., Rajeevan, M., Pai, D.S., Srivastava, A.K. and Preethi, B., 2013. On the observed variability of monsoon droughts over India. Weather and Climate Extremes, 1, pp.42-50.

Kumar, P., Das, G.L. and Garg, A., 2021. Heavy metal accumulation in marine sediments-An assessment in ONGC's platforms in Mumbai High Region, Arabian Sea. World Journal of Advanced Engineering Technology and Sciences, 2(1), pp.060-068.

Kumar, V.S. and Kumar, K.A., 2010. Waves and currents in tide-dominated location off Dahej, Gulf of Khambhat, India. Marine Geodesy, 33(2-3), pp.218-231.

Kumar, V.S., Dora, G.U., Philip, C.S., Pednekar, P. and Singh, J., 2012. Nearshore currents along the Karnataka coast, west coast of India. The International Journal of Ocean and Climate Systems, 3(1), pp.71-84.

Kumar, V.S., George, J., Dora, U. and Naseef, M., 2019. Surface wave dynamics off Mumbai coast, north-eastern Arabian Sea. Ocean Dynamics, 69(1), pp.29-42.

Lata, K.S., Jesu, A. and Dheenadayalan, M.S., 2015. Seasonal Variation of Cauvery River Due To Discharged Industrial Effluents at Pallipalayam in Namakkal. Rasāyan Journal of Chemistry, 8(3), pp.380-388.

Manjunatha, B.R., Yeats, P.A., Smith, J.N., Shankar, R., Narayana, A.C. and Prakash, T.N., 1999. Accumulation of heavy metals in sediments of marine environments along the southwest coast of India.

Marine EIA Study For Replacement of Existing Seawater Intake Pipeline and Enhancement in Seawater Intake of Saurashtra Chemicals, Division of Nirma Ltd. SPONSORED BY Saurashtra Chemicals Division of Nirma Ltd, Porbandar June 2017.

Marine Environmental Impact Assessment for Discharge Channel of 4000 MW Ultra Mega Power Project Near Mundra, Gulf of Kachchh SPONSORED BY Coastal Gujarat Power Limited, New Delhi FEBRUARY 2009

Marine Environmental Impact Assessment for Rerouting the 42” Sour Gas Pipeline Segment of ONGC in the Nearshore and Intertidal Areas of Umbhrat, Navsari District SPONSORED BY OIL AND NATURAL GAS COMMISSION, JANUARY 2015

Maya, K., Das, P., Sreelash, K. and Babu, K.N., 2018. The Coastal Springs of Southern Kerala, SW India–Hydrology and Water Quality Assessment. Journal of the Geological Society of India, 92(5), pp.616-625.

Mishra, R.K., Shaw, B.P., Sahu, B.K., Mishra, S. and Senga, Y., 2009. Seasonal appearance of Chlorophyceae phytoplankton bloom by river discharge off Paradeep at Orissa Coast in the Bay of Bengal. Environmental monitoring and assessment, 149(1), pp.261-273.

Mitra, A., Kumar, V.S. and Naidu, V.S., 2020. Circulation in the Gulf of Khambhat—A Lagrangian Perspective. Journal of Marine Science and Engineering, 8(1), p.25.

Murphy, J.A.M.E.S. and Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica chimica acta, 27, pp.31-36.

Murthy, C.R., Sinha, P.C. and Rao, Y.R. eds., 2008. Modelling and monitoring of coastal marine processes. Springer.

Murty, K.V.S. and Ramakrishna, M., 1980. Structure and tectonics of Godavari–Krishna coastal sedimentary basins. Bulletin of Oil and Natural Gas Corporation, 17(1), pp.147-158.

Naik, S., Mahapatro, D., Behera, D.P., Kumar, M., Panda, C.R. and Mishra, R.K., 2013. Spatio-temporal Study of Zooplankton Community in Mahanadi Estuary, Bay of Bengal. Int J Ecosyst, 3(6), pp.185-195.

Nair, M., Balachandran, K.K., Sankaranarayanan, V.N. and Joseph, T., 1997. Heavy metals in fishes from coastal waters of Cochin, Southwest Coast of India.

Nayak, B.B., Das, J., Panda, U.C. and Acharya, B.C., 2001. Industrial effluents and municipal sewage contamination of Mahanadi estuarine water, Orissa. In Proceedings (pp. 77-86).

Nayak, R.K. and Shetye, S.R., 2003. Tides in the Gulf of Khambhat, west coast of India. Estuarine, coastal and shelf science, 57(1-2), pp.249-254.

Nelson, G., Cai, Z., Hassan, R., Godfray, C., Santos, M. and Swaminathan, H., 2012. Food security and climate change: A report by the high level panel of experts on food security and nutrition.

Neprochnov, Y.P., 1964. The structure and thickness of the sedimentary layer of the Arabian Sea, the Bay of Bengal and the Andaman Sea. Trans. Inst. OceanoL, Acad. Sci. USSR, 69, pp.214-226.

Nutrients And Its Influence On Biological Productivity Along Kerala Coast, India Robin, R.S, Pradipta, R . Muduli, Vishnu Vardhan, K., Raj Kumar, J.S.I., Prasun Goswami4 and Balasubramanian, T, International Journal of Current Research Vol. 10, pp.038-045, November, 2010

P. D. Kunte, B. G. Wagle and Y. Sugimori, "Sediment Transport and Depth Variation Study of the Gulf of Kutch Using Remote Sensing," International Journal of Remote Sensing, Vol. 24, No. 11, 2003, pp. 2253-2263.

Panda, U.C., Sundaray, S.K., Rath, P., Nayak, B.B. and Bhatta, D., 2006. Application of factor and cluster analysis for characterization of river and estuarine water systems–a case study: Mahanadi River (India). Journal of hydrology, 331(3-4), pp.434-445.

Pandit, P.R. and Fulekar, M.H., 2017. Quality characterization of coastal water in Gujarat Coast, India. Journal of Biotechnology and Biochemistry, 3(4), pp.8-15.

Panigrahy, P.K., Das, J., Das, S.N. and Sahoo, R.K., 1999. Evaluation of the influence of various physico-chemical parameters on coastal water quality, around Orissa, by factor analysis.

Panseriya, H.Z., Gosai, H.B., Sankhwal, A.O., Sachaniya, B.K., Gavali, D.J. and Dave, B.P., 2020. Distribution, speciation and risk assessment of heavy metals: geochemical exploration of Gulf of Kachchh, Gujarat, India. Environmental Earth Sciences, 79(213), p.213.

Patel, D., Nagababu, G., Radadia, N., Parsana, S., Sheth, M. and Sheth, N., 2018, May. GIS-based approach for the evaluation of offshore wind power potential for Gujarat. In IOP Conference Series: Earth and Environmental Science (Vol. 154, No. 1, p. 012001). IOP Publishing.

Patel, R., Salvi, H., Bhagat, R. and Kamboj, R.D., 2017. Zooplankton Diversity at important Coral and Mangrove areas of Gulf of Kachchh, Gujarat, India. Bulletin of Environmental and Scientific Research, 6(3-4), pp.1-7.

Patel, R., Salvi, H., Bhagat, R., Vankar, J., Christian, L. and Kamboj, R.D., 2018. Assessment of spatial and temporal variations in coastal water quality of Gulf of Kachchh, Gujarat using GIS application.

Perumal, N.V., Rajkumar, M., Perumal, P. and Rajasekar, K.T., 2009. Seasonal variations of plankton diversity in the Kaduviyar estuary, Nagapattinam, southeast coast of India. J. Environ. Biol, 30(6), pp.1035-1046.

Philip, A.S., Babu, C.A. and Hareeshkumar, P.V., 2013. Meteorological aspects of mud bank formation along south west coast of India. Continental Shelf Research, 65, pp.45-51.

R. R. Nair, N. H. Hashimi and V. P Rao, “On the Possibility of High Velocity Tidal Streams as Dynamic Barriers to Long Shore Sediment Transport: Evidence from the Continental Shelf of the Gulf of Kuchchh,” Indian Marine geology, Vol. 47, 1982, pp. 77-86.

Radhakrishna, I., 2001. Saline fresh water interface structure in Mahanadi delta region, Orissa, India. Environmental Geology, 40(3), pp.369-380.

Raghunathan, C., Gupta, R.S., Wangikar, U. and Lakhmapurkar, J., 2004. A record of live corals along the Saurashtra coast of Gujarat, Arabian Sea. Current Science, pp.1131-1138.

Raghunathan, C., Tewari, A., Joshi, H.V., Kumar, V.G., Trivedi, R.H. and Khambhaty, Y., 2003. mpact of turbidity on intertidal macrofauna at Gopnath, Mahuva and Veraval coasts (west coast of India).

Raju M. Patil , Sagar T. Sankpal and Pratap V. Naikwade ,“ DISTRIBUTION OF HEAVY METALS IN WATER AND SEDIMENT OF RATNAGIRI COAST, MAHARASHTRA.” Indian Streams Research Journal | Volume 4 | Issue 6 | July 2014 | Online & Prin

Rao, A.D., 2010. Variability of coastal ocean processes along the west coast of India.

Rao, C.; Indusekhar, V. (1986) Manganese, Zinc, Copper, Nickel and Cobalt Contents in Sea Water and Seaweeds from Saurashtra Coast. Mahasagar – Bull. Natl. Inst. Oceanography, 19, 129–136

Rao, G.N., 2001. Sedimentation, stratigraphy, and petroleum potential of Krishna-Godavari basin, East Coast of India. AAPG bulletin, 85(9), pp.1623-1643.

Rao, V.R., Ramu, K., Dash, S.K., Patra, S., Vishnuvardhan, K., Rao, V.D. and Mohan, R., 2015. A Study on Hydrodynamic Behaviour of SW Coast of India–Implication to Ecosystem Model. Procedia engineering, 116, pp.746-754.

Rasheed, M.A., Lakshmi, M., Rao, P.L.S., Kalpana, M.S., Dayal, A.M. and Patil, D.J., 2013. Geochemical evidences of trace metal anomalies for finding hydrocarbon microseepage in the petroliferous regions of the Tatipaka and Pasarlapudi areas of Krishna Godavari Basin, India. Petroleum Science, 10(1), pp.19-29.

Report On Status Of Ground Water Quality In Coastal Aquifers Of India, 2014

Rodolfo, K.S., 1969. Sediments of the Andaman basin, northeastern Indian Ocean. Marine Geology, 7(5), pp.371-402.

Saisastry, A.G.R. and Chandramohan, P., 1990. Physicochemical characteristics of Vasishta Godavari estuary, east coast of India: Pre-pollution status.

Salvi, H., Patel, R., Thakur, B., Shah, K. and Parmar, D., 2014. Assessment of Coastal Water Quality Parameters of Selected Areas of Marine National Park & Sanctuary (Okha, Sikka & Khijadiya). Available at SSRN 2456093.

Sampathkumar, P. and Kannan, L., 1998. Seasonal variations in physico-chemical characteristics in the Tranquebar-Nagapattinam Region, South-East coast of India. Pollution Research, 17, pp.397-402.

Samuel, A., Joy, K.J. and Bhagat, S., 2017. Integrated Water Management of the Mahanadi Basin.

Satpathy, K.K., 1996. Seasonal distribution of nutrients in the coastal waters of Kalpakkam, East Coast of India.

Sediment quality and Heavy metals:

Shahi, N., Godhe, A., Mallik, S.K., Härnström, K. and Nayak, B.B., 2015. The relationship between variation of phytoplankton species composition and physico-chemical parameters in northern coastal waters of Mumbai, India.

Shahul Hameed, T.S., Kurian, N.P., Thomas, K.V., Rajith, K. and Prakash, T.N., 2007. Wave and current regime off the southwest coast of India. Journal of Coastal Research, 23(5), pp.1167-1174.

Shankar, D., 2000. Seasonal cycle of sea level and currents along the coast of India. Current Science, 78(3), pp.279-288.

Sharma, A.N.U.P.A.M. and Rajamani, V., 2001. Weathering of charnockites and sediment production in the catchment area of the Cauvery River, southern India. Sedimentary geology, 143(1-2), pp.169-184.

Sharma, G.S., 1978. Upwelling off the southwest coast of India. Indian Journal of Marine Sciences, 7(4), pp.209-218.

Sheeja, T.E., Chattopadhayay, D. and Mandal, A.B., 2001. A glimpse on medicinal plants of Andaman and Nicobar Islands with special reference to endemic and extra Indian taxa. In Poster presented at 88th session of Indian Science Congress.

Shetye, S.R., 1998. West India coastal current and Lakshadweep high/low. Sadhana, 23(5), pp.637-651.

Shetye, S.R., Gouveia, A.D., Shenoi, S.S.C., Michael, G.S., Sundar, D., Almeida, A.M. and Santanam, K., 1991. The coastal current off western India during the northeast monsoon. Deep Sea Research Part A. Oceanographic Research Papers, 38(12), pp.1517-1529.

Srivastava, P.K., Mukherjee, S., Gupta, M. and Singh, S.K., 2011. Characterizing monsoonal variation on water quality index of River Mahi in India using geographical information system. Water Quality, Exposure and Health, 2(3), pp.193-203.

Status Report on Coastal Protection & Development in India by Central Water Commision, 2016

Subeesh, M.P., Unnikrishnan, A.S., Fernando, V., Agarwadekar, Y., Khalap, S.T., Satelkar, N.P. and Shenoi, S.S.C., 2013. Observed tidal currents on the continental shelf off the west coast of India. Continental Shelf Research, 69, pp.123-140.

Sukumaran, S., Vijapure, T., Mulik, J. and Ridha, H., 2021. Marine macrobenthos of NorthWest India-Reviewing the known and unknown. Frontiers in Marine Science, p.954.

Sundaray, S.K., Pand, U.C., Nayak, B.B. and Bhatta, D., 2005. Behaviour and distribution pattern of nutrients in river-estuarine waters of Mahanadi, Orissa, India. Asian Journal of Water, Environment and Pollution, 2(1), pp.77-84.

Thakur, B., Chavda, C. and Salvi, H., 2015. Phytoplankton diversity at some selected sites of the Gulf of Kachchh, Gujarat, India. Bulletin of Environmental and Scientific Research, 4(4), pp.7-12.

Thornes, J.E., 2002. IPCC, 2001: Climate change 2001: impacts, adaptation and vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by JJ McCarthy, OF Canziani, NA Leary, DJ Dokken and KS White (eds). Cambridge University Press, Cambridge, UK, and New York, USA, 2001. No. of pages: 1032.

Tiwari, T.N. and Mishra, M.A., 1985. A preliminary assignment of water quality index of major Indian rivers. Indian J Environ Prot, 5(4), pp.276-279.

Uma, G. and Sannasiraj, S.A., 2021. Swell and sea characteristics along the south-west coast of India during the monsoon. Ocean Engineering, 237, p.109572.

UNESCO, 1994. JGOFS Protocols.

Upadhyay, S., 1988. Physico-chemical characteristics of the Mahanadi estuarine ecosystem, east coast of India.

Vaithiyanathan, P., Ramanathan, A.L. and Subramanian, V., 1992. Sediment transport in the Cauvery River basin: sediment characteristics and controlling factors. Journal of Hydrology, 139(1-4), pp.197-210.

Venkatachalapathy, R. and Karthikeyan, P., 2013. Physical, chemical and environmental studies on Cauvery River in parts of Tamil Nadu (Mettur and Bhavani). Universal Journal of Environmental Research and Technology, 3(3), pp.415-422.

Verardo, D.J., Froelich, P.N. and McIntyre, A., 1990. Determination of organic carbon and nitrogen in marine sediments using the Carlo Erba NA-1500 Analyzer. Deep Sea Research Part A. Oceanographic Research Papers, 37(1), pp.157-165.

Vineethkumar, V., Sayooj, V.V., Shimod, K.P. and Prakash, V., 2020. Estimation of pollution indices and hazard evaluation from trace elements concentration in coastal sediments of Kerala, Southwest Coast of India. Bulletin of the National Research Centre, 44(1), pp.1-16.

Vivekanandan, E., Srinath, M., Pillai, V.N., Immanuel, S. and Kurup, K.N., 2003. Marine fisheries along the southwest coast of India. WorldFish.

Vybhav, K., Narasimha, P., Mujumdar, P.P., Nagendra, R. and Gobalakrishnan, N., 2018. Geochemical Characterization and Provenance Study of Ilmenites from Fluvial Sediments of River Cauvery in Parts of Tamil Nadu, Southern India. International Journal of Economic and Environmental Geology, 9(4), pp.45-48.

Water Quality Monitoring and Its Assessment on Mahanadi Basin, 2019

World Health Organization (WHO, 1993) Guidelines for drinking water quality. World Health Organization, Geneva, Switzerland.

Y. Pradhan, A. S. Rajawat and S. R. Nayak, “Application of IRS-P4 OCM Data to Study the Impact of Tidal Propagation on Sediment Dynamics in the Gulf of Kachchh,” Indian Journal of Marine Sciences, Vol. 34, No. 2, 2004, pp. 157-163.

ANNEURE

1.1 Chemical and biological characteristics of the Gulf of Kutch

a) Water quality

The annual variation of water temperature is between 23 °C and 30 °C, though localised higher temperatures up to 35 °C can result in isolated water pools formed in shallow intertidal depressions during low tide. Suspended sediment (SS) is highly variable (5-700 mg/l), spatially as well as temporally, and largely results from the dispersion of fine sediment from the bed and the intertidal mudflats by tidal movements (Table 1.1). Evidently, nearshore shallow regions invariably sustain higher SS than the central portions. The region between Okha and Sikka has low SS varying within a narrow range (10-50 mg/l), whereas the inner Gulf areas contain markedly higher SS, sometimes in excess of 100 mg/l. The average pH of the Gulf water is remarkably constant (8.0-8.3) and is within the range expected for the coastal tropical seas. The evaporation exceeds precipitation, leading to markedly higher salinity than the typical seawater. This is particularly evident in the inner Gulf, where salinities as high as 40 psu have commonly been reported to occur off Kandla and Navlakhi. Although the salinities decrease considerably for a brief period in some creeks of the Little Gulf of Kachchh under the influence of monsoonal runoff, the impact of this decrease in salinity in the Gulf proper is small, and salinities exceed 36 psu off Sikka and Mundra during normal monsoon periods. The average Dissolved Oxygen (DO) is fairly high (3-5 ml/l), and the Biological Oxygen Demand (BOD) is low (<0.1 – 4.0 mg/l), indicating good oxidising conditions. Hence, the organic load in the water column is considered to be effectively oxidised. The nutrients (PO_4^{3-}, NO_3^-, NO_2^-, NH_4^+) are more or less uniformly distributed in the OkhaSikka-Mundra segment, and their concentrations indicate healthy natural waters. Their levels, however, are marginally high in the Kandla-Navlakhi segment. The networks of creeks of the Little Gulf of Kachchh sustain high natural concentrations of nutrients, perhaps due to high regeneration rates. As expected for an unpolluted coastal environment, the concentrations of PHC and phenols are low.

Table 1.1 Minimum, Maximum and Average representation of observed Water quality at Gujarat Basin

Parameter	Minimum	Maximum	Average
Temp (°C)	19.9	31	26
pH	7.9	8.5	8.1
Turbidity (NTU)	4.02	6.8	5.1
SS (mg/l)	7	742	98
Salinity (psu)	32.1	43.7	37.9
DO (ml/l)	2.3	7	4.29
BOD (mg/l)	0.5	4.9	1.8
PO_4^{3-} (µmol/l)	0.3	6.7	1.5
P_{Total} (µmol/l)	1.2	4.2	2.3
NO_3^- (µmol/l)	0.5	31.9	7.2
NO_2^- (µmol/l)	0.1	1.1	0.4
NH_4^+ (µmol/l)	0.1	3.7	0.9
N_{Total} (µmol/l)	6.9	102.7	29.2
PHC (µmol/l)	0.2	14	3.2
Phenols (µmol/l)	2.7	163	36.3

b) Sediment quality

The central portion of the Gulf extending from the mouth to upstream of Sikka is rocky, with sediments confined only to the margins. The nearshore sediment that consists of light grey silt and clay and fine sand with patches of coarse sand in between is poorly sorted with highly variable skewness. This sediment's major source is the shore material and the load transported by the Indus River (Table 1.2). The portion of sediment derived from the hinterland is considered small because of the low runoff. Moreover, the streams discharging in the Gulf (during the brief monsoon season) are short, with dams constructed on many of them. The concentrations of heavy metals such as chromium, manganese, cobalt, nickel, copper, zinc, mercury and lead, though variable, indicate natural background levels, and there is no evidence of gross sediment contamination. The concentrations of PHC are also low, though large quantities of petroleum crude and its products are offloaded at Vadinar and Kandla.

Table 1.2 Minimum, Maximum and Average representation of Sediment quality at Gujarat Basin

Constituents	Minimum	Maximum	Average
Al (%)	0.4	8.7	5
Cr (µg/l)	1.2	176	74
Mn (µg/l)	389	1450	726
Fe (%)	0.5	38	4
Co (µg/g)	5	54	26
Ni (µg/g)	14	70	43
Cu (µg/g)	7	78	34
Zn (µg/g)	15	126	66
Hg (µg/g)	0.009	0.62	0.15
Pb (µg/g)	1.2	20	9.8
C (%)	0.1	1	0.5
P (µg/g)	189	812	602
PHc (µg/g)	0.1	3	0.7

c) Flora and fauna

The Gulf abounds in marine wealth and is considered one of the biologically richest marine habitats along the west coast of India. The marine flora is highly varied, including sand-dune vegetation, mangroves, seagrasses, macrophytes, and phytoplankton. The dominant species of sand dune flora are *Euphorbia caudicifolia*, *E.nerifolia*, *Aloevera sp*, *Ephedra foliata*, *Urochodra setulosa*, *Sporobolus maderaspatenus, Eragrostis unioloides, Calotropis procera, Fimbristylis sp, Indigofera sp* and *Ipomoea pescaprae*. The common seagrasses found growing on the mudflats are *Halophila ovata*, *H.beccarii* and *Zostrea marina*. The most common marine algal species are *Ulva fasciata, U.reticulata, Enteromorpha intenstinalis, Dictyota sp, Hypnea musciformis, Sargassum tennerimum, S.ilicifolium, Gracilaria corticata, Cystocera sp, Padina tetrastomatica, Corallina sp, Laurencia sp, Caulerpa racemosa, C.peltata, Bryopsis sp, Turbinaria sp, Ectocarpus sp, Acanthophora sp, Chondria sp,* and *Codium sp*. As assessed from chlorophyll-a concentration, the water column's primary production is generally good in the outer Gulf but decreases in the inner regions. The major phytoplankton genera are *Rhizosolenia, Synedra,* *Chaetoceros, Navicula, Nitzschia, Pleurosigma, Thalassiothrix, Biddulphia, Stauroneis, Coscinodiscus* and *Skeletonema*. The Gulf has a vast intertidal area with rich biota. Sheltered bays, creeks and mudflats provide ideal sites for mangrove vegetation over an estimated area of about 1036 km^2. The formations are of open scrubby type, with isolated and discontinuous distribution from KandlaNavlakhi in the northeast to Jodia, Jamnagar, Sikka, Salaya and Okha in the southwest, as also at Pirotan, Poshitra, Dohlani and Dwarka. Vast stretches of mangroves also exist along the northern shore of the Gulf. The dominant species of mangroves are *Avicennia marina var acutissima, A officinalis, Bruguiera parviflora, B gymnorphiza, Rhizophora mucronata, R apiculata, Ageiceros corniculata* and *Sonneratia apetata* along with the associated species of *Salicornia brachiata, Sueda fruticosa, Artiplex stocksii* and a lichen*, Rosella montana*. The marine fauna of the Gulf is rich in variety and abundance. Sponges having an array of colours are seen, both in the intertidal and subtidal biotopes. The common species of sponge is *Adocia sp*, which is associated with coral reef fauna. Tetilla dactyloidea (Carter) is common in sandy and silty mud shores. The most frequently encountered hydrozoans are *Sertularia sp* and *Plumularia sp*. The giant sea anemone (*Stoichactis gigantum*) is common in the coral ecosystem. Sea anemones belonging to *Anemonia, Bunodactis, Paracondylactis, Anthopleura* and *Metapeachia*, are widespread. A zoantharian, *Gemmaria sp*, is found forming extensive hexagonal green mats in the coral pools. Another interesting actiniarian is the *Cerianthus sp* found in tubes in the soft mud.

One of the most interesting biotic features of the Gulf is the presence of living corals, thriving as patches rather than reefs, either on the intertidal sandstones or on the surface of wave-cut, eroded shallow banks along the southern shore of the Gulf. However, the species diversity is poor, with 44 species of Scleractinian and 12 species of soft corals identified. Several polychaete worms, sedentaria and errantia, with the dominant genera of Eurythoe, Terebella, Polynoe, Iphione and Nereis are common. Amongst a variety of sipunculid and echiuroid worms, the dominant species are *Dendrosromum sp, Asphidosiphon sp* and *Ikadella misakiensis* (Ikeda). The intertidal crustacean fauna is very rich and equally diverse, with spider crab (Hyas sp) and furry crab (*Pillumnus sp*), as specialities. Amongst the invertebrate component of the marine fauna of the Gulf, the molluscs have the highest representatives. As many as 92 species of bivalves, 55 species of gastropods, 3 species of cephalopods and 2 species each of scaphopods and amphineurans have been reported. The most notable members of the molluscan fauna are octopus, pearl oyster, and various chanks, including the sacred chank. The echinoderm fauna, represented by four classes and 14 genera, have the commonest genera of *Palmpsis, Astropecten, Asteria, Temnopleura* and *Holothuria*. The subtidal benthic fauna of the Gulf is dominated by polychaetes, crustaceans, echinoderms, gastropods and bivalves, with an average biomass of 25 g/m^2. The Gulf has a variety of exploitable species of finfish and shellfish. Sciaenids, polynemids, perches, eels, catfishes, elasmobranchs and prawns are the commercially important groups, with an average catch of 1.4x105 t/y. Ghol, Karkara, Khaga, Dhoma, Magra, and Musi are fishing grounds in the Gulf. The Gulf region offers plenty of facilities for feeding, breeding and shelter to a variety of birds. The birds find a near-perfect environment in the mangrove forests lining the islands and along the coast. In addition, they are well placed to reach their food supply, i.e. the shoals of fish, squids, mud-skippers and other animals, during low tide. All along the creeks and around islands, mangrove trees and mudflats are seen crowded with Grey Herons, Pond Herons, Painted Storks, Large and small Egrets, Reef Heron, Darters, Cormorants, Flamingos, Lesser Flamingos, etc., during the periods of seasonal migration (November-March). Many migratory birds pass through the Gulf, and a small population of most species, comprising mainly juveniles and non-breeding adults, take shelter in this area during summer. Saltworks spread out along the coast are also important for feeding and breeding of birds. They act as alternate sites for them to roost during high tide. Though a detailed systematic survey of biota is lacking, a number of species have been reported, as shown in Table 1.3. Because of its high biogeographical importance and rich flora and fauna, several areas along the southern Gulf are notified under the Marine National Park (16289 ha) and the Marine Sanctuary (45798 ha).

Table 1.3 Flora/Fauna of the Gujarat basin

Flora/Fauna	Species (no)
Algae	130
Sponges	70
Corals	37
Fishes	200
Sharks	8
Prawns	27
Crabs	30
Molluscs	200
Sea turtles	3
Sea mammals	3
Birds	200

Minimum, maximum and average biological characteristics of the Gujarat basin

	Minimum	Maximum	Average
Phytoplankton			
Chlorophyll a (mg/m^3)	0.2	4.3	1.2
Phaeophytin (mg/m^3)	0.2	1.8	0.6
Cell counts (nox10^3/l)	6	412	51
Total genera (no)	7	25	12
Zooplankton			
Biomass (ml/100m^3)	0.5	53	7
Population (nox10^3/100m^3)	0.3	117.3	26.8
Total groups (no)	7	22	13
Macrobenthos			
Biomass (g/m^2, wet wt)	0.1	15.2	3.2
Population (no/m^2)	6.9	5700	907
Total groups (no)	1	17	6

Marine fish landings (t x10^3/y) of Gujarat state and districts adjoining the Gujarat basin. Source: Department of fisheries, Government of Gujarat

Year	State	Jamnagar	Rajkot	Kachchh	Total contribution (%)
1965-66	109.9	4.2	--	2.4	6.0
1966-67	115.2	2.8	--	3.0	5.0
1967-68	124.9	3.8	--	3.3	5.7
1968-69	131.7	2.8	--	2.3	3.8
1969-70	140.0	2.9	--	2.7	4.0
1970-71	151.2	4.7	--	3.9	5.7
1971-72	147.0	5.5	--	4.1	6.5
1972-73	151.2	4.6	--	4.8	6.2
1973-74	177.6	6.8	--	6.9	7.7
1974-75	157.4	3.0	0.3	4.3	4.8
1975-76	208.3	5.1	2.2	3.8	5.3
1976-77	225.4	21.7	1.3	5.4	12.6
1977-78	176.9	14.5	0.4	6.3	12.0
1978-79	230.0	21.8	2.7	6.3	13.4
1979-80	206.7	24.8	0.6	5.7	15.0
1980-81	218.9	32.3	1.7	4.4	17.5
1981-82	220.6	34.2	2.0	6.3	19.3
1982-83	192.7	29.7	0.5	13.8	22.8
1983-84	223.3	27.4	1.3	23.3	17.3
1984-85	290.7	31.5	0.7	34.3	22.9
1985-86	306.6	25.2	1.7	35.4	20.3
1986-87	315.9	28.0	0.5	31.3	18.9
1987-88	327.6	40.2	0.5	29.7	21.5
1988-89	414.1	44.2	2.8	46.9	22.7
1989-90	432.4	45.4	2.5	49.6	22.5
1990-91	500.5	54.3	1.8	65.4	24.3
1991-92	530.0	63.5	2.7	61.8	24.1
1992-93	609.1	66.2	1.1	63.0	21.4
1993-94	619.8	58.9	1.5	63.2	19.9
1994-95	645.3	58.9	1.5	76.8	21.0
1995-96	598.4	68.1	1.0	72.6	23.7
1996-97	660.1	76.2	0.9	76.7	23.3
1997-98	702.4	56.0	0.8	71.8	18.3
1998-99	551.7	28.6	0.2	69.7	17.9
1999-00	671.0	71.7	0.8	75.0	22.0
2000-01	620.5	72.6	1.7	64.7	22.4
2001-02	650.8	83.4	2.1	80.0	25.4
2002-03	743.4	102.8	1.5	80.7	24.9
2003-04	609.1	37.9	1.7	72.0	18.3
2004-05	585.0	45.9	1.9	64.7	19.2
2005-06	663.9	66.5	1.5	62.4	19.6

1.2 Chemical and biological characteristics of Saurashtra basin

a) Water quality

Water temperature was in the range of 22.5°C-31.2 °C. The average pH of the basin was 7.9-8.5 and was in the range of seawater. The average concentration of SS was in the range of 9.3 to 45.3 mg/l (Table 1.4). The salinity values were as expected for coastal seawaters (36.0-37.0 psu), with no freshwater influx. The average DO concentration was in the normoxic range (DO value 6.0 mg/l or above), indicating good oxic condition in the region. Low BOD (1.2-3.1 mg/l) values indicated the area was free from organic load. Concentrations of nitrogen and phosphorous compounds in the coastal waters of Porbandar were low except for $NH4_{+}{}^{-}N$. A comparably high NH4 + -N concentration during ebb indicates its association with effluent. The PHC values (4.1-10.3 µg/l) were in the range generally observed in the nearshore coastal waters. Concentrations of phenols were higher in the nearshore regions than offshore, indicating some anthropogenic perturbations. Comparison with previous data indicated that the coastal waters of the Saurashtra basin had good water quality, ammonia and phenols.

Table 1.4 Minimum, maximum and average water quality of Saurashtra basin

Parameter	Minimum	Maximum	Average
Water temperature (°C)	22.5	31.2	25.3
pH	7.9	8.5	8.1
Suspended solids (mg/l)	9.3	45.3	22.7
Salinity (psu)	35	36.7	35.9
DO (mg/l)	6.0	7.1	6.6
BOD (mg/l)	1.2	3.1	1.7
PO_4^{3-} (µmol/l)	0.4	1	0.6
NO_3^- (µmol/l)	0.2	14.7	3.9
NO_2^- (µmol/l)	0.1	1.3	0.4
NH_4^+ (µmol/l)	1.2	3	1.9
PHc (µg/l)	4.1	10.3	6.6
Phenols (µg/l)	23.4	122.1	84.2

b) Sediment quality

Sediment analyses indicated that the intertidal sediment texture was sandy 93.2 to 97.8% sand, whereas the subtidal sediment texture was clayey-silt with 58.3 to 90.6 % silt (Table 1.5). The results also clearly indicated no accumulation of heavy metals, organic carbon, phosphorus and PHC in the sediments in the study area. The concentration of trace metals in the study region was in the range generally observed in the uncontaminated sediments. Hence, there was no build-up of trace metals in the sediment of the study region. The Saurashtra basin indicated the variation during different sampling events, which is summarised below:

Table 1.5 Minimum, maximum and average sediment quality of Saurashtra basin

Parameter	Minimum	Maximum	Average
Al (%)	4	6.3	5.1
Cr (μg/g)	56.5	102	79
Mn (μg/g)	490.7	623	567
Fe (%)	2.3	4.6	3.5
Co (μg/g)	10	39.7	24
Ni (μg/g)	14	66.3	44
Cu (μg/g)	26	60.6	44
Zn (μg/g)	39.5	82.7	62
Ca(μg/g)	22	31.2	25.7
Hg (μg/g)	0.1	0.1	0.1
P (μg/g)	555	1049	856
Corg (%)	0.8	1.4	1
PHC (μg/g)	1.1	7.4	3.3

c) Flora and fauna

During both March and November, the distribution of chlorophyll a was patchy, with values fluctuating from 0.4 to 23.8 mg/m3 (av. 4.9 mg/m3) and 0.2 to 5.3 mg/m3 (av 1.9 mg/m3), respectively. A decline in the chlorophyll value as compared to 1981-1982 was observed (Table 1.6). High chlorophyll a and pheophytin concentrations in most regions indicated healthy conditions for phytoplankton growth. Diurnal observations indicated higher phytopigment concentrations during ebb than during flood. Overall, 49 (March) and 38 (November) phytoplankton genera were identified during recent studies. Overall, the phytoplankton results revealed good productivity regarding the phytoplankton population with fairly good generic diversity. The intertidal area, being rocky and sandy, was devoid of mangrove vegetation. The present zooplankton biomass was lower than that of the 1981-82 data. Overall, 18 and 21 zooplankton groups were observed during March and November, respectively. Decapod larvae occurred in all zooplankton samples but contributed only about 2.2% and 0.3% during March and November, respectively, to the zooplankton population. Fish eggs were present in low numbers (0.1%) during March, but considerable numbers (2.6%) were present in the zooplankton samples during November. Fish larvae, though at a low percentage, were encountered in most zooplankton collections. The macrobenthic abundances of the intertidal zones near the intake and outfall were comparable during March. The major faunal component in the study area was polychaetes during both seasons. Overall, 11 and 14 faunal groups were recorded in the area during March and November, respectively. Porbandar is one of the major marine fish landing stations in Gujarat, and from January to December, the total landing was 3.0x10^7 t. September to May is the peak fishing period, while the period from June to August is the lean season.

Table 1.6 Minimum, maximum and average biological characteristics of Saurashtra basin

	Phytoplankton		
	Minimum	**Maximum**	**Average**
Chlorophyll a (mg/m^3)	0.2	8.5	3.5
Phaeophytin (mg/m^3)	0.5	0.6	0.5
Cell counts (nox10^3 cells/l)	10.3	1092.9	440
Total genera (no)	8	17	12
	Zooplankton		
Biomass (ml/100m^3)	3.3	33.5	12.5
Population (nox10^3/100m^3)	15.2	46.6	29
Total groups (no)	10	14	11
	Macrobenthos		
Biomass (g/m^2, wet wt)	7.9	65.4	34.8
Population (no/m^2)	547	18913	6086
Total groups (no)	2	3	3

The year-wise total marine fish landing (t) of Porbandar from 2010-2015 in the Saurashtra basin.

Year	Total (x10^7 t)
2010-11	8.3
2011-12	9.2
2012-13	10.2
2013-14	10.6
2014-15	10.6

Total petroleum hydrocarbons (TPH) from fish in the Mumbai basin

	Minimum	Maximum	Average
TPH (μg/g)	**2.18**	**13.11**	**7.27**

Heavy metals in fish

Heavy Metal in mg/kg	Minimum	Maximum	Average
V	0.1	0.93	0.46
Cr	0.11	0.49	0.28
Mn	0.35	2.52	1.27
Fe	7.99	65.25	30.83
Co	0.01	0.05	0.02
Ni	0.01	0.1	0.03
Cu	0.12	0.32	0.23
Zn	2.08	6.98	4.33
As	0.1	0.4	0.2
Cd	0.02	0.46	0.11
Ba	0.08	2.88	0.61
Pb	0.01	0.13	0.02

1.3 Chemical and biological characteristics of Mumbai offshore

a) Water quality

The Mumbai Basin's temperature varied from 25.1 °C-28.3 °C (Table 1.7). The salinity showed a 35.1-38.77 PSU variation, and pH varied from 6.86 to 8.16. The turbidity showed a maximum fluctuation of 10-57 NTU. Similarly, suspended solids were also showing fluctuation of 10-139 mg/l. Dissolved oxygen in the Mumbai basin was shown a 3.3-6.8 mg/l variation. Among the nutrients, Nitrite (NO_2^-) was below detectable; Nitrate (NO_3^-) varied as 0.07-6.32 µmol/l, Phosphate as 0.07-0.62 µmol/l and silicate varied as 0.05-2.94 µmol/l, TPH was below detectable.

Table 1.7 Water quality of Mumbai basin

Parameter	Minimum	Maximum	Average
Temperature^{0}C	25.1	28.3	26.7
Salinity (PSU)	26.5	37.5	32.9
pH	6.86	8.16	7.5
Turbidity (NTU)	10	57	26
Suspended solids mg/l	10	139	68
Dissolved oxygen in mg/l	3.3	6.8	5.2
Nitrite (NO_2^-) in µmol/l	BDL	BDL	BDL
Nitrate (NO_3^-) in µmol/l	0.07	6.32	2.26
Phosphate (PO_4^{3-}) in µmol/l	0.07	0.62	0.26
Silicate (SiO_4^-) in µmol/l	0.05	2.94	0.3
Hydrocarbon TPH in µg/l	BDL	BDL	BDL

b) Heavy metals in seawater

The concentrations of heavy metals viz., Vanadium, Chromium, Manganese, Iron, Cobalt, Nickel, Copper, Zinc, Arsenic, Cadmium, Barium and Lead in the seawater samples collected from the surface, mid-depth and above bottom have been tabulated in Table 1.8. The average concentrations of heavy metals in different portions of the study domain are given below. Ranges of certain significant heavy metals that can cause a threat to aqua life in higher concentrations than the usual oceanographic ranges may be considered to have a close watch from a pollution point of view.

The data shows that the distribution of heavy metals in the water column did not reveal any clear pattern either vertically or horizontally. The spatial distribution also did not yield any clear trend of either enrichment or depletion. The heavy metal concentrations observed in the reference stations around Bombay High are slightly lower than those recorded near the installations; however, all measured concentrations of heavy metals around various installations are comparable with reference station concentrations and the previous year's reported values. It is also observed that all measured concentrations are within acceptable limits of the marine environment as prescribed by regulatory agencies. This shows that there is not much enrichment in the concentration of heavy metals due to oil field activities. Although the drilling mud discharges and the disposal of produced water are said to have reflected as sources of heavy metals around an oil field installation, their absence of enrichment indicates their dispersal within short distances from the installations. Though it is observed that values in open oceans are less than those found near the oil installations, almost all analysed metal concentrations are within permissible limits of heavy metals for coastal marine water. Therefore, it can be safely concluded that the values observed near Bombay High and other fields are below the toxicity limits for metals in the literature.

Table 1.8 Minimum, maximum and average of heavy metal in seawater at Mumbai basin

Heavy Metal in µg/l	Minimum	Maximum	Average
V	0	2.9	1.8
Cr	0	29.1	0.7
Mn	0	30.7	1.7
Fe	0	2010.7	80.7
Co	0	28.8	0.5
Ni	0	34.5	2.5
Cu	0	29.7	2.4
Zn	0	31.4	2.9
As	0	31.24	1.2
Cd	0	26.6	0.49
Ba	0	27.6	2.4
Pb	0	21.7	0.6

c) Heavy metals in sediments

The sediments of the present study area were mainly composed of clayey silt (>95%) with varied proportions of clay and sand. Silt and clay were the dominant textural class at all the deep-sea blocks. The measured concentrations of various heavy metals in sediments have been tabulated in Table 1.9. It is observed that the distribution of metal concentrations in the present study area has not followed a particular trend as concentration varied from one station to another, but variation is minimal when area, depth, and other oceanographic parameters are considered.

Table 1.9 Minimum, maximum and average of heavy metals in sediment at Mumbai basin

Heavy Metal in mg/kg	Minimum	Maximum	Average
V	0.36	261.44	36.42
Cr	0.38	311.48	34.25
Mn	25.19	4142.62	554.85
Fe	2369.35	101302.57	26766.51
Co	0.83	116.52	12.82
Ni	2.65	257.45	24.78
Cu	2.96	330.02	28.57
Zn	1.73	287.78	30.26
As	0	86.3	25.69
Cd	0	0.45	0.10
Ba	0.98	1542.64	375.92
Pb	0.74	22.96	3.70
Hg	0.66	47.38	8.91

d) Flora and fauna

The marine environment supports the vast population of organisms distributed in both pelagic and benthic realms. Most of the organisms of the pelagic realm constitute plankton (Table 1.10). Phytoplankton and zooplankton together constitute this community and form the primary food source for most marine species. Their response to the physio-chemical characteristics of the water column determines their distribution, abundance, and production. The occurrence of marine species, both plants and animals, has largely been controlled by the physio-chemical properties of ocean water. Chlorophyll-a in the Mumbai basin varied from 0.8 – 3.1 mg/m^3. Phytoplankton abundance ranges from 38-321 units/L with total genera ranging from 10-22. Zooplankton abundance ranges from 20-150 units/L with total genera ranging from 7-14. Chlorophyll content in the sediment extracted in acetone was below detectable limits. The meiobenthic organisms collected along with sediments by using the van-Veen grabs were represented by two groups of meiofauna, Nematode worms and

Polychaete worms. The total number of macrobenthic organisms varied from 90-510 no/m^2.

Table 1.10 Minimum, maximum and average biological characteristics of Mumbai basin

Phytoplankton			
	Minimum	**Maximum**	**Average**
Chlorophyll a (mg/m^3)	0.8	3.1	1.2
Abundance Range UNITS/L	38	321	149
Total genera (no)	10	22	16
Zooplankton			
Abundance Range UNITS/L	20	150	72
Total groups (no)	7	14	11
Macrobenthos			
Population (no/m^2)	90	510	257
Total groups (no)	2	2	2

Scientific name and common name of the fishes, crustaceans and other major groups in the Mumbai basin

GROUP	FAMILY & Scientific name	Common name
CEPHALOPOD S	FAMILY ; SEPIIDAE *Sepia pharanis*	Cuttle Fish
	Family: PENAEIDAE *Penaeus indicus* *Penaeus monodon*	Indian White Prawn TigerPrawn
TELEOSTS (Bony fishes)	Family: Bramidae Pampus argenteaus	Silver Pomfret
	Family: Soleidae Cynoglossus lida	Shoulder spot Tongue sole
	Family: Scombridae Thunnus tonggol	Long Tail Tuna
	FamilY;CLUPEIDAE *Sardinella longiceps*	Sardine
	Family: Congridae *Uroconger lepturus*	Slender Conger Eel
	FamilY: MURAENESOCIDAE *Congresox telabonoides*	Common EEL
	Family:HARPADONTIDAE *Hardpodon nehereus*	Bombay Duck
	Family: SCOMBRIDAE *Rastrelliger kanagurta*	Indian Mackerel

Relative abundance in the fish & shellfish caught during the sample fishing

Sr.No	Common name	Relative abundance no/Haul	Relative biomass gm/ haul
1	Cuttle Fish	11	7100
2	Indian White Prawn	41	2720
3	Tiger Prawn	52	3960
4	Shoulder spot Tongue sole	5	1130
5	Long Tail Tuna	3	640
6	Sardine	6	1310
7	Common EEL	2	280
8	Bombay Duck	11	1460
9	Indian Mackerel	6	1370
10	Silver Pomfret	7	3140
11	Round tail Alligator Gar/ Spot tail needlefish	4	130
12	Giant Marine Catfish	2	140

1.4 Chemical and biological characteristics of Kerala-Lakshadweep-Konkan basin

a) Water quality

The monthly mean seawater temperature varies in space and time along the southwest coast. Off Quilon (9º N, 76º 30' E), for instance, the mean sea surface temperature (SST) is low (27º C) during January - February and June - August and high (29 °C to 31ºC) during May (Devaraj et al. 1997). High values are associated with the summer season before the onset of the southwest monsoon. The mean water temperature is higher in the northern part of the coast compared to the southern part. For instance, water temperature is 25º C and 17 to 21º C during January - February and June - August, respectively, at 100 m depth off Quilon, while during the same periods it is 29º C and 30º C off Karwar (15º N,74º E) (Devaraj et al. 1997). The lower temperature is recorded in areas where upwelling intensity is comparatively higher. The mean depth of the top of the thermocline also varies from season to season. The top of the thermocline is deepest during the winter months of December to February off Quilon (120 m) and during January - February off Karwar (70 to 80 m). The thermocline reaches near the surface in April and October, i.e. before and after the southwest monsoon. Mean sea surface salinity has two peaks, one during May - June before the onset of the southwest monsoon and another during September - October immediately after the southwest monsoon. Monthly mean surface salinity varies between 32.5 and 36.1 psu (Table 1.11). The maxima occur comparatively late in the southern areas and are associated with the advection of highly saline Arabian Seawater and highly saline bottom water brought upward to surface levels in upwelling areas. The minima are associated with monsoon rains, river runoff, and the incursion of low salinity equatorial surface waters. The minima occur first in the southern region and progressively move northward following the trend in monsoon rainfall (Devaraj et al. 1997). The salinity maximum occurs at depths of 100 to 150 m during the northeast monsoon and between 30 and 50 m during the southwest monsoon. The salinity maximum associated with the main thermocline probably represents an intrusion of high saline waters below the less saline surface layers (Pillai 1983).

The shelf waters are generally well-aerated during most of the year except during the southwest monsoon and the associated upwelling season. A good correlation between the depth of the top of the thermocline and oxycline has been observed. By May, oxygen-deficient waters start penetrating the shelf. By June/July, the oxygen-deficient waters penetrate below the thermocline and cover the entire bottom of the shelf. In August, the oxycline becomes very shallow, and the low-oxygen intermediate water reaches near the surface in the upwelling areas. Oxygen-deficient water remains on the shelf until October, especially when upwelling is intense. By December, the shelf waters are well-aerated again. Mean monthly sea surface DO values range between 6.0 mg/l and 1.5 mg/l. Oxygen-deficient waters remain in the continental shelf of the northern region (off Karwar: 6 months) for a longer duration than in the southern region (off Quilon: 2 months) (Pillai 1983).

The surface water temperature ranged from 26.3°C to 31.4°C. The basin's surface water temperature variation is highly correlated to a variable intensity of solar radiation, evaporation and water column turbidity, and the upwelling phenomena during monsoon season. There was a significant fluctuation in salinity among the coastal and offshore basin waters. The maximum salinity of 35.64 was recorded offshore during the upwelling, and the minimum of 14.7 was recorded at the Cochin nearshore. Among the basin, all coastal waters recorded low salinity compared to offshore. This could be attributed to a large quantity of freshwater discharge (from backwaters), which is one of the prime factors influencing the abundance and distribution of the fauna and flora in the coastal and offshore waters. There was not much variation in DO concentration, ranging from 4.29 to 5.18 mg/l. pH values remained alkaline throughout the study period at all the stations, varying from 6.21 to 8.2. Turbidity of water is generally caused by the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter and other microscopic organisms. It has been reported that wave action increases during the pre-monsoon season, resulting in turbulence in the coastal waters favouring the resuspension of the bottom sediment due to stirring action that causes low water transparency. The high turbidity of water during the monsoon period could be due to the influx of heavily silt-laden freshwater. The turbidity of water samples varied from 0.5 to 20.55 NTU.

Table 1.11 Water quality of Kerala Konkan Lakshadweep basin

Parameter	Minimum	Maximum	Average
Temp ^{0}C	26.3	31.4	29.1
Salinity (PSU)	14.7	35.64	34.93
pH	6.21	8.2	7.66
Turbidity (NTU)	0.5	20.55	4.2
Suspended solids mg/l	2.16	12.56	4.24
Dissolved oxygen in mg/l	4.29	5.18	4.83
Nitrite (NO_2^-) in µmol/l	0.04	9.61	0.82
Nitrate (NO_3^-) in µmol/l	0.05	16.35	1.95
Phosphate (PO_4^{3-}) in mg/l	1.36	2.78	2.08
Silicate (SiO_4^-) in µmol/l	1.73	11.86	6.27
Hydrocarbon TPH in µg/l			

b) Heavy metals in seawater

The magnitude of different heavy metals followed the hierarchy, Zn>Mn>Pb>Cu> Cd>Hg (Table 1.12). In this study, dissolved Hg, Cd, Cu, Pb, Mn, and Zn concentrations ranged from 0.007 to 0.065 µg/ l, 0.10 to 0.23 µg/ l, 0.18 to 6.2 µg/ l, 1.6 to 1.99 µg/ l, 0.68 to 13.48 µg/ l and 0.89 to 17.18 µg/ l, respectively.

Table 1.12 Heavy metals in the Seawater of Kerala Konkan Lakshadweep basin

Heavy Metal in µg/l	Minimum	Maximum	Average
V	--	--	--
Cr	--	--	--
Mn	0.68	13.48	4.21
Fe	--	--	--
Co	--	--	--
Ni	--	--	--
Cu	0.18	6.2	1.28
Zn	0.89	17.18	9.45
As	--	--	--
Cd	0.1	0.23	0.7
Ba	--	--	--
Pb	1.6	1.99	1.86
Hg	0.007	0.065	0.03

c) Heavy metals in sediment

The sediments were generally rich in organic carbon and predominant in sandy-silt fraction. A high sand fraction characterised the nearshore (Table 1.13). The textural analysis of the sediment showed a higher sand percentage (77%), followed by silt (23%). The distribution of organic carbon availability in the soil was irregular, with comparatively lower concentrations. The nearshore sediment was recorded as low in organic carbon, with a low percentage of clay, silt and a high percentage of sand. The hierarchy of sediment heavy metals in the basin was as follows: Fe>Zn > Cr > Ni > Cu > Pb >Mn> Cd>Al > Hg>As.

Table 1.13 Heavy metals in the sediment of Kerala Konkan Lakshadweep basin

Heavy Metal	Minimum	Maximum	Average
V	--	--	--
Cr (µg/g)	41.7	212	118
Mn (µg/g)	0.12	4.2	1.75
Fe (µg/g)	5.05	248.62	78.36
Co	--	--	--
Ni (µg/g)	26.4	97	53.3
Cu (µg/g)	21	66.5	35.2
Zn (µg/g)	44.8	219	10.04
As (µg/g)	0.006	0.17	0.02
Cd (µg/g)	0.11	2.3	0.7
Ba	--	--	--
Pb (µg/g)	11	33	19.7
Hg (µg/g)	0.04	0.65	0.2
Al (µg/g)	0.43	11.12	4.12
Sand (%)	20.77	87.10	77.26
Silt (%)	14.88	41.43	24.04
Clay (%)	7.89	37.12	13.25

d) Flora and Fauna

Chlorophyll-*a* concentration positively correlated with plankton density and nutrient concentration. The chlorophyll concentration ranged from 0.85 to 3.83 mg.m^{-3} (Table 1.14). The distribution and succession of phytoplankton are influenced by physical parameters, seasonal variations in rainfall and its subsequent effect on the spatial distribution of salinity. Phytoplankton abundance in the basin ranged from 330 to 5928 cells/L, averaging 4260 cells/L. The zooplankton population density in the basin ranged from 117 to 1218 No. L-1 with an average of 544 No. L-1. *Copepoda* was the most important group in terms of species number and abundance. Along the basin, macrobenthic biomass varied between 0.05 g m^{-2} and 13.8 g m$^{-2,}$ with an average of 4.93 g m^{-2}. The abundance ranged from 105 ind. m^{-2} to 6400 Ind. m^{-2} with an average of 1539 ind. m^{-2}. Major groups that contributed to the biomass and abundance were polychaetes and crustaceans.

Table 1.14 Minimum, maximum and average biological characteristics of Kerala Konkan Lakshadweep basin

Phytoplankton			
	Minimum	**Maximum**	**Average**
Chlorophyll a (mg/m^3)	0.85	3.83	2.7
Abundance Range cells/L	330	5928	4260
Total genera (no)	21	29	25
Phytoplankton production (mg C·m-2·day-1)	1.1	49.9	11.2
Zooplankton			
Population No/L	117	1218	544
Total groups (no)	15	19	17
Zooplankton production (mg C·m-2·day-1)	6.4	27.5	9.3
Macrobenthos			
Biomass (g/m^2)	0.05	13.8	4.93
Abundance (Ind.m^2)	105	6400	1539

e) Fishery Resources and Potentials in the Kerala Lakshadweep Konkan basin

Due to high productivity, the southwest coast is one of India's most important areas in terms of marine fish production. While the length of the southwest coast is only about 16% of the Indian coastline, it contributes 31.7% (0.74 million t) annually to national marine fish production. Landings are higher around the southwest monsoon (July to September: 28.6%) and post-monsoon (October to December: 34.6%) seasons. Using stratified multistage random sampling, the Central Marine Fisheries Research Institute (CMFRI) has collected data on marine fish landings along the southwest coast. The information on the fishery resources provided here is based on CMFRI's statistical and periodic publications.

Marine fish landings along the Kerala, Lakshadweep Konkan basin

State	Jan. - Mar.	Apr. - June.	July - Sept.	Oct. - Dec.
Kerala	18.6	18.1	33.7	29.6
Karnataka	26.9	11.9	19.2	42.0
Goa	23.6	9.5	18.7	48.2
SW coast	21.1	15.7	28.6	34.6

Estimates of the potential yield of fish resources along the Kerala Lakshadweep Konkan basin

Depth zone	Potential yield ($x10^3$ t)	Source
0 - 200 m (oceanic)	1 422	George et al. (1977)
0 to 200 m (only demersals)	438	Joseph (1980)
0 to 500 m (oceanic)	853	Joseph et al. (1976)
0 to 200 m	900	Alagaraja (1989)
0 to 200 m (only demersals)	332	Sudarsan et al. (1989)
0 to 50 m (only demersals)	361	Anon. (1991)
0 to 50 m (only pelagics)	589	Anon. (1991)
51 to 100 m	63	Anon. (1991)
101 to 200 m	29	Anon. (1991)
201 to 500 m (only oceanic tunas)	265	Anon. (1991)
0 to 500 m	1 307	Anon. (1991)

1.5 Chemical and biological characteristics of the Cauvery basin

a) Water quality

Water temperature was recorded as more or less similar and differed during seasons. Water temperature varied from 23.4 ºC to 29.4 ºC (Table 1.15). The maximum temperature was observed during summer (May), and the minimum was recorded during monsoon (October). Water salinity varied between 24 psu and 32.7 psu. The maximum salinity was recorded during May (summer), and the minimum was observed during October (monsoon). pH values varied in the range 8.05 - 8.29. The changes influence the seawater pH and pCO_2 levels. Photosynthetic activity increases pH, whereas respiration tends to lower the pH. Thus, the pH is greatly influenced by biological activity and carbon cycling. The relatively high pH of oceanic surface waters keeps pCO_2 at moderately low levels. Although the biological pump operates in all areas, the rate at which it removes CO_2 from surface waters may vary due to biological productivity differences. Dissolved oxygen is an important parameter influencing the biogeochemical processes in the sea. The dissolved oxygen distribution in the sea is mainly regulated by air-sea interaction, photosynthesis, and respiration. The other processes that affect the oxygen saturation in the sea are surface circulation, upwelling, coastal input, nitrification, and sediment-water exchange. Generally, a saturated water column indicates the oxidising capacity of that region, while an under-saturation is caused by increased respiration or chemical oxidation. An increased organic matter supply may considerably reduce seawater's dissolved oxygen concentration. DO in the surface waters ranged from 4.80 to 6.23 mg/l (mean 5.67 mg/). The nitrite (NO_2^-) concentrations in the study region ranged from 0.02 to 0.53 µmol/l with a mean value of 0.12 µmol/l. Nitrate (NO_3^-) is the primary nutrient species in the sea. The surface nitrate concentrations were 0.22 to 15.61 µmol/l (mean 3.22 µmol/l). The silicate concentrations ranged from 5.11 to 16.3 µmol/l. The Cauvery Basin generally showed less contamination due to PHC in water, which ranged from 0.3 to 0.58 µg/l. Moderate contamination due to PHC is possible in this region due to port activities and mechanised fishing vessels since it is an active fishing zone.

Table 1.15 Water quality parameters in the Cauvery basin

Parameter	Minimum	Maximum	Average
Water Temperature (°C)	23.4	29.4	26.01
Salinity (psu)	24	32.7	28.82
pH	8.05	8.29	8.15
DO (µmol/l)	187.36	242.63	221.47
NO_3^- (µmol/l)	0.22	15.61	3.22
PO_4^{3-} (µmol/l)	0.24	1.04	0.66
NO_2^-	0.02	0.53	0.12
SiO_4^- (µmol/l)	3.11	15.77	8.36
PHC (µg/l)	0.3	0.58	0.08

b) Heavy metal concentrations

Coastal regions are experiencing rapid growth in urbanisation and industrialisation, which leads to the inflow of heavy metals into marine ecosystems. It has now become a major threat to the aquatic ecosystem. Coastal ecosystems are highly affected by pollutants, such as heavy metals, pesticides, and antifoulants, entering the water column and sediments. Investigating heavy metals in the marine environment is more important because their consumption is highly harmful and results in poisoning. Table 1.16 shows water/sediment concentrations of different metals in the Cauvery basin.

Table 1.16 Heavy metal concentrations in the water and surface sediments of the Cauvery basin

Element(µg/l)	**Concentration values**		
	Minimum	**Maximum**	**Average**
	Water		
Cd	0.02	0.45	0.23
Cu	0.01	0.54	0.27
Pb	0.08	1.55	0.67
Hg	0.05	2.01	0.75
Zn	0.33	1.27	0.54
Element(µg/g)	**Concentration values**		
	Minimum	**Maximum**	**Average**
	Sediment		
Cd	0.12	2.26	1.06
Cu	0.38	3.87	2.07
Pb	0.43	5.63	3.15
Hg	0.06	1.12	0.31
Zn	0.2	1.28	0.87

c) Sediment quality

The sediments during the present study were mainly comprised of sand, calcareous organisms, seagrass, and shells. Organic carbon in the sediment from the area ranged from 0.35-3.59% (mean 1.34). These values are comparable to the reported values from the region (Mazumdar et al., 2007; Ramana et al., 2009). In the region, sediment TN varied from 0.025-0.081 %. The sediment TN content was low on the shelf compared to the offshore. Sediment TP in the area ranged from 0.021 to 0.083 %. The distribution of heavy metals in the marine environment is complicated since geochemical and biogeochemical processes like sedimentation, precipitation, and flocculation regulate it. The distribution of trace metals spatially varied in the coastal and offshore regions (Table 1.17 and 18).

Table 1.17 Visual identification of sediment (colour, smell, and presence of fauna) in the Cauvery basin

Colour	Munsell notation	Smell	Texture	Presence of conspicuous fauna
Dark Grey	4/1	Nil	Sandy	Calcareous shells
Very dark grey	3/1	Nil	Sandy	Calcareous shells
Reddish Brown	5/3	Nil	Sandy	Calcareous shells
Brown	5/4	Nil	Sandy	Nil
Very Dark Grey	3/1	Nil	Sandy	Calcareous shells
Grey	6/1	H_2S	Sandy	Sea grass
Reddish brown	5/6	Nil	Sandy	Calcareous shells
Reddish grey	5/2	Nil	Sandy	Nil
Reddish brown	4/4	Nil	Sandy	Large Calcareous shells
Yellow	7/6	Nil	Sandy	Nil

Table 1.18 Shows sediment parameters in the Cauvery basin

Parameter	Minimum	Maximum	Average
PHC (μg/g)	0.19	0.82	0.60
TP (%)	0.021	0.083	0.05
OC (%)	0.35	3.59	1.34
TN (%)	0.025	0.081	0.04

d) Biological parameters

The phytoplankton are mainly classified as diatoms and dinoflagellates, and the benthic organisms are grouped as macro-benthos and meiobenthos (Table 1.18). Phytoplankton are microscopic plants living in the ocean surface layer, especially in the euphotic water column, and they are mainly composed of diatoms, dinoflagellates, and cyanobacteria. Usually, in marine environments, diatoms usually outnumber dinoflagellates, especially in nutrient-enriched waters, where the BOB basin has been considered a region of low biological productivity. However, high plankton production is evident along the coastline in the inshore waters, which is associated with river influx and several mesoscale coastal processes. In fact, this region shows more productivity than a general trend found in the Bay of Bengal as a whole. Surface water chlorophyll was found to have a maximum value of 3.12 µg/L, and the lowest was0.21 µg/L. Among zooplankton groups, Copepod dominated in the basin. Apart from Copepod, Gastropod larvae, Decapod larvae, Bivalve larvae, Fish egg, Lucifer and Appendicularia contribute more to the abundance, whereas the groups Cladocera, Fish larvae and siphonophores contribute least to the abundance. The macrobenthic biomass was the highest at 21.01 gm^{-2}. The average meiobenthic density is 1933.81 No. m^{-2}.

Table 1.18 Shows biological parameters in the Cauvery basin

Parameter	Minimum	Maximum	Average
Phytoplankton			
Chl a (µg/l)	0.21	3.12	1.36
Abundance (No/l)	379	2305	1298.3
Diatom abundance (No/l)	281	1589	906
Dinoflagellate abundance (No/l)	98	716	392
Zooplankton			
Biomass (ml/m^3)	0.23	1.5	0.69
Density (No/m^3)	838.75	5587.92	2156.75
Macro-benthos			
Sediment chlorophyll (µg/g)	0.34	3.61	1.21
Biomass (g/m^2)	1.0725	21.01	7.02
Density (no./m^2)	150	5700	1736.45
Meio-benthos			
Biomass (g/m^2)	0.002	0.045	0.0165
Density (no./m^2)	416	3376	1933.81

e) Experimental fishing in the Cauvery basin

The abundance and diversity of fish are good indicators of the biological productivity of a marine area. This would also help to understand how an altered marine environment could impact higher trophic-level organisms. Experimental fishing was conducted in <100m depth) using trawler in basin region. Details are shown below.

Experimental fishing in the Cauvery basin

Composition	Total Quantity (Kg)
Shrimp	12.2
Leognathid	6.9
Crab	7.2
Cat fish	5.9
Carangids	6.6
Flat fish	3.2
Cephalopods	4.9
Upenoids	4.4
Sciaenids	1.6
Seer fish	6.1
Elasmobranch	6.1
Clupeoid	4.7
Indian drift fish	3.7
Silver belly	5.9
Ribbon fish	2.7
Nemipterids	3.8
Priacanthid	0.7
Others	2.2

1.6 Chemical and biological characteristics of the Krishna Godavari basin

a) Water quality

The temperature range varied from 27.0 °C to 28.8°C with an average of 27.88 °C (Table 1.19). The temperature variation across the water column was insignificant and followed a normal pattern, indicating the absence of any significant stratification. Salinity is an important parameter that governs the spatial distribution of marine organisms. Normally, the salinity of seawater is about 35 PSU in the world's oceans. Seawater salinity values varied between 31.6 and 34.5 PSU, averaging 33.82 PSU. Identifying pH for acidic or alkaline disturbances may help locate pollution zones and other qualifying seawater conditions. pH ranged from 8.20 to 8.32, with an average of

8.27. There was no conspicuous variation in average pH values between the station and the surface and bottom. The higher pH might be due to the influence of seawater penetration, high biological activity, and the occurrence of high photosynthetic activity. The amount of oxygen dissolved in the water column at a given time balances consumption and replenishment. These two processes should be at equilibrium in an ideal ecosystem to keep the water column saturated with DO. DO levels below 2 mg/l will cause respiratory impacts on marine fauna. The DO concentration varied from 5.1 to 6.1 mg/l, averaging 5.59 mg/l. DO concentration in this coastal water was largely dependent on the freshwater influx. The rate of aerobic utilisation of oxygen is a useful tool to evaluate the intensity of deterioration in an aquatic medium. The oxygen taken up for the breakup of organic matter leads to a reducing environment, or in the event of a release of excess nutrients, it may cause eutrophication. The BOD values varied from 1.2 to 1.9 mg/l, averaging 1.48 mg/l. The low BOD values indicate that the oxidisable organic matter brought to the nearshore water is effectively assimilated in coastal waters. The range of variation in BOD values suggests that the water column is well-mixed. Turbidity is the measure to understand the suspended particulate matter, which controls the photosynthesis in the water column. The mean value was 5.95 NTU, which varied between 4.1 to 9.0 NTU. The bottom water showed higher turbidity than the surface, resulting in a turbulent condition in the coastal waters that favoured the resuspension of the bottom sediment due to stirring action that caused low water transparency. Total Suspended Solids (TSS): Total Suspended Solids in Seawater originate either from autochthonous (biological life) or allochthonous (derived from the terrestrial matter) sources. The TSS value varied from 14.0 to 34.0 mg/l, with an average was 22.31 mg/l.

Nutrients determine an ecosystem's potential fertility; hence, it is important to know their distribution and behaviour in different geographical locations and seasons. An area's fishery potential depends on the availability of primary nutrients like nitrogen and phosphorus. Enrichment of these nutrients by anthropogenic inputs in the coastal waters may result in eutrophication. Unpolluted waters are generally devoid of ammonia and nitrite. However, coastal input by sewage and other nitrogenous organic matter and fertilisers can increase these nutrients to higher levels. In addition, ammonia in seawater can also come from various organisms as an excretory product due to the metabolic activity and the decomposition of organic matter by microorganisms. The concentration of ammonia varied from 0.26 to 0.35 µmol/l with an average of 0.30 µmol/l. Nitrite (NO_2^-) is an important element in seawater as an intermediate compound in the microbial reduction of nitrate or ammonia oxidation. In addition, nitrite is excreted by phytoplankton, especially during a plankton bloom. The Nitrite concentration ranged from 0.03 to 0.31 µmol/l with an average of 0.21 µmol/l. There was no significant variation among the stations. Nitrate (NO_3^-) values are generally higher than nitrite values. Nitrate is the final oxidation product of nitrogen compounds in seawater and is considered to be the only thermodynamically stable oxidation level of nitrogen in seawater. Nitrate is the micronutrient that controls primary production in the euphotic surface layer. The nitrate concentration is governed by several factors, of which microbial oxidation of NH_3 and uptake by primary producers may be important. Nitrate concentration varied from 1.21 to 3.59 µmol/l with an average of 2.18 µmol/l. The total nitrogen concentration varied from 8.21 to 13.43 µmol/l with an average of 10.92 µmol/l. The station-wise average value significantly differed between the coastal and open seas waters. Inorganic Phosphate (PO_4^{3-}) is also an important nutrient, like nitrogen compounds, in the primary production of the sea. The concentration of Phosphate, especially in the coastal waters, is influenced by river runoff and anthropogenic activity. The phosphate concentration varied from 0.12 to 0.56 µmol/l with an average of 0.30 µmol/l. The mean value of total phosphorus was 1.28 µmol/l, ranging from 1.05 to 1.28 µmol/l.

Table 1.19 Water quality parameters in the KG basin

Parameter	Minimum	Maximum	Average
Water Temperature(°C)	27	28.8	27.88
Salinity(psu)	31.6	34.5	33.82
pH	8.20	8.32	8.27
Turbidity (NTU)	4.1	9	5.95
Total Suspended Solid((mg/l))	14	34	22.31
DO (mg/l)	5.1	6.1	5.59
BOD (mg/l)	1.2	1.9	1.48
NO_3^- (µmol/l)	1.21	3.59	2.18
PO_4^{3-} (µmol/l)	0	1.04	0.66
NO_2^- (µmol/l)	0.03	0.31	0.21
SiO_4^- (µmol/l)	3.36	15.96	9.08
PHC (µg/l)	0.3	0.58	0.08

b) Heavy metal concentrations

Coastal marine sediments are a major repository of trace metals and a major potential source of trace metals. Heavy metals are classified as the most persistent of the pollutants in sediments since they are relatively stable and cannot be degraded in natural conditions. Fine-grained sediments are often used as a good indicator of trace metal contamination due to their large adsorption capabilities for metals (Table 1.20).

Table 1.20 Heavy metal concentrations in the water and surface sediments of the KG basin

Element(ppm)	Water			Sediment		
	Minimum	Maximum	Average	Minimum	Maximum	Average
^{51}V	23.41	47.46	37.58	2.67	53.9	12.58
^{52}Cr	0.96	6.97	1.6	2.33	78.54	16.51
^{55}Mn	0.05	1.84	0.57	15.73	703.61	156.61
^{56}Fe	2.52	79.66	27.56	2336.58	28865.05	12518.32
^{59}Co	0.63	0.88	0.78	0.45	17.53	4.12
^{60}Ni	0.25	3.2	1.35	1.21	38.85	8.6
^{63}Cu	33.94	65.89	54.17	1.66	41.91	9.36
^{66}Zn	0.56	10.51	1.99	2.07	34.57	8.68
^{75}As	42.03	70.35	58.57	2.47	5.85	4.27
^{111}Cd	0	0.17	0.07	0	0.3	0.08
^{138}Ba	3.86	6.09	4.86	6.19	371.5	89.39
^{208}Pb	0	0.6	0.14	0.3	9.38	1.99

c) Sediment quality

The organic matter in sediments, expressed as total organic carbon (TOC) and total nitrogen (TN), represents an important reservoir for the global carbon cycle. It plays an important role in ocean chemistry (Table 1.21). Total Organic Carbon: Since most marine organic carbon comes from photosynthetic fixation of CO2 by phytoplankton, the excess of nutrients from human activities represents an issue for many water bodies. In eutrophic environments, the amount of organic matter deposited exceeds the assimilative capacity of the sediments. Total organic carbon content ranged from 0.14% to 0.59%, with a mean value of 0.33%. Total Nitrogen: TN plays an important role as a source of nutrients, decreasing with depth due to the remineralisation of organic matter and non-biological oxidation. Total nitrogen concentration varied from 117 to 284 µg/g with a mean value of 185 µg/g. Total Phosphorus: Sediments may play an important role in the regeneration of Phosphate. Much of the regeneration takes place in shallow environments (lakes, estuaries, and continental shelves). In the aquatic environment, dissolved Phosphate is consumed during the growth of phytoplankton and is regenerated during the bacterial decomposition of organic matter. Total phosphorus concentration ranged from 15.5 to 39.80 µg/g with a mean value of 23.86 µg/g. Calcium Carbonate (CC): Virtually all calcium carbonate deposits in the oceans are formed by organisms. In shallow and open ocean water, the calcareous organisms are primarily foraminifera, coccoliths, corals, molluscs, and algae. When the planktonic organisms die, their calcareous shells fall to the ocean bottom. The calcium carbonate content in the sediments varied from 6.9% to 11.0%, with a mean value of 8.54%.

Table 1.21 Shows sediment parameters in the KG basin

Parameter	Minimum	Maximum	Average
OC (%)	0.35	3.59	1.34
TN (%)	0.025	0.081	0.04
TP (µg/g)	15.5	39.80	23.86
CC (%)	6.9	11	8.54

d) Biological parameters

Phytoplankton are microscopic plants living in the ocean surface layer, especially in the euphotic water column, and they are mainly composed of diatoms, dinoflagellates, and cyanobacteria. Usually, in marine environments, diatoms outnumber dinoflagellates, especially in nutrient-enriched waters, where they contribute most of the chlorophyll-a concentration. Zooplankton are drifting small animals that can be microscopic or visible to the naked eye. They are considered the secondary producers in marine ecosystems and are formed of the most complex components comprising about 15 to 21 taxonomic groups. Usually, copepods contribute to a significant proportion of the zooplankton community in the marine environment by their high number and biomass to the total. Benthos are organisms living in or on the seafloor, which can be grouped into categories based on their body size: macrobenthos (>0.5mm) and meiobenthos (<0.5mm). Biomass in the present study was calculated based on the wet weight of the organism. Gastropods, bivalves, polychaetes, foraminifera, and crustaceans contributed to the macro-benthos community, whereas nematodes, smaller polychaetes, and foraminiferans contributed to the meiobenthos community. The disturbance in the bottom substratum due to natural and anthropogenic activities is usually reflected in the abundance, biomass, and diversity of benthos. Benthos are one of the most essential organisms in the continental shelf region, and they can be used as important indicators of water pollution, as they respond quickly to minor environmental changes. The distribution of benthic animals in marine ecosystems depends on the sediment quality, organic matter, and bottom dissolved oxygen concentration. A detailed summary of biological parameters in the KG basin is shown in Table 1.22

Table 1.22 Shows biological parameters in the KG basin

Parameter	Minimum	Maximum	Average
Phytoplankton			
Chl a (µg/L)	0.07	0.59	0.36
Abundance (No/L)	228	679	457
Diatom abundance (No/L)	145	514	332.5
Dinoflagellate abundance (No/L)	69	254	167
Zooplankton			
Biomass (ml/m^3)	0.13	1.18	0.65
Density (No/m^3)	23.06	4906.52	2464.79
Macro-benthos			
Sediment chlorophyll (µg/g)	0.21	0.97	0.61
Biomass (g/m^2)	0.09	1.48	0.78
Density (no./m^2)	50	1675	862.67
Meio-benthos			
Biomass (g/m^2)	0.008	0.089	0.0195
Density (no./m^2)	356	3486	1873.81

1.7 Chemical and biological characteristics of the Mahanadi-northeast basin

a) Water quality

The basin's chemical characteristics of coastal water ranged between pH: 7.8-8.06, temperature: 25.1 °C-31.6 °C and turbidity: 1-158 NTU (Table 1.23). The total suspended solids vary from 26-288 mg/l. Salinity values have been found to vary between 28.3 and 32.9 PSU. Dissolved oxygen available in water at any given time results from the amount consumed by aquatic organisms and replenishment through natural processes. Dissolved oxygen was found in the range of 2.5 to 4.9 mg/l. Biochemical oxygen demand (BOD) is widely used to determine the quantitative load of biochemically oxidisable organic matter and the degree of organic pollution. The BOD values were less than 10 mg/l. Nutrients determine the primary production potential of the waterbody, and therefore, it is important to know their distribution and behaviour in different geographical locations and seasons. Nitrogen and phosphorus compounds are major sources of nutrients for the growth of phytoplankton. Nitrate is an essential nutrient for the growth of many photosynthetic autotrophs and has been identified as a growth-limiting nutrient. Nitrate as NO_3^- levels in the region were found in the 0.38 to 0.42 mg/l range, and total Phosphates in the 0.4-0.6 mg/l range.

Table 1.23 Summary of marine water quality in the Mahanadi basin

Parameters	Units	Minimum	Maximum	Average
pH at 25ºC	--	7.8	8.06	7.9
Temperature	°C	25.1	31.6	27.5
Turbidity	NTU	1	159	25.6
Salinity	psu	28.3	32.9	29.9
Total Suspended Solids	mg/l	28	36	32
Silica as SiO_2	mg/l	33.8	34.5	34.06
Phosphate as PO_4^{3-}	mg/l	0.4	0.6	0.5
Nitrite (NO_2^-)	mg/l	0.38	0.42	0.40
Nitrate (NO_3^-)	mg/l	41.6	42.1	41.86
Calcium as Ca	mg/l	516	536	524
Sodium as Na	mg/l	7159.6	7477.5	7281
Potassium as K	mg/l	5.2	5.6	5.4
Dissolved Oxygen	mg/l	2.4	4.9	2.4
Chemical Oxygen Demand	mg/l	20	30	24.6
Biochemical Oxygen Demand (5 days @ 20ºC)	mg/l	7	10	8.3
Ammonia as NH_3-N		0.68	0.89	0.8
Phenol	mg/l	<0.001	<0.001	<0.001
Oil & Grease	mg/l	0.1	0.1	0.1
Total Plate Count	CFU/100ml	32	40	36
Feacal coliform	CFU/100ml	4	7	5.6

b) Heavy metals in seawater

Inorganic elements such as metals, even at trace levels, invite attention due to their persistence in waterbodies (Table 1.24). Some of the heavy metals, viz. arsenic, cadmium, chromium, copper and lead, are toxic at very low concentrations and can affect the prey and predator equilibrium in the water body. Heavy metals were found to be as Arsenic: 0.001-0.006 mg/l, Chromium: 0.008-0.021 mg/l, Iron: 0.422-3.486 mg/l, Molybdenum: 0.015-0.021 mg/l, Nickel: 0.001-0.009, Lead: 0.015-0.022 mg/l, Selenium: 0.001-0.003 mg/l and Vanadium: 1.272-1.428 mg/l;

Table 1.24 Heavy metal concentrations of seawater in the Mahanadi basin

Element(µg/L)	Concentration values		
	Minimum	**Maximum**	**Average**
As	0.001	0.006	0.003
Cr	0.008	0.021	0.014
Fe	0.422	3.486	1.95
Mo	0.015	0.21	0.11
Ni	0.001	0.009	0.005
Pb	0.015	0.022	0.018
Se	0.001	0.01	0.005
V	1.273	1.428	1.35

c) Biological parameters

Phytoplankton in the study area comprised of 41 genera belonging to the class Cyanophyceae, Chlorophyceae, Bacillariophyceae and Dinophyceae (Table 1.25). The density of phytoplankton varied from 1.17 X 104 No. L-1 to 2.53 X 105 No. L-1. Bacillariophyceae dominated the phytoplankton group in all the surface water almost three-fold, comprising 66.67-100 % of the total Phytoplankton class, followed by Cyanophyceae, Chlorophyceae, and Dinophyceae. Phytoplankton genera belonging to class Chlorophyceae and Dinophyceae were comparatively less, comprising 0.0-33.3% and 0.0-29.41% of the total Phytoplankton composition. Zooplankton species composition comprised 25 genera belonging to Class Granuloreticulosea, Oligotrichea, Hydrozoa, Scyphozoa, Polychaete, Hexanauplia, Malacostraca, Ostracoda, Sagittoidae, eggs and larvae, and zoea and Nauplius Eggs and larvae of chordates, polychaetes, arthropods; and initial developmental stages of decapod crustaceans in the form of zoea and Nauplius were also identified. The zooplankton density varied from 1120 to 12640 No. m-3 Hexanauplia (Copepoda) dominated the zooplankton class at all the sampling locations with a species composition of 36.84-85.71%. Zooplankton genera belonging to class Granuloreticulosea, Oligotrichea, Hydrozoa, Scyphozoa, Polychaete, Malacostraca, Ostracoda, and Sagittoidae were comparatively less; thereby, comprising of 0.0-4.35%, 0.0-5.06%, 0.0-4.35%, 0.0-13.04%, 0.0-10.34%, 0.0-3.8%, 0.0-1.92% and 0.0-12.82% of the total Zooplankton composition, respectively. Benthic organisms in the study area comprised fifty-three genera belonging to nineteen groups. Macrobenthos comprised of Coelenterata, Annelida, Decapoda, Macrura, Gastropoda, Pelecypoda and Cirripedia; while Protozoa, Aschelminthes, Nemertina, Polychaete, Rotifera, Copepoda, Cladocera, Amphipoda, Mysida, Ostracoda, Foraminifera and Trematoda constituted the meiobenthos. The density of macrobenthos varied from 47 No./ m3 to 2570 No./ m3.

Table 1.25 shows biological parameters in the Mahanadi basin

Parameter	Minimum	Maximum	Average
Phytoplankton			
Chl a (µg/L)	0.29	3.78	1.67
Abundance (No/L)	398	2513	1328.3
Diatom abundance (No/L)	296	1498	898
Dinoflagellate abundance (No/L)	91	705	378
Zooplankton			
Biomass (ml/m^3)	0.29	1.57	0.63
Density (No/m^3)	829.84	5592.87	2156.75
Macro-benthos			
Sediment chlorophyll (µg/g)	0.43	3.16	1.12
Biomass (g/m^2)	1.0527	21.1	7.2
Density (no./m^2)	105	5500	1637.54
Meio-benthos			
Biomass (g/m^2)	0.002	0.045	0.0165
Density (no./m^2)	416	3376	1933.81

d) Marine fisheries

The basin's proximity to the rich shrimp grounds in the northern Bay of Bengal as well as the existence of a broad continental shelf (in the north zone), is characterised by a high proportion of commercially important species like hilsa, pomfrets, shrimp, lobster, squids and cuttlefish. Among the finishes, croakers constituted 13.22%, followed by Mackerel (10.36%), Trichuridae (10.32%) and Clupeids (7.85%). Cephalopods, comprising Squids and cuttlefish, constituted 7.39% of the average annual landing; crabs and lobsters constituted 4.89% and 0.17%, respectively. Moreover, the fish catch also consists of Bombay duck, Silver Bar, Polynemids, Carangids, Mullets, Eels, Catfishes, and Flatfishes.

1.8 Chemical and biological characteristics of the Andaman basin

a) Water quality

The analysis helps to conclude that the pH of all the samples was found to vary between 7.12 and 7.30 (Table 1.26). It should be noted that the values obtained were within the desirable limit for pH as prescribed by CPCB. The total hardness was observed to range between 198 and 210 mg/l. The concentration of Total Dissolved Solids was estimated to range from 334 mg/l to 385 mg/l. The Chemical Oxygen Demand (COD) & Biochemical Oxygen Demand (BOD) values were calculated to be 11.3 mg/l to 16.6 mg/l & 5.2 mg/l to 6.5 mg/l, respectively. The variation of heavy metals in the sedimentary region of the Andaman Sea is listed in Table 1.27.

Table 1.26 The water quality of the Andaman basin

Parameters	Value		
	Minimum	Maximum	Average
pH Value	7.12	7.3	7.21
Temperature (°C)	24.6	24.8	24.7
Conductivity, (mhos/cm)	514	592	553
Turbidity (NTU)	<1	<1	<1
Total Dissolved Solids (mg/l)	334	385	359.5
Total Suspended Solids (mg/l)	<2	<2	
Total Hardness	198	210	204
Chloride as Cl (mg/l)	44	52	48
Total Alkalinity (mg/l)	180	238	209
Sulphates as SO_4 (mg/l)	18	22	20
Nitrates as NO_3^- (mg/l)	0.88	0.98	0.93
Fluoride as F (mg/l)	0.56	0.62	0.59
Iron as Fe (mg/l)	0.62	0.84	0.73
Zinc as Zn (mg/l)	<0.01	<0.01	<0.01
Calcium as Ca (mg/l)	67.2	72.8	70
Magnesium as Mg (mg/l)	7.3	6.8	7.05
Sodium as Na (mg/l)	11	13	12
Potassium as K (mg/l)	2.3	3.2	2.75
Cadmium as Cd (mg/l)	<0.01	<0.01	<0.01
Copper as Cu (mg/l)	<0.01	<0.01	<0.01
Nickel as Ni (mg/l)	<0.01	<0.01	<0.01
Lead as Pb (mg/l)	0.025	0.046	0.0355
Mercury as Hg (mg/l)	<0.001	<0.001	<0.001
Chromium (Total as Cr) (mg/l)	<0.05	<0.05	<0.05
Arsenic as As (mg/l)	<0.01	<0.01	<0.01
Phenolic compound (mg/l)	<0.001	<0.001	<0.001

Table 1.27 Heavy metal concentration in sediments

Element(µg/g)	Concentration values		
	Minimum	Maximum	Average
Sediment			
Cd	0.29	2.1	1.19
Cu	0.55	3.71	2.13
Pb	0.6	5.47	3.03
Hg	0.23	0.96	0.59
Zn	0.37	1.12	0.74

b) Biological parameters

The phytoplankton species recorded belonged to families Asterolampraceae, Bacillariaceae, Biddulphieae, Ceratiaceae, Chaetocereae, Coscinodisceae, Cyanophyceae, Fragilaroideae, Hemiaulineae, Naviculoideae, Oxytoxaceae, Peridiniaceae, Prorocentriaceae and Soleniae. A total of 105 species were recorded from seven different stations. The phytoplankton density (Nos./l) recorded during the period of study ranged from 613.64 to 19825.24 Nos./l. A total of 96 species of zooplankton belonging to 19 groups and 74 genera were recorded. Copepods were the dominant group, and their composition of occurrence ranged from 30.39% to 44.30%. Foraminiferans were the subdominant group in the region. Their composition varied from 6.90% to 14.70%; besides that, chaetognaths, Appendicularians, Crustacean larvae and Molluscs occurred in considerable composition at quite a number of stations. The number of species recorded for individual groups ranged from 1 to 37 (Table 1.28).

Table 1.28 shows biological parameters in the Andaman basin

Parameter	Minimum	Maximum	Average
Phytoplankton Density (Nos./l)	613.64	19825.24	4251.766
Zooplankton			
Fresh weight(mg/100m^3)	2540	4580	3364.286
Dry weight (mg/100m^3)	718	1240	956.1429
Volume (ml/100m^3)	4.7	12.7	9.028571
Numerical density (No/100m^3)	17300	31620	26321.43
Groups			
Amphipods	1.32	1.71	1.4725
Annelid larvae	1.37	4.7	3.392
Appendicularians	3.92	10.27	6.977143
Chaetognaths	5.13	11.76	7.818571
Cladocerans	1.96	5.23	3.39
Copepods	30.39	44.3	37.75143
Crustacean larvae	4.79	12.5	7.735714
Doliolids	1.31	2.14	1.803333
Echinoderm larvae	1.71	3.36	2.5325
Foraminiferans	6.90	14.7	11.18714
Isopods	2.61	2.61	2.61
Leptomedusae	1.34	3.43	1.898
Molluscs	2.61	7.69	5.122857

c) Biological environment

The Andaman and Nicobar Islands are very rich in biodiversity, harbouring unique endemic life forms. The islands have both rich terrestrial and marine ecosystems, such as mangroves, coral reefs, and seagrass beds. The marine biodiversity includes marine mammals such as whales, dolphins, and dugongs; marine turtles; estuarine or saltwater crocodiles; fishes; prawns and lobsters; corals; seashells, including rare and endangered Trochus species and Giant Clam Shells and numerous other marine life forms, including coelenterates and echinoderms etc. The sandy beaches on some islands provide nesting places for four species of marine turtles. The nearshore waters are rich in finfish, shellfish and other economically important species such as seashells, sea cucumbers, crabs, lobsters, etc. At the same time, the seas around these islands are also rich in pelagic fish such as tunas, Indian mackerel, seer fish, and sharks (Table 1.29).

Table 1.29 Marine biodiversity and endemism

Animal group	No. of species/ sub	No. of endemics	Percentage of endemism
Mammalia (mammals)	7	–	–
Reptilia (reptiles)	12	–	–
Pisces (fishes)	1,200	2	0.2
Echinodermata (star fishes, etc.)	350	4	0.4
Mollusca (squids, octopus, etc.)	1,000	18	1.9
Crustacea (crabs, lobsters etc.)	600	6	1.0
Polychaeta (marine worms)	184	4	2.2
Anthozoa (sea anemones and corals)	326	2	0.6
Porifera (sea sponges)	72	–	–
Meiofauna (small invertebrate sea creatures)	490	102	21.0
TOTAL	4,241	138	0.11

Source: State Action Plan on Climate Change Andaman and Nicobar Islands (2013)

d) Coral reefs and marine biodiversity

Andaman & Nicobar islands are fringed with one of the world's most spectacular and extensive reefs. Andaman reefs comprise about 83% of coral diversity found anywhere in the world and are at par with the "Coral Triangle" of Indonesia. ANI has the last pristine reefs in the Indian Ocean region and is one of the world's most important coral reef sites. Coral reefs are intimately connected to other marine communities, such as mangrove forests, seagrass beds, and the open seas, as water currents transport larvae, plants, animals, nutrients, and organic materials. They play a significant role in the development of other ecosystems, such as mangroves and wetlands and protect coastlines from wave and storm damage and erosion. Life-saving medicines, such as anticoagulants and anticancer agents, such as prostaglandins, come from coral reefs. Around 180 species of corals have been recorded. At least two species appear to be endemic to Andaman waters. They are Deltocyathus andamanicus (Alcock) and Polycyathus andamanensis (Alcock), both belonging to the family Caryophyllifae. Two more species, namely, Pocillopora ankeli (Scheer and Pillai) and Pavona xarifae (Scheer and Pillai) have been described as new species from Nicobar waters. The highest number of coral species has been recorded from the Andaman and Nicobar coral reefs compared to reefs occurring along the Indian mainland coast.

e) Marine fishery

More than 1150 fish species under 507 genera of 151 families have been recorded from the sea around Andaman and Nicobar Island. These species occur in freshwater, brackish water, coastal waters and offshore. The interesting groups are, chimaerids (Chimaeridae), pelagic sharks (Carchaehinidae), deep sea sharks (Squalidae), skates (Rhinobatidae) sting rays (Rajidae), herrings, moray eels (Muraenidae), sardines (Clupeidae), Milkfish, catfish, (Ariidae), lizard fish (Synodontidae), flying fish (Exocoetidae), halfbeaks (Hemirhamphidae), alligator gar (Belo-nidae) , soldier fish (Holocentridae), pipefish (Syngnathidae), groupers (Serranidae), grunters (Teraponidae), flag tails (Kuhlidae),Bulls eye (Priacanthidae), cardinal fishes (Apogonidae), whitings (Sillaginidae), sucker fish (Echeneididae), travellys (Carangidae), silver belly (Leiognathidae), snappers (Lutjanidae), fusiliers (Caesionidae), silver biddys (Gerridae), grunters (Haemulidae), sweetlips (Haemulidae), breams (Sparidae, Lethrindae), threadfins (Nemipterdae), jaw fish (Sciaendae), goat fish (Mullidae), bat fish (Ephippididae), butterfly fish (Chaetodontidae), angel fish (Pomacanthide), Tilapia (Cichlidae), demoiselles (Pomacentridae), anemone fish (Pomacentridae), mullets (Mugilidae), barracuda (Sphyraenidae), tassel fish (Polynemidae), wrasses (Labridae), Parrot fishes

(Scaridae), blennids (Blennidae), dragonets (Callionymides), gudgeons (Eleotrididae), gudgeons (Eleotrididae), goby (Gobidae), sword fish (Istiophoridae), mackerel (Scombridae), tunas (Scombi-dae), flounders (Pleuro-nectidae), soles (Cynoglassidae, sollidae), file fish (Balitidae), tiger fish (Balistidae), Box fish (Ostra-cidae), Blow fish (Tetrodontidae), and porcupine fishes (Diodontidae). Sharks, sardines, mackerels, travellys, catfish, mullets, ribbon fish, barracudas, groupers, snappers, seer fish and tunas are from important fish groups in the commercial fishery.

****