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Sri Lanka Marine Climate Change Evidence Report and Risk Assessment

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Executive Summary

This Marine Climate Change Evidence Report summarises climate change impacts on the coastal and marine environment of Sri Lanka, both currently and into the future, and includes a high-level overview of Sri Lanka's climate change-relevant plans, policies and actions. The findings were developed from a comprehensive literature review and validated at a stakeholder workshop in August 2024 in Colombo, regarding climate change impacts on the coastal and marine environment of Sri Lanka, both currently and into the future. The report also includes a high-level overview of Sri Lanka's climate change-relevant plans, policies and actions. The evidence review comprised information from both quantitative and qualitative information sources, and at a variety of spatial scales. This report organises the information collected, structured to describe the current and future projected changes in key climate variables in Sri Lanka, followed by observed impacts and predicted future risks to biodiversity and to human systems. Finally, a register of key marine climate change risks for Sri Lanka was extracted and scored in terms of confidence and severity.

Key findings of risks to marine and coastal species and habitats include decreasing plankton productivity levels; threats to breeding sea turtle populations; changes to fish assemblages; increasing threat of severe bleaching to coral reefs; changes in extent and species composition of mangroves and seagrass meadows; changes to sandy shorelines; and increasing risk of invasion by marine non-native species. Risks to societal and economic sectors include declining fisheries; damage and disruption to critical coastal infrastructure and services; threats to tourism notably eco-tourism; impact on seagrass habitats and fishery catch potentials; and loss of natural protective coastal habitats. These risks are summarised and tabulated, linking to the main climate drivers associated with them, and discussed in detail. Finally, key knowledge gaps and evidence needs are extracted.

This report is the first comprehensive review of climate change impacts on the marine and coastal environment of Sri Lanka. It complements other important climate plans and actions that are already underway in Sri Lanka, and it can help highlight and prioritise climate risks and guide future research and monitoring to inform and support climate change policy, action and preparedness in Sri Lanka.

1. Introduction

This report summarises the findings from a comprehensive literature review regarding evidence of climate change impacts in Sri Lanka's coastal and marine environments, both past observed, as well as predicted into the future.

The report structure includes general contextual sections about Sri Lanka, details about the climate risk assessment method, followed by a summary of the results of the evidence review. These findings are organised starting with trends in key physical and chemical marine climate variables, followed by detailed sections focussing on impacts to biodiversity as well as impacts on societal and economic sectors linked to marine ecosystem services. At the end of the results, we present a risk register, that links to the main climate drivers. The discussions examine those key findings in more detail, to finish with remarks and recommendations on key knowledge gaps and evidence needs.

1.1. Sri Lanka – climate change policy context

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty that came into force on 19 March 1994. It was one of the key outcomes of the 1992 Rio Earth Summit. The aim is to stabilise global levels of greenhouse gases that may cause deleterious anthropogenic changes to the Earth's climate systems. At subsequent meetings, since 1995, parties to the Convention have strengthened its provisions. In 1997, the Kyoto Protocol was agreed, setting legally binding emission reduction targets for greenhouse gases for signatory countries over the period 2008–2012. The 2010 conference in Cancún agreed that a limit of no greater than a 2-degrees Celsius rise in the Earth's global average temperature above pre-industrial levels should be the aim of signatories to the Convention, while aiming to limit the rise to 1.5 degrees Celsius to avoid the most more severe climate change effects on people, wildlife and ecosystems. The Paris Agreement came into force on 4 November 2016 and Article 2 crystallized the well below 2-degree Celsius goal and encouraged global pursuit of 1.5 degree Celsius from 2020 onwards.

Sri Lanka is a signatory party to the UNFCCC Paris Agreement on Climate Change and submitted its initial Nationally Determined Contribution (NDC) in 2016, followed by an updated NDC in 2021 (MoE, 2021). NDCs are established and submitted by signatories to the Paris Agreement every five years, and these set out their targets, policies and measures to curb national emissions and adapt to climate change impacts.

Sri Lanka's updated NDC represents a more ambitious, quantified, and robust assessment of the mitigation potential and adaptation measures for the next decade

(2021-2030) and was informed by up-to-date analysis, improved information and data, and an extensive stakeholder consultation process (MoE, 2021). It includes new evidence on Sri Lanka's climate vulnerability and highlights the country's overall ambition to achieve carbon neutrality by 2050 (MoE, 2021).

Sri Lanka's per capita greenhouse gas emission in 2010 was 1.02 tonnes and its global cumulative contribution in 2019 was 0.03%. However, while its carbon footprint is relatively small, Sri Lanka is highly vulnerable to the adverse impacts of climate change. The country is focusing on building resilience of key sectors, including fisheries, biodiversity, coastal and marine and tourism. It has committed to increasing forest cover by 32% by 2030, which also includes coastal mangrove areas, and reducing greenhouse gas emissions by 14.5% for the period of 2021–2030 across power, agriculture and other industry sectors. Other ambitions in Sri Lanka's NDCs include achieving 70% renewable energy in electricity generation by 2030 and reaching carbon neutrality by 2050 in electricity generation with no addition of coal power plants (MoE, 2021). Sri Lanka has already launched major sustainability initiatives focusing on management of waste and waste by-products, fertilisers, single-use plastics and circular economy, among others (MoE, 2021).

Sri Lanka's NDC also includes a strong marine and coastal focus (MoE, 2021). As an island nation with a third of its population concentrated on or near the low-lying coast belt, Sri Lanka is exposed to the risks of submergence, coastal flooding, saltwater intrusion and erosion, driven by sea level rise and ocean warming. In addition, changing precipitation patterns and altering hydrological systems are affecting water resources, extreme and unpredictable weather events are causing extensive damage and human fatalities, and marine species are perceived as shifting their distribution ranges and seasonal migration/reproductive patterns. However, there is also a recognition in the NDC that to implement effective decarbonisation, and climate adaptation and resilience measures, more evidence is needed (MoE, 2021). In that regard, there are plans to establish an accurate sea level rise forecasting system, expand the network of tide gauge stations, and re-establish the required database with historical data and a sustained long-term data collection programme, including monitoring of ocean waves and marine sediment transport. The government of Sri Lanka also recognise a need for updating the country's prediction and forecasting capabilities, high-resolution and accurate coastal inundation risk maps and forecasts being a high priority. As part of a package of measures to enhance coastal resilience, Sri Lanka has committed to improve nature-based coastal protection of sensitive areas through the restoration, conservation and management of coral reefs, seagrass, mangroves and sand dunes, overall establishing 1000 hectares of forests and green belt along the coastline. The aim is to complete a detailed habitat map including a Digital Elevation Model (DEM) of the entire coastal region, down to 2 km landward, which should highlight suitable sites for conservation, rehabilitation and restoration and help prioritise pilot projects at vulnerable sites.

To address climate change-induced impacts, Sri Lanka has taken steps by introducing national policies, strategies and actions, such as:

- National Climate Change Adaptation Strategy for Sri Lanka in 2010.
- Nationally Appropriate Mitigation Actions (NAMA) for energy, and Climate Change Sector Vulnerability Profiles in 2010.
- National Climate Change Policy of Sri Lanka in 2012.
- Technology Needs Assessment and Technology Action Plans for Climate Change Adaptation and Mitigation in 2014.
- National Adaptation Plan (NAP) for climate change impacts in Sri Lanka in 2016.
- National REDD+ Investment Framework and Action Plan (NRIFAP) in 2017.
- Coastal Zone and Coastal Resource Management Plan in 2018.

These are helping inform mitigation measures, including low emission developments. Meanwhile, the government is also addressing climate vulnerability and weather-related hazards and impacts in the form of investments to prevent or limit coastal erosion, water scarcity and floods and landslides, such as resettlement of communities living in landslide and flood-prone areas, and inclusion of climate exposure/vulnerability factors in public infrastructure. However, the introduction of large-scale climate mitigation and adaptation measures in Sri Lanka can be a financial and technological challenge.

1.2. Sri Lanka – geographical context

Sri Lanka is an island nation in the Indian Ocean, southeast of the Indian subcontinent. The nation has a total area of 65,610 km^2, and a 1,340 km-long coastline, making it the twenty-fifth largest island in the world. Dozens of offshore islands account for the remaining 342 km^2 area, the largest of which is Mannar Island (130 km^2). As of 2021, Sri Lanka has a population of approximately 22,156,000 people and the annual population growth rate was 0.53% between 2020 and 2021 (DCS, 2024). Population density is highest in western Sri Lanka, and in and around the capital, Colombo.

Most of the island consists of plains 30–200 m above sea level. In the southwest, ridges and valleys rise gradually to merge with the Central Highlands, giving a dissected appearance to the plain (Figure 1). The transition from the plain to the Central Highlands is especially abrupt in the southeast. The rugged Central Highlands includes Sri Lanka's highest mountains, with Pidurutalagala as the highest point at 2,524 m.

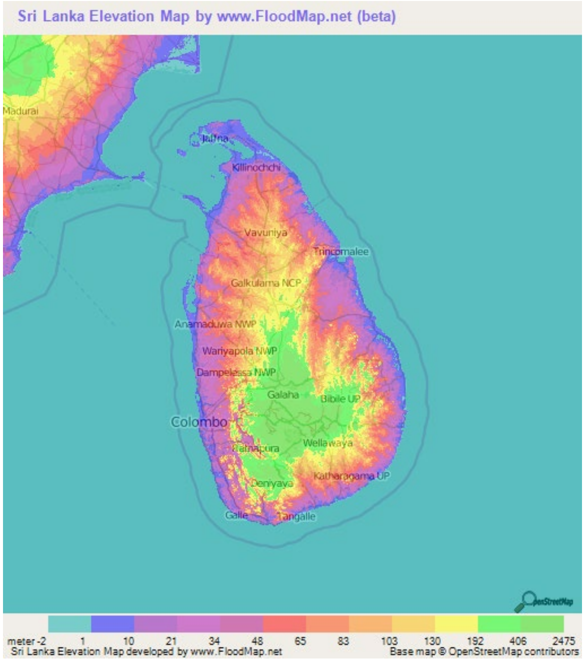

Figure 1. Elevation map of Sri Lanka, scale represents metres above sea level. From FloodMap.net.

Sri Lanka possesses a territorial sea of 21,500 km^2 and an Exclusive Economic Zone (EEZ) out to 200 nautical miles (370 km) from the coast of 517,000 km^2, i.e. roughly six times the total land area (Figure 2). The topography of the seafloor around Sri Lanka is characterised by a narrow coastal shelf and steep continental slope around most of the island (the east, south and west) with depths increasing rapidly to more than 2000 m, while it is shallower in the north, where Sri Lanka nears the mainland portion of the Indian subcontinent through the Gulf of Mannar and Palk Strait. Water depth in Palk Bay, the semi-enclosed shallow area between Sri Lanka and the southeast coast of India, is only 13 m.

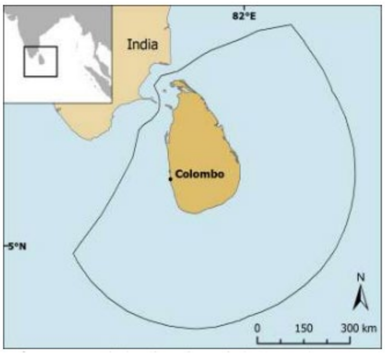

Figure 2. Map of Sri Lanka’s Exclusive Economic Zone. From O’Meara et al. (2011).

Inshore waters support highly productive marine ecosystems such as fringing coral reefs and shallow beds of coastal and estuarine seagrasses. Sri Lanka has 45 estuaries and 40 lagoons. Sri Lanka's mangrove ecosystem spans over 7,000 hectares, these coastal forests played a vital role in buffering the force of destructive waves in the 2004 Indian Ocean tsunami.

According to the International Monetary Fund, Sri Lanka's GDP (total ~ $318.6 billion; $14,234 per capita) in terms of purchasing power parity is the second highest in the South Asian region in terms of per capita income. The country's main economic sectors are tourism, tea export, clothing, rice production, and other agricultural products. As of 2020, the service sector made up 59.7% of GDP, the industrial sector 26.2%, and the agriculture sector 8.4%. Approximately 32% of the population live in the coastal zone. At the same time about 65% of the urbanized land area is located near the coast. The main rail transportation and other important infrastructure is also located in this area. 65% of industrial output, 80% of tourism related infrastructure are also located in the coastal zone. Four commercial ports and 22 fisheries harbours are located around Sri Lanka's coasts.

Sri Lanka has two main seasons, the Maha season associated with the northeast monsoon (September-March) and the Yala season associated with the southwest monsoon (May-August). With an average temperature of around 27–28°C, Sri Lanka is one of the hottest countries in the world. Sri Lanka’s commercial capital, Colombo, experiences average temperatures of 28–29°C and, like much of the rest of the country, has little monthly variation in temperature. Daily maximum temperatures average around 31°C all year round. The most important factor affecting temperature variations within Sri Lanka is altitude, with considerably lower temperatures experienced in its south-central mountain ranges. Sri Lanka’s precipitation regime is divided into wet, intermediate and dry zones. The wet zone in the southwest, receives a mean annual rainfall of over 2,500 mm, with a strong contribution from the southwest monsoon. The dry zones, in the south and northwest, receive less than 1,750 mm. The intermediate zones, in the eastern and central regions, receive between 1,750 mm and 2,500 mm, primarily from the northeast monsoon. Areas of the southwest slopes of the central hills are known to experience as much as 5,000 mm in a year and annual rainfall can vary by more than 1,000–2,000 mm over distances of less than 100 km. All regions receive steady rainfall during the inter-monsoon seasons.

Sri Lanka’s high temperatures, unique and complex hydrological regime, and exposure to extreme climate events make it highly vulnerable to climate change. In 2012, the Ministry of Environment submitted the Second National Communication to the UNFCCC highlighting key vulnerabilities in the agriculture and water resources sectors, as well as significant risks to human health and in coastal zones. These key climate-related risks were again emphasized in Sri Lanka’s NDC submitted after it signed and ratified the Paris Climate Agreement in 2016. Sri Lanka’s NDC outlines the country’s commitment to addressing its vulnerability to climate change in line with its commitments to a low carbon pathway through sustainable development efforts. At the time of writing this report, Sri Lanka’s NDC was under review (World Bank, 2021).

Estimates suggest that climate-change impacts could result in a loss of 2% of the GDP of South Asian countries by 2050 and 9% by 2100 (Ahmed and Suphachalasai, 2014). These impacts will be felt in major vulnerable sectors, including agriculture, water, coastal, marine, health and energy, and will have significant impact on the economic growth and poverty reduction in the region. Countries could differ widely in terms of the economic costs they face. In South Asia, the economic costs for Sri Lanka are projected as 6.6% of its GDP (IPCC, 2021).

1.3. Purpose and scope of this report

This report is the first comprehensive review of climate change impacts on the marine and coastal environment of Sri Lanka. It complements other important climate plans and actions that are already underway in Sri Lanka and aims to help the country towards building a more resilient and sustainable future.

2. Methodology

This report was compiled from sources including, but not limited to, peer review scientific journals, technical reports, book chapters, monitoring datasets, IPCC model outputs, and public media communications. In reviewing the evidence, the authors made use of quantitative and qualitative information at a variety of spatial scales, from local studies through to global-scale analyses.

The risk assessment methodology used in the present analysis follows that of the first United Kingdom Climate Change Risk Assessment in 2012 (Baglee et al., 2012), which has subsequently been applied in a number of other risk assessments of marine climate change impacts in other parts of the world (e.g. Maltby et al., 2022). The assessment comprises four key steps as per Maltby et al. (2022): 1) determining key climate drivers, 2) identifying climate risks, 3) scoring individual risks and 4) ranking and prioritising risks (Figure 3).

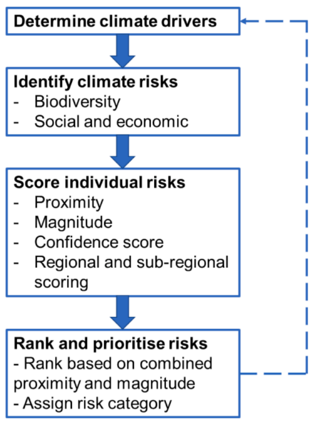

Figure 3. Simplified risk assessment framework, informed by the 2012 UK CCRA, used to identify and prioritise marine climate change risks in Sri Lanka. The dashed line represents the fact that this risk assessment can be updated as and when new evidence or risks emerge. From Maltby et al. (2022).

For this assessment the definition of 'risk' given by United Nations Intergovernmental Panel on Climate Change (IPCC) was used, whereby risk is '*the potential for adverse consequences to lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure and where the outcome is uncertain*', or in other words, risk is '*the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur*' (Oppenheimer et al., 2014).

Steps 3 and 4 of the process, involving the scoring, ranking and prioritising of risks as outlined in Figure 3, were undertaken during a two-day workshop held in Colombo, Sri Lanka between 6–8th August 2024. Technical experts from across the country were invited to each of the two day-sessions according to the relevance of their work and expertise. A list of the organisations and number of participants attending each of the workshop sessions is shown in Table 1 below.

Table 1. List of the organisations and number of participants attending each of the climate change risk assessment workshop sessions, held in Colombo, Sri Lanka between 6–8th August 2024.

Workshop Day 1 (Biodiversity Session)	Number of participants
Blue Resources Trust	2
Central Environmental Authority (CEA)	3
Department for Fisheries and Aquatic Resources (DFAR)	1
Dilmah Conservation	1
Disaster Management Centre	1
University of Sri Jayewardenepura	2
Janathakshan Guarantee Limited	2
Lanka Environment Fund	2
Ministry of Fisheries	2
National Aquaculture Development Authority (NAQDA)	1
Oceanswell	3
South Asia Co-operative Environment Programme (SACEP)	1
Sri Lanka Wildlife Conservation Society	2
The Pearl Protectors	2
Uva Wellassa University	2
Wildlife and Nature Protection Society (WNPS) and Horizon Campus (HC)	1
Wayamba University	1
Workshop Day 2 (Societal and economic sectors Session)	**Number of participants**
Central Environmental Authority (CEA)	2
Disaster Management Centre	1
University of Sri Jayewardenepura	3
UK Foreign, Commonwealth and Development Office (FCDO)	1
Janathakshan Guarantee Limited	1
Lanka Environment Fund	1
Marine Environment Protection Authority	1
Ministry of Fisheries	2
Ministry of Ports Shipping and Aviation	1
National Aquaculture Development Authority (NAQDA)	1
National Aquatic Resources Research & Development Agency (NARA)	1
Oceanswell	2
The Pearl Protectors	3
Uva Wellassa University	1
Wildlife and Nature Protection Society (WNPS) and Horizon Campus (HC).	2

The gender participation at the Marine Climate Risk Assessment Workshop consisted of 57% male and 43% female representatives on Day 1, and 40% male and 60% female representatives on Day 2 (Figure 4).

Figure 4. Participants at the OCPP Marine Climate Risk Assessment Workshop held in Colombo, Sri Lanka, between 6 and 8th August 2024.

2.1. Data sources

The types of evidence can be categorised based on the geographical scale, from site-specific monitoring and local research to regional overviews and global studies (Table 2). Through this report we indicate the types of evidence sources found that support each section.

Table 2. Categories of the geographical scale of sources information used in this report.

Data Type	Description	Example
SITE-SPECIFIC STUDIES	Time-series of site-specific data collected for monitoring status and trends of ecosystem components	Outputs from tide gauges and weather stations.
LOCAL STUDIES	Research studies and surveys conducted within Sri Lanka that provide information and understanding on the impact of climate change on ecosystem components	Local-scale studies of coral bleaching and climate change impacts
REGIONAL STUDIES	Monitoring or research studies that do not come from Sri Lanka specifically but from the wider Indian Ocean region	Regional modelling studies on observed and projected trends in temperature, salinity and sea-level
GLOBAL STUDIES	Studies conducted Internationally that identify trends that can be used to broadly evaluate changes in Sri Lanka	IPCC assessments based on global climate models.

Systematic monitoring and local studies provide the most accurate characterisation of baseline conditions and trends, but often this level of detail was not available for Sri Lanka.

2.2. Confidence

To aid decision making, risks are marked according to the degree of confidence and uncertainty surrounding the supporting information. Confidence ratings reflect the level of agreement among researchers and across evidence sources, as well as the level of evidence about the impacts associated with each risk. The confidence scoring levels used are represented in Figure 5 and are based on the 9-cell grid scheme used by the IPCC (Mastrandrea et al., 2011).

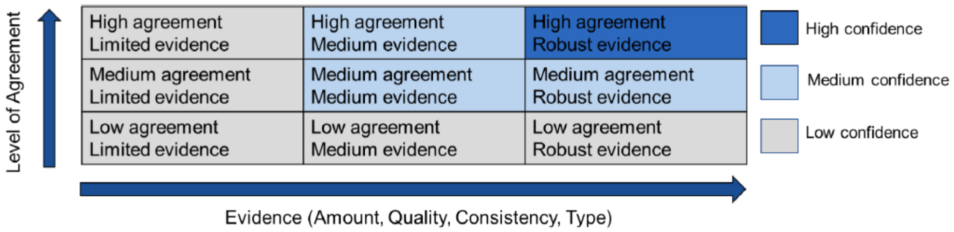

Figure 5. IPCC matrix used for qualitative scoring of confidence associated with each risk. Adapted from Mastrandrea et al., (2011).

Each risk was assigned a confidence level in advance, and this was the reviewed during the risk assessment workshops, where experts were given the opportunity to discuss whether they agreed or disagreed, upon which some confidence levels were refined.

2.3. Proximity

In the context of a climate risk assessment, proximity indicates the time horizon after which substantial impacts are anticipated to be felt.

Table 3. Numerical scoring of categories of risk proximity or urgency.

Proximity categories	Score
Now	4
Within next 20 year	3
Within next 50 years	2
Over 50 years	1

Risks that are thought to be already occurring at present were given a ‘4’ whereas risks that are anticipated to manifest themselves in the more distant future were assigned a ‘1’, with ‘2’ and ‘3’ representing the time slices in between, as outlined in Table 3.

2.4. Magnitude

Magnitude represents the perceived significance and consequences of a particular risk happening, based on an assessment of combined environmental, economic and social impacts. Each risk was scored in terms of anticipated magnitude or severity, considering economic, environmental and social concerns. Risks were considered HIGH magnitude if many billions of Rupees of economic losses were anticipated in the future or a significant impact on the national economy. Similarly, HIGH magnitude was associated with 1000s of human lives or livelihoods being impacted and/or large-scale environmental damage with a high proportion of ecosystems being affected throughout the country. By contrast, LOW magnitude risks were characterised by small-scale localised economic, environmental and social impacts, with little impact on the national economy. Table 4 below explains in more detail how the magnitude or severity of a given risk is assessed and scored, according to the likely impact.

Table 4. Semiquantitative scoring of categories of risk magnitude or severity. The guidance for scoring the likely impacts on economy, environment and society is adapted from the first United Kingdom Climate Change Risk Assessment (CCRA, 2012). HIGH magnitude risks were scored as 3, MEDIUM = 2 and LOW = 1.

Score	Magnitude of economic impacts	Magnitude of environmental impacts	Magnitude of social impacts
HIGH (3)	Major impact/damage to property, infrastructure, transport links, economies and loss/gains of employment opportunities Significant impact on national economy	Major loss or decline in species/habitat/ecosystems Widespread decline in air/water/land quality Significant area of impact	Potential for many fatalities or serious harm Loss or major disruption to utilities (water/gas/electricity/desalination) Major damage or loss of cultural assets/community impact ~1000s affected, ~100s harmed, ~10s fatalities
MEDIUM (2)	Moderate impact/damage to property, infrastructure, transport links, economies and loss/gain of employment opportunities Detectable impact on economy	Important/medium-term consequences on species/habitat/ecosystem Regional decline in land/water/air quality Moderate area of impact	Significant numbers affected Minor disruption to utilities (water/gas/electricity/desalination) Increasing inequality, e.g. through rising costs of service provision ~100s affected, ~10s harmed, few fatalities
LOW (1)	Minor or localised impact No consequence on regional and territory-wide economy Localised disruption of transport Minor or regional financial impact	Short-term and reversible effects on species/habitat/ecosystem services Localised decline in land/water/air quality Sporadic or transitory areas of impact with some recoverability	Small numbers affected with small reduction in community services Within “coping range” ~10s affected

2.5. Overall risk

The magnitude and proximity scores were combined using the following formula to obtain an overall risk score:

$$100 \times \left(\frac{Magnitude}{3}\right)\left(\frac{Proximity}{4}\right)$$

This calculation means that the lowest possible score is 8.3 and highest possible score 100. Scores above a set threshold were be considered HIGH PRIORITY. The initial threshold for overall risk scores was set to 60 and above. This was revised to 75 and above during the workshop scoring evaluation reflecting the highly scored risks.

The collation of published evidence and the extraction of risks were the initial steps in the process of a systematic climate change risk assessment, followed by a validation exercise with input from stakeholders and experts from Sri Lanka, during a participative workshop. During this workshop the risks were refined and rationalised, the confidence in the evidence assessed, the primary climate drivers associated with each risk are identified, and an overall score is calculated for each risk based on its potential proximity and magnitude.

The end point of the assessment process is a final, prioritised list of climate change risks to the coastal and marine environment in Sri Lanka.

3. Results

3.1. Observed and projected trends in climate variables

Several key sources are available when considering trends in climate variables for Sri Lanka. These include observations from meteorological stations and tide gauges around the island, but also previous collations of climatic datasets and projections, most notably:

1. Climate Risk Country Profile: Sri Lanka (World Bank Group, 2021)
2. Climate Risk Profile – Sri Lanka (USAID, 2018)
3. IPCC Sixth Assessment Report (AR6) (IPCC, 2021)
4. Indian Ocean warming (Roxy et al., 2021)
5. NOAA's Climate Change Web Portal CMIP6, Ocean and Marine Ecosystems (NOAA, 2024)
6. Sea level projections for South Asia (Harrison, 2020)

The following sections summarise current observed and projected future trends of key climate variables including air and sea temperature, ocean circulation and currents, salinity, sea level rise, ocean acidification and pH, seawater dissolved oxygen, extreme weather events, and rainfall and changes in monsoon patterns. Each climate variable is tagged to indicate geographical coverage, level of agreement and confidence rating of the available evidence.

3.1.1. Air and sea temperature

Data sources	Levels of evidence and agreement	Confidence rating
SITE-SPECIFIC STUDIES, LOCAL STUDIES, REGIONAL STUDIES, GLOBAL STUDIES	HIGH agreement MEDIUM evidence	MEDIUM

Current climate impacts

Seasonal and annual surface air temperatures in locations across South Asia reveals a significant warming trend of 0.78°C per century (Lal, 2003). Temperature rise has accelerated toward the end of the 20th Century (Esham and Garforth, 2013). During recent decades, the observed increases in India, Bangladesh, Nepal, Pakistan and Sri Lanka range between 0.07°C and 1°C per decade (Cruz et al., 2007; Esham and Garforth 2013).

Daily maximum air temperatures average around 31°C all year-round in Sri Lanka. The most important factor affecting temperature variations is altitude, with considerably lower temperatures experienced in its south-central mountain ranges (World Bank, 2021). Air temperatures fluctuate very little on an annual basis, with mean average ranging between 26°C and 28°C in coastal areas and between 15°C and 19°C at higher altitudes above 1500 m. An analysis of average temperatures in Sri Lanka over 1900–1917 and 2000–2017 suggests a warming of around 0.8°C in the course of the 20th Century (based on the Berkeley Earth dataset), and this broadly agrees with the estimate of 0.16°C of warming per decade between 1961–1990 reported in Sri Lanka's Second NDC (World Bank, 2021). Annual mean surface air temperature anomalies over Sri Lanka during the period 1869–1993 suggest a conspicuous and gradual increase of about 0.308°C over the 100 years (Rupakumar and Patil, 1996). Mean surface temperature increased during the 30-year period 1961–1990 at a rate of 0.0168°C per year (Chandrapala, 1996). Significant warming has taken place in all climatic zones and most locations exceed the global average rate of warming (De Costa, 2008). The rate of warming has accelerated in recent years: during the 1987–1996 period temperature increased by 0.0258°C per year (Fernando et al., 2007; Zubair et al., 2010).

Recent IPCC reports assessed that the frequency of cold (warm) days and nights have decreased (increased) since about 1950 (Hartmann et al., 2013). The hottest air temperature measured in Sri Lanka from 1949 to January 2023 was reported by the Trincomalee weather station. In September 2012, the record temperature of 39.5°C was reported here. The hottest summer from July to September, based on all 7 weather stations in Sri Lanka below 1,900 meters altitude, was recorded in 1991 with an average temperature of 29.1°C (Hartmann et al., 2013).

The Indian Ocean stands out as one of the most rapidly warming ocean basins in the world (Gnanaseelan et al., 2017; Beal et al., 2019). The global average rise in Sea Surface Temperature (SST) during 1951–2015 0.11°C per decade, while the tropical

Indian Ocean SST has risen by about 0.15°C per decade (Roxy et al., 2021). A 138-year (1870–2007) monthly observed SST time series averaged along a ship track extending from the Gulf of Aden through the Malacca Strait has suggested a warming of 1.4°C during the entire period (Chowdary et al., 2012). Historical simulations show warming trends of 0.1–0.18°C per decade during 1976–2005, with maximum warming trends over the northern Arabian Sea (Roxy et al., 2021). Warming in the tropical Indian Ocean has been basin-wide but spatially non-uniform, with the largest increasing trends seen in the central equatorial Indian Ocean and lowest warming trends off the Sumatra and Java coasts (Roxy et al., 2021).

On a global basis, ocean surface temperature increased by 0.88 [0.68 to 1.01]°C between 1850–1900 and 2011–2020, with 0.60 [0.44 to 0.74]°C of this warming having occurred since 1980 (IPCC, 2021). A key characteristic of ocean temperature change relevant for ecosystems is climate velocity, a measure of the speed and direction at which isotherms move under climate change (Burrows et al., 2011), which gives the rate at which species must migrate to maintain constant climate conditions. It has been shown to be a useful and simple predictor of species distribution shifts in marine ecosystems (Chen et al., 2011; Pinsky et al., 2013; Lenoir et al., 2020). Median climate velocity globally in the surface ocean has been 21.7 km per decade since 1960, but with higher values in the Arctic/subArctic and within 15° of the Equator [e.g. very high around Sri Lanka] (IPCC, 2021).

Seawater temperatures around Sri Lanka typically vary between 26 and 31°C over the course of a year, with peak temperatures occurring in April and again in November, while lowest sea surface temperatures occur in July-September and are associated with the southwest monsoon (Figure 6).

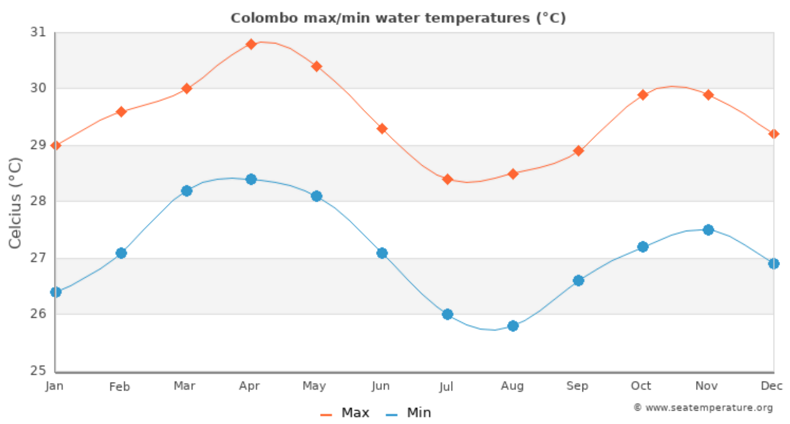

Figure 6. Measurements of maximum and minimum sea surface temperature at Colombo, Sri Lanka, as indicated by the daily satellite data provided by NOAA (World Sea Temperature, 2024).

Marine heatwaves are sustained periods of anomalously high near-surface temperatures that can lead to severe and persistent impacts on marine ecosystems. Since the 1980s, they have approximately doubled in frequency and have become more intense and longer in duration (IPCC, 2021). Studies since the IPCC Special

Report on the Ocean and Cryosphere in a Changing Climate (SROCC; Collins et al., 2019) confirm that marine heat waves can lead to severe and persistent impacts on marine ecosystems, from mass mortality of benthic communities, including coral bleaching, changes in phytoplankton blooms, shifts in species composition and geographical distribution, and toxic algal blooms, to decline in fisheries catch and mariculture (Smale et al., 2019; Cheung and Frölicher, 2020; Hayashida et al., 2020; Piatt et al., 2020). Satellite observations have noted a moderate increase of 1–4 annual marine heat waves events between 1982–1988 and 2000–2016 over some areas in the Indian Ocean (IPCC, 2021).

Expected future climate impacts

For Sri Lanka, models show a consistent warming trend in the future regardless of emissions scenario, according to CMIP5 models of temperature and precipitation (World Bank, 2021). Four greenhouse gas emissions scenarios, or Representative Concentration Pathways (i.e. RCP2.6, RCP4.5, RCP6.0, and RCP8.5) were defined by their total radiative forcing (GHG emissions from all sources). Table 5 (below) provides information on temperature projections and anomalies for the four RCP scenarios over two distinct time horizons (2040–2059 and 2080–2099), presented against the reference period of 1986–2005 (World Bank, 2021).

Table 5. Projected anomaly (changes in °C) for maximum, minimum and average daily air temperatures in Sri Lanka for 2040–2059 and 2080–2099, relative to the reference period 1986–2005 for all four Representative Concentration Pathways (RCPs). The table shows the median of the CCKP ensemble and the 10th-90th percentiles in brackets (from World Bank 2021).

	Average daily max. temperature		Average daily temperature		Average daily min. temperature	
	2040–2059	2080–2099	2040–2059	2080–2099	2040–2059	2080–2099
RCP2.6	0.8 (0.1, 1.8)	0.9 (0.0, 1.8)	0.9 (0.1, 1.5)	0.9 (0.1, 1.6)	0.9 (0.3, 1.6)	0.9 (0.3, 1.6)
RCP4.5	1.1 (0.1, 2.0)	1.6 (0.5, 2.7)	1.1 (0.4, 1.8)	1.6 (0.7, 2.5)	1.1 (0.5, 1.8)	1.6 (0.5, 2.5)
RCP6.0	1.0 (0.0, 2.0)	1.9 (0.8, 3.1)	1.0 (0.3, 1.7)	1.9 (1.0, 2.9)	1.0 (0.5, 1.7)	2.0 (1.2, 3.0)
RCP8.5	1.5 (0.4, 2.5)	3.2 (1.9, 4.6)	1.5 (0.7, 2.3)	3.2 (2.2, 4.5)	1.6 (0.9, 2.3)	3.4 (2.4, 4.5)

Average SST rise in Sri Lanka is expected to be smaller than the rise in global temperatures, reaching approximately +3.2°C by the 2090s under emissions pathway RCP8.5 (Table 5), compared to the projected global rise of 3.7°C, with maximum and minimum temperatures projected to rise faster than the average, albeit still below global averages (World Bank, 2021). High-resolution projections from the KNMI Climate Explorer show a rise in the region of +3.5°C under RCP8.5, and +1.2°C under RCP2.6 by the 2090s (World Bank, 2021). Projected rises are very likely to push ambient temperatures over 30°C on a more regular basis, suggesting that Sri Lanka faces a significant threat from extreme heat, with the number of days surpassing 35°C, potentially rising from a baseline of 20 days to more than 100 days by the 2090s, under emissions pathway RCP8.5 (World Bank, 2021).

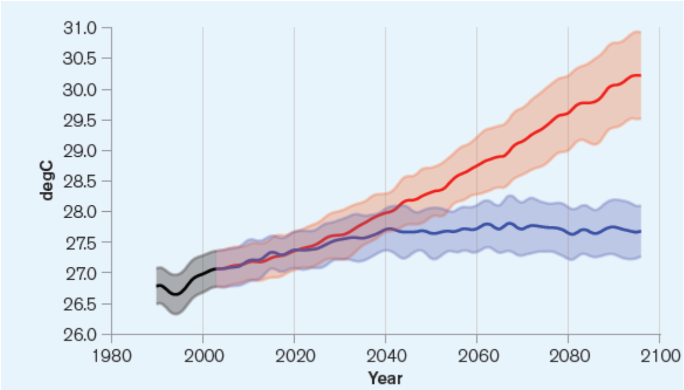

Figure 7. Historic and projected average annual temperature in Sri Lanka under RCP2.6 (blue) and RCP8.5 (red) estimated by the CMIP5 model ensemble. Shading represents the standard deviation of the model ensemble (World Bank, 2021).

Future projections using CMIP5 simulations suggested continued SST warming in the Indian Ocean with increasing anthropogenic emissions (high confidence) (Figure 7). However, changes in SSTs projected for the end of the 21st Century show regional and seasonal variability (Roxy et al., 2021; Cai et al., 2014). Stronger warming appears more likely in the north-western Indian Ocean, with weaker warming off the Sumatra and Java coasts (Zheng and Xie 2009; Roxy et al., 2021).

It is virtually certain that global mean SST will continue to increase in the 21st Century, and projections indicate an increase of +0.86°C under the lowest emission Shared Socioeconomic Pathway (SSP) SSP1-2.6 and +2.89°C under the highest emission pathway, SSP5-8.5, by 2081–2100, relative to the 1995–2014 baseline period (IPCC, 2021).

There is a pool of typically cooler water located off the southwest of the island associated with monsoonal upwelling, as well as warmer tropical waters offshore to the south and along the western side of Sri Lanka compared to the east (Figure 8). Future projections indicate SST rises of around +3.2°C under the SSP5-8.5 scenario and +1.6°C under the SSP2-4.5 scenario, all around the island, relative to the 1985–2014 baseline period, while by contrast, projections of warming near the seabed (sea bottom temperatures – SBT) are less marked around +0.8–1.0°C by 2070–2099 under both scenarios (see Figure 8).

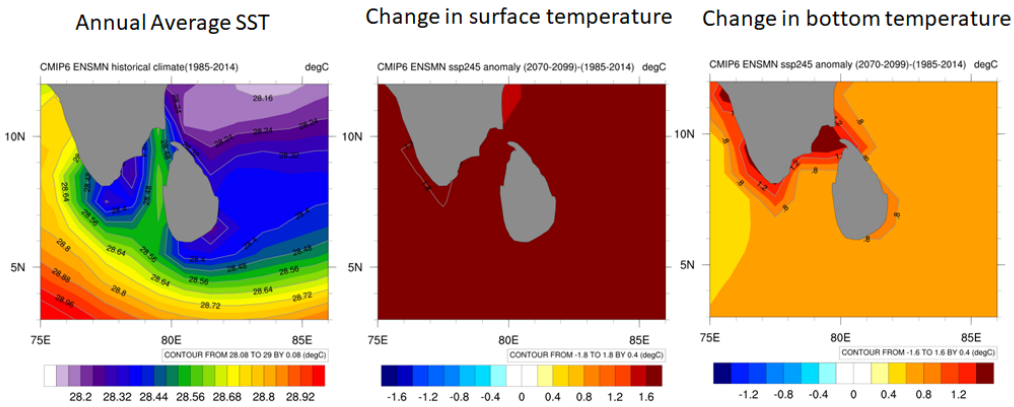

Figure 8. Average annual sea surface temperature (SST) for the period 1985-2014 around Sri Lanka (left panel); projected change in SST by 2070-2090 assuming an SSP2-4.5 scenario (central panel) relative to the baseline period; projected change in sea bottom temperature by 2070-2090 assuming an SSP2-4.5 scenario (right panel). From NOAA (2024).

3.1.2. Sea level rise

Data sources	Levels of evidence and agreement	Confidence rating
SITE-SPECIFIC STUDIES REGIONAL STUDIES	HIGH agreement ROBUST evidence	HIGH

Current climate impacts

Global mean sea level (GMSL) rose faster in the 20th Century than in any prior century over the last three millennia, with a 0.20 m rise over the period 1901–2018 (IPCC, 2021). GMSL rise has accelerated since the late 1960s, with an average rate of 2.3 mm per year over the period 1971–2018 increasing to 3.7 mm per year over the period 2006–2018 (IPCC, 2021). A new tide gauge-based reconstruction identified a regional mean sea level change of 1.33 mm per year in the Indian Ocean region (Frederikse et al., 2020), compared to a GMSL change of around 1.7 mm per year. For the period 1993–2018, the regional sea level rise, based on satellite altimetry, increased to 3.65 mm per year (Frederikse et al., 2020), compared to a GMSL change of 3.25 mm per year (IPCC, 2021).

A combined ground and satellite observations dataset for the Indian Ocean identified a clear spatial pattern in sea-level rise since the 1960s (Han et al., 2010; Palamakumbure et al., 2020). According to tidal gauge data, sea level has increased about 12.9 cm per century along the coasts of the north Indian Ocean (Unnikrishnan and Shankar, 2007). Han et al., (2010) also identified that coastlines around the Bay of Bengal and the Arabian Sea have experienced rapid and substantial sea-level rise owing to an expansion of the ‘Indo-Pacific warm pool’ (Palamakumbure et al., 2020). Due to thermal expansion of seawater, the average sea-level has risen by 12.7 mm along the northern Indian Ocean coasts during the past decade (Han et al., 2010), making Sri Lanka one of the most affected countries (Palamakumbure et al., 2020).

Sea-level variations in the central Indian Ocean based on tidal data show seasonal variations (Figure 9). However, seasonally adjusted tidal gauge data of Colombo, Sri Lanka show that sea-level has increased with a rate of 0.288 ± 0.118 mm per month. Similarly, Hulhule and Gan stations in the Maldives also indicate that sea-levels have increased with a rate of 0.368 ± 0.027 mm per month and 0.234 ± 0.025 mm per month, respectively (Palamakumbure et al., 2020).

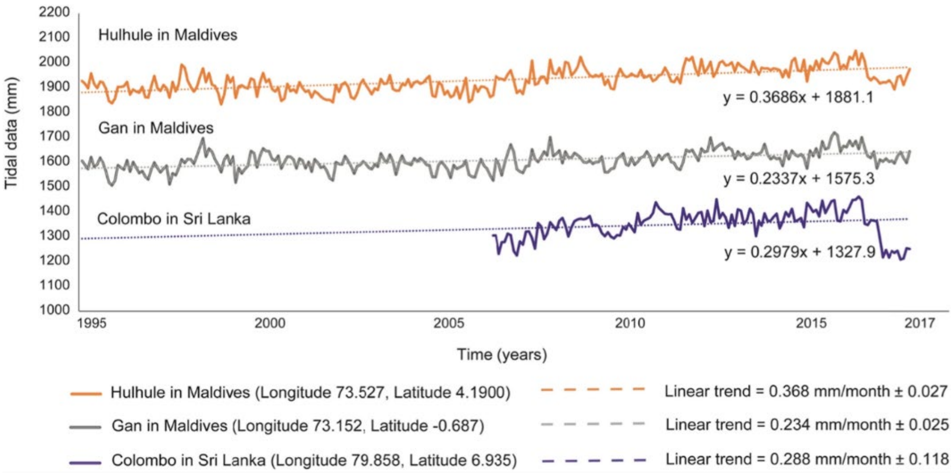

Figure 9. Sea level tidal gauge data corrected for seasonal component (solid lines), and linear trend line (dotted lines), from the Hulhule and Gan tidal stations in the Maldives, and Colombo tidal station in Sri Lanka. From Palamakumbure et al. (2020).

Expected future climate impacts

It is virtually certain that GMSL will rise until at least 2100, because all assessed contributors to GMSL are certain to continue throughout this century (e.g thermal expansion of the oceans, melting of the Greenland and Antarctic ice caps etc; IPCC, 2021).

The methods developed for the 2018 UK marine climate projections (Palmer et al., 2018; Lowe et al., 2018) have been used to generate sea level projections for tide-gauge locations around the world, including Sri Lanka and the wider Indian Ocean (Harrison, 2020). Projections for the 21st Century are compared to a baseline period of 1986 to 2005, under three future greenhouse gas scenarios (RCP2.6, RCP4.5 and RCP8.5), with extended projections to the year 2300 (Harrison, 2020; see Figure 10). In the Arabian Sea and Bay of Bengal, projected sea level changes are generally smaller (0.11–0.95 m, likely range across RCPs) compared to projected global average sea level changes (0.29–1.10 m, likely range across RCPs) by the end of the 21st Century (Harrison, 2020). In Equatorial Indian Ocean and far south of the Arabian Sea and Bay of Bengal, projected sea level changes are larger (0.22–1.20 m, likely range across RCPs by 2100) than projections for global sea level change (Harrison, 2020). Of the cities in the region, Male in the Maldives and Colombo in Sri-Lanka show the largest values for sea level rise (Harrison, 2020). The projected ranges under

RCP2.6, RCP4.5, and RCP8.5 for Colombo are 0.4–2.0 m, 0.7–3.0 m, and 1.2–5.8 m (see Figure 10).

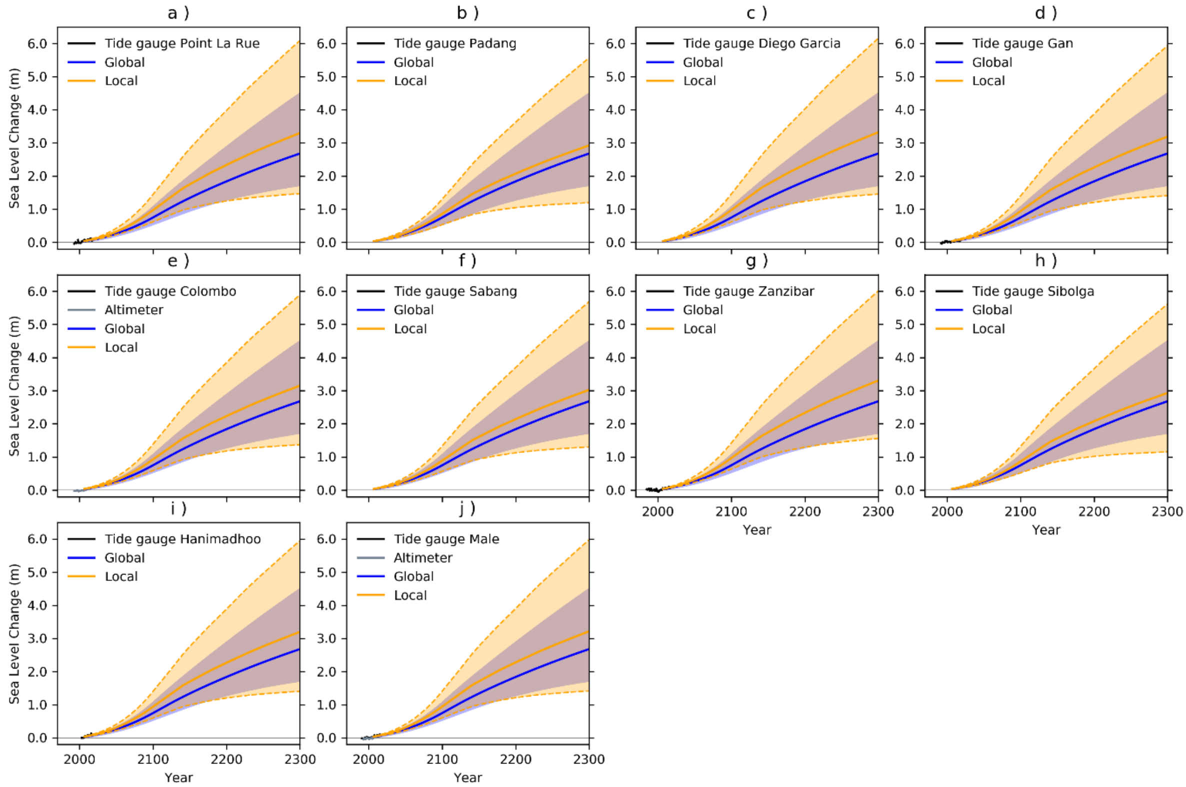

Figure 10. Extended range projections of local sea level under RCP8.5 for the Equatorial Indian Ocean, based on the nearest tide gauge location compared with the corresponding GMSL timeseries. The solid lines indicate the central estimate, and the shaded areas indicate the 5th to 95th percentile range, yellow for the location changes and blue for global changes. Colombo in Sri Lanka is featured in panel “e” (Harrison, 2020).

Sri Lanka has a moderate level of vulnerability to slow onset sea-level rise impacts but highly vulnerable to the combined impacts of storm surge and sea-level rise (World Bank, 2021). While the total population likely to be exposed to permanent flooding by 2070–2100 may appear relatively low, 66,000 people without adaptation actions, the population exposed to a 1-in-100-year coastal flood induced by storm surge is high: by the 2030s, approximately 230,000–400,000 people could reside in exposed floodplains, growing to 400,000 to 500,000 by the 2060s (World Bank, 2021). These estimates assume modest sea-level rise of 10 cm by 2030 and by 21 cm by 2060 (World Bank, 2021).

3.1.3. Ocean circulation and salinity

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES GLOBAL STUDIES	LOW agreement MEDIUM evidence	LOW

Current climate impacts

Sri Lanka’s location within the equatorial belt of the northern Indian Ocean, with the Arabian Sea to the west and the Bay of Bengal to the east, drives bi-annually reversing monsoon winds. Southern Sri Lanka is therefore characterised by a reversing current system in response to the changing wind field (see Figure 11); the eastward flowing Southwest Monsoon Current during the southwest monsoon transporting 11.5 Sv (mean over 2010– 2012) and the westward flowing Northeast Monsoon Current transporting 9.6 Sv during the northeast monsoon, respectively (de Vos et al., 2014).

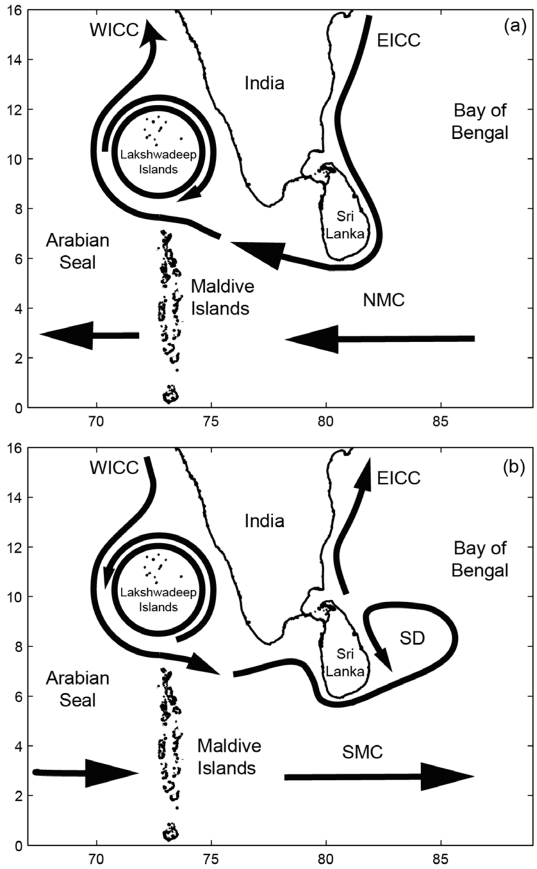

Figure 11. Circulation patterns around Sri Lanka and southern India for **(a)** Northeast monsoon and **(b)** Southwest monsoon. WICC = West Indian Coastal Current; EICC = East Indian Coastal Current; SMC = South Monsoon Current; NMC = North Monsoon Current; SD = Sri Lanka Dome (de Vos et al., 2014).

The southwest monsoon generally operates between June and October, and the northeast monsoon operates from December through April (de Vos et al., 2014). Along the eastern and western coasts, during both monsoon periods, flow is southward converging along the southern coast (see Figure 11). The major upwelling zone, during both monsoon periods, is located along the southern coast. The location of the flow convergence and hence the upwelling centre is dependent on the relative strengths of wind-driven flow along the eastern and western coasts: during the southwest monsoon, the flow along the western coast is stronger, migrating the upwelling centre to the east (de Vos et al., 2014).

Observations of ocean heat content in the upper Indian Ocean, reveal significant decadal variability (Han et al., 2014; Mohapatra et al., 2020; Roxy et al., 2021). The observed decadal variability results primarily from forcing by Indian Ocean winds (Srinivasu et al., 2017), as modulated through a significant contribution (or otherwise) from the Indonesian through flow transport to the interior of the south Indian Ocean, which has notably strengthened after 1990 (Han et al., 2014). For the Pacific and Indian Oceans, decadal shifts have primarily been observed in the upper 350 m, including an abrupt increase of ocean heat in the Indian Ocean over the last decade (Cheng et al., 2017; Roxy et al., 2021).

Low salinity in the upper ocean along the western boundary of the Bay of Bengal enhances the strength and southward extent of the East India Coastal Current in October–December (Jana et al., 2018). Transport of low-salinity Bay of Bengal water around Sri Lanka and in the West India Coastal Current impacts surface stratification and mixed layer depth in the eastern Arabian Sea (Shankar et al., 2016; Varna et al., 2021). Varna et al., (2021) identified a 2 to 3-fold increase in the influx of low-salinity water to the eastern Arabian Sea in 1990–2010 associated with strengthening of the Northeast Monsoon Current and the West India Coastal Current. The observed decreasing trend of sea surface salinity in the southeastern Arabian Sea is due to the changes in basin-scale circulation of the northern Indian Ocean in winter. Another time series study from a coastal ocean site in the eastern Arabian Sea reported a decline of >2 salinity units in 20 years (from 34 to ~31 during 1990–2010 (Godhe et al., 2015)).

Expected future climate impacts

A global modelling study with high resolution over South Asia (Sabin et al., 2013) indicated that a juxtaposition of regional land-use changes, anthropogenic-aerosol forcing, and the rapid warming signal of the Equatorial Indian Ocean, were crucial to simulate the observed Indian summer monsoon weakening in recent decades (medium confidence) (IPCC, 2021). Many ocean currents will change in the 21st Century as a response to changes in wind stress associated with anthropogenic warming (IPCC, 2021). In the Indian Ocean, sea surface salinity is projected to decrease by between 0.49 and 0.75 psu by 2080, compared to 2015, under RCP2.6 and RCP8.5, respectively (Akhiljith et al., 2019; IPCC, 2021).

3.1.4. Ocean acidification and pH

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES	HIGH agreement MEDIUM evidence	MEDIUM

Current climate impacts

Approximately 30% of CO_2 emissions have been absorbed by the oceans since the pre-industrial era (e.g. Canadell et al., 2007). The increasing oceanic uptake of CO_2 has changed seawater chemistry and resulted in ocean acidification, with profound impacts on biological ecosystems in the upper ocean (Roxy et al., 2021). Long-term increasing trends in ocean acidification, consistent with the increase in atmospheric CO_2, are evident over the past several decades (Dore et al., 2009). Indian Ocean pH is reducing owing to the accumulation of anthropogenic CO_2 from the atmosphere, which is comparable with the other major oceans (Sreeush et al., 2019; Sabine et al., 2004). Surface ocean pH over the Indian Ocean has declined by about 0.1 unit (current mean is 8.1) relative to pre-industrial levels and this reduction is larger over the western Indian Ocean (e.g. Sreeush et al., 2019). The western Arabian Sea has undergone more rapid acidification than the rest of the tropical Indian Ocean basin due to strong upwelling in this region drawing up anthropogenic CO_2 embedded in the deeper ocean (Roxy et al., 2021).

Simulations of pH seasonality and trends over various bio-provinces of the Indian Ocean, validated with pH measurements over the basin (from Takahashi et al., 2014), were used to discern the regional response of pH seasonality (1990–2010) and trend (1961–2010) to changes in SST, Dissolved Inorganic Carbon (DIC), Total Alkalinity (ALK), and salinity (Madkaiker et al., 2023). Total acidification in the Indian Ocean basin was 0.0675 units from 1961 to 2010, with 69.3% contribution from DIC followed by 13.8% contribution from SST. For most of the bio-provinces, DIC remains a dominant contributor to changing trends in pH except for the Northern Bay of Bengal and Around India (NBoB-AI) region (including Sri Lanka), wherein the pH trend is dominated by ALK (55.6%) and SST (16.8%) (Madkaiker et al., 2023). A strong correlation between SST and pH trends infers an increasing risk of acidification in the bio-provinces with rising SST and points out the need for sustained monitoring of Indian Ocean pH in such hotspots Madkaiker et al. (2023).

Seawater pH in the NBoB-AI region has decreased by 0.06 units from 8.129 in 1961 to 8.069 units in 2010 (see Figure 12), comparable to Sarma et al., (2013). Coastal ocean dynamics strongly dominate the variability of this region, and the physical, chemical, and biological conditions are different from other regions (Madkaiker et al., 2023). It can be inferred from the trend analysis that the pH trend is mostly dominated by ALK in this region (55.6%), followed by SST (16.08%). NBoB-AI is a basin characterized with high river runoff and warmer seawater temperature, and this discharge influences the ALK in this region, thereby controlling pH variability (Madkaiker et al., 2023).

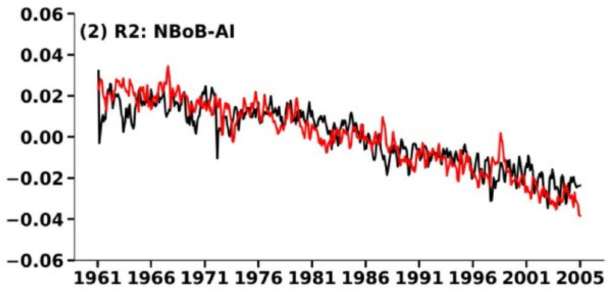

Figure 12. Ocean Tracer Transport Model (black line) pH anomaly with CanESM2 (red line) for the Northern Bay of Bengal and Around India (NBoB-AI) region from 1961 to 2005 (Madkaiker et al 2023).

Expected future climate impacts

Mean open-ocean surface pH is projected to decline by 0.08 ± 0.003, 0.17 ± 0.003, 0.27 ± 0.005 and 0.37 ± 0.007 pH units in 2081–2100 relative to 1995–2014, for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively (See WGI AR6 Section 4.3.2; IPCC, 2021). Projected changes in surface pH are relatively uniform in contrast with those of other surface ocean variables (IPCC, 2021).

Figure 13 outputs indicate generally lower values of pH and alkalinity to the north of Sri Lanka associated with riverine run-off from the Indian sub-continent into the Bay of Bengal (and especially the plumes of the Kaveri River). By contrast pH values and alkalinity, are on the whole lower and higher (respectively) off the south of Sri Lanka, as influenced by wider oceanic values (NOAA, 2024). Future projections (2070–2099) suggest that ocean pH will decline in a fairly uniform manner around Sri Lanka, by 0.32 pH units under SSP5-8.5 scenario and by 0.16 pH units under SSP2-4.5 (see Figure 13), relative to the 1985–2014 baseline period. By contrast, projections of changes in alkalinity are more spatially varied, and more marked in the south of Sri Lanka compared to the north. Overall, alkalinity is projected to decline by around 0.02–0.03 mol/m3 by 2070–2099 under both scenarios (see Figure 13).

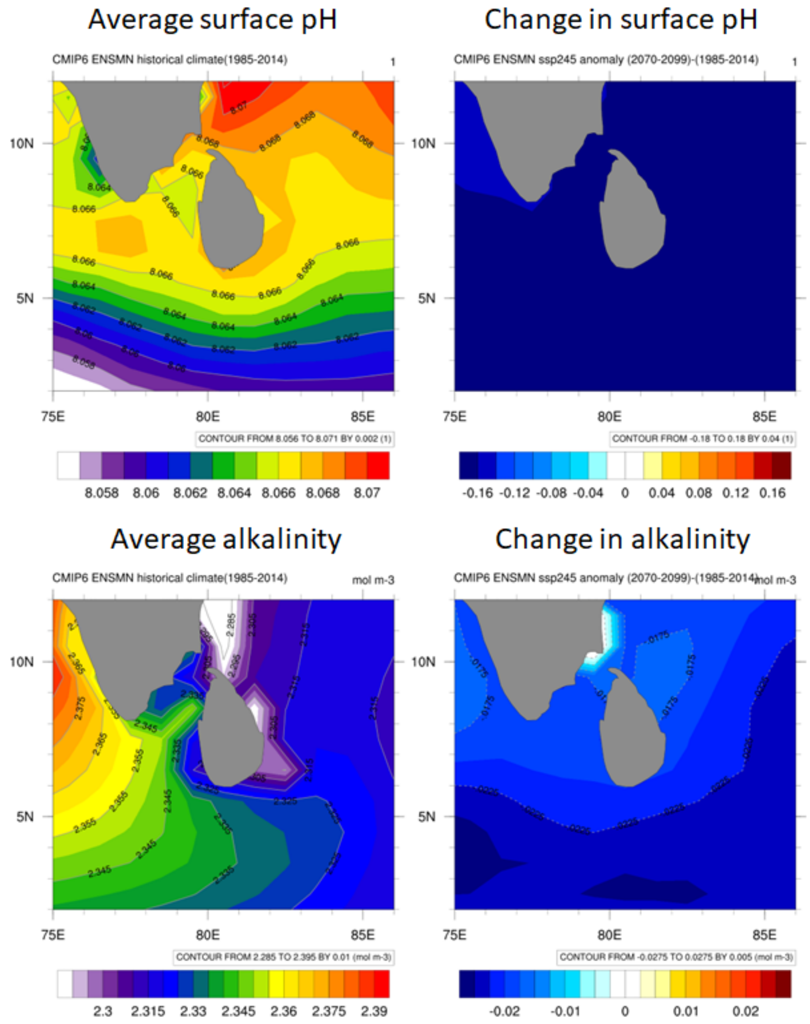

Figure 13. Average annual sea surface pH for the period 1985–2014 around Sri Lanka (upper left panel); average surface alkalinity in mol/m^3 (lower left panel); projected change in surface pH by 2070–2090 assuming an SSP2-4.5 scenario (upper right panel) relative to the baseline period; projected change in surface alkalinity in mol/m^3 assuming an SSP2-4.5 scenario (lower right panel). From NOAA (2024).

3.1.5. Dissolved oxygen

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES GLOBAL STUDIES	LOW agreement MEDIUM evidence	LOW

Due to the solubility effect, warmer waters carry less dissolved oxygen compared to cooler waters (Carpenter, 1966). Warmer water also increases respiration rates of marine organisms, which in-turn lead to further declines in oxygen concentrations. Increased stratification because of SST warming can adversely affect the oxygenation/ventilation of deeper water masses, leading to the formation of oxygen minimum zones (OMZs) or hypoxic areas in the ocean. Reports of coastal hypoxia, also called ‘dead zones’, where nearshore oxygen values fall below 61 µmol/kg (or equivalent 63 µM, 2 mg/l, or 1.5 ml/l), have increased exponentially over the last few decades, impacting more than 245,000 square kilometres of the coastal ocean (Pearson et al., 2022).

Current climate impacts

Dissolved oxygen is a major determinant of the abundance and distribution of the marine organisms worldwide. Concentrations in tropical oceans have decreased at a rate of 0.1–0.3 μ mol kg^{-1} $year^{-1}$ during the past five decades (Stramma et al., 2008). Long-term measurements over the tropical Indian Ocean show a pronounced decrease (at a rate of 20–30 mol m^{-2} per decade; Koslow et al., 2011). This oxygen decline is a result of warming-induced decline in oxygen solubility as well as reduced ventilation of the deep ocean due to enhanced ocean surface stratification (Roxy et al., 2021).

Two vast and naturally occurring OMZs persist in the Arabian Sea and the Bay of Bengal, accounting for a disproportionately large fraction of the global volume of hypoxic waters (21%; Rixen et al., 2020). The rim of the northern Indian Ocean, including the area around Sri Lanka, where the upper boundaries of the OMZs intersect the continental margins, is subject to strong seasonal and interannual variations in coastal upwelling, which can sustain or instigate coastal hypoxia by modulating the supply of oxygen-poor and nutrient-rich waters from the OMZs onto the continental shelf (Pearson et al., 2022).

Observations suggest that warming-driven oxygen loss only had a mild effect in the Northern Indian Ocean in the past decades, while coastal eutrophication could be a significant deoxygenation factor in the region (Pearson et al., 2022). The countries that border the Indian Ocean account for about 30% of the world's population, with urbanization, untreated waste waters, and fertilizers leading to high inputs of nutrients, which could further stimulate subsurface biological oxygen demand (Pearson et al., 2022).

Seasonally, the risk of hypoxia is highest in the entire Arabian Sea and western Bay of Bengal (i.e., Oman, Iran, Pakistan, India, Sri Lanka) in summer/fall due to a combination of wind- and wave-driven upwelling, as well as potentially an increase in biological oxygen demand. On interannual timescales, the risk of hypoxia is modulated by Indian Ocean Dipole (IOD) anomalies in upwelling and downwelling motions. For example, in the eastern Bay of Bengal (i.e., Bangladesh, Myanmar, Thailand, Malaysia, Sumatra) the risk is increased from moderate to high year-round during positive IODs, and decreased from moderate to low during negative IODs. In the eastern Arabian Sea (i.e. west coast of India, southwestern Sri Lanka), the risk of summer/fall hypoxia is reduced from high to moderate during positive IOD phases. The strength and frequency of positive IOD events have increased over the latter half of the 20th Century (Abram et al., 2008), including an unusual number of strong positive IOD events since 1960 compared to the last millennium (Abram et al., 2008; Wright, et al., 2020).

There appears to be a positive association of fish density with oxygen concentrations around Sri Lanka and a negative correlation with temperature and salinity (Athukoorala et al., 2021). Rixen et al., (2020) provide a review and synthesis of present and past trends associated with the oxygen minimum zone located in the northern Indian Ocean, as a well as a perspective on future developments.

Expected future climate impacts

Future trends in the northern Indian Ocean OMZs derived from Earth System Models (ESM) are highly uncertain (Rixen et al., 2020), with projected potential increases or decreases in the volume of low-oxygen waters, depending on the particular model and the oxygen levels under consideration (Bopp et al., 2013; Cocco et al., 2013). ESMs reproduce large-scale features and global OMZ trends but produce mismatches between measured and model oxygen concentrations in the ocean (Bopp et al., 2013; Rixen et al., 2020). In comparison to observational data, they underestimate oxygen losses significantly (e.g. Oschlies et al., 2018, and references therein), and simulated volumes of OMZs differ considerably, particularly for the Indian Ocean. In most ESMs the east–west contrast between the Arabian Sea and Bay of Bengal is opposite to what observations show, with most global models producing lower oxygen concentrations in the Bay of Bengal than in the Arabian Sea. Even the much-improved CMIP6 models still tend to overestimate oxygen concentrations in the Arabian Sea (Séférian et al., 2020). The poor representation of the OMZs of the northern Indian Ocean in ESMs reduces the reliability of future projections of potential changes in the OMZs related to natural and anthropogenic forcing (Rixen et al., 2020).

Global models suggest a general decline of oxygen for the entire ocean, but there is no clear trend visible in the Indian Ocean (Oschlies et al., 2017). However, Bopp et al., (2013) shows that a decrease in productivity is consistently simulated across all CMIP5 models and scenarios in the tropical Indian Ocean. By 2100, all models project an increase in the volume of waters with an oxygen concentration below 80 μM, relative to 1990–1999. This response is more consistent than that of the previous generation of ESMs (Cocco et al., 2013).

Given the link between hypoxia, the IOD, and anomalies in upwelling and downwelling motions, the frequency of extreme positive events is likely increasing under climate change, suggesting that the Sri Lanka could be particularly vulnerable to hypoxia in the future (Pearson et al., 2022).

3.1.6. Extreme weather

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES GLOBAL STUDIES	LOW agreement MEDIUM evidence	LOW

Current climate impacts

Warming of the western Indian Ocean has increased frequency and intensity of severe weather, including tropical cyclones (IPCC, 2021; Roxy et al., 2014; Murakami et al., 2017; Roxy et al., 2017). Historically, Sri Lanka has experienced relatively moderate cyclone events, mostly in the northern region, but cyclone-related storm surges and coastal erosion are becoming a major threat to major population centres all around the island.

Long-term tropical cyclone datasets for the Northern Indian Ocean (NIO) show 1433 synoptic-scale cyclonic disturbances during the period 1891–2018, of which 55%, 24%, and 21% were characterised as Depressions (D), Cyclonic Storms (CS), and Severe Cyclonic Storms (SCS) respectively (Vellore et al., 2020). The tropical cyclone contribution from the Bay of Bengal is about 80% versus 20% from the Arabian Sea. Figure 14 shows the observed monthly frequency of CS and SCS for the period 1891–2018. The TC activity in the NIO basin exhibits a bimodal distribution with larger number of occurrences during the pre-monsoon and post-monsoon seasons, and a large number of tropical cyclones observed during the months of October and November in the Bay of Bengal and Arabian Sea (Vellore et al., 2020).

A comprehensive study of tropical cyclone impacts on Sri Lanka during 1845–1958 found that 71 (approximately 72%) of the total of 99 cyclones and depressions observed occurred between October and December (Thambyahpillay, 1959). A similar pattern emerges when compared with the data from 1881–2001, showing that 73% of cyclones tracking over or near Sri Lanka occurred during the months of November and December (Srisangeerthanan et al., 2015). When considering the direction of approach and/or coastal impact, 17 among those 22 cyclones affected the east coast of Sri Lanka, three affected the west coast and one each had affected the north and south coasts of the country, with 22 classified as CS and the rest as SCS (Srisangeerthanan et al., 2015).

Figure 15 show the inter-annual and inter-decadal variability in the frequency distribution annual tropical cyclones observed in the Northern Indian Ocean region and trends in the frequency of CS and SCS for the period 1891– 2018 (Vellore et al., 2020). There is a significant decline in the annual frequency of tropical cyclones overall, i.e. −0.18 per decade (1891–2018), and −0.23 per decade (1951–2018) (see also Singh et al., 2000, 2001; Singh 2007; Mohapatra et al., 2014, 2017). However, there is a significant upward trend (+0.07 per decade) in occurrence of SCS in the NIO region during the post-monsoon seasons of 1891–2018. There is a significant decline in the annual frequency of CS and SCS in the Bay of Bengal region during the 1951–2018 period with trend values of −0.26 per decade and −0.15 per decade. By contrast, there is also an upward trend of CS and SCS observed in the Arabian Sea region both on annual and seasonal scales during the 1951–2018 period, with larger trend values (+0.02 per decade; <90% confidence level) during the post-monsoon season (Vellore et al., 2020).

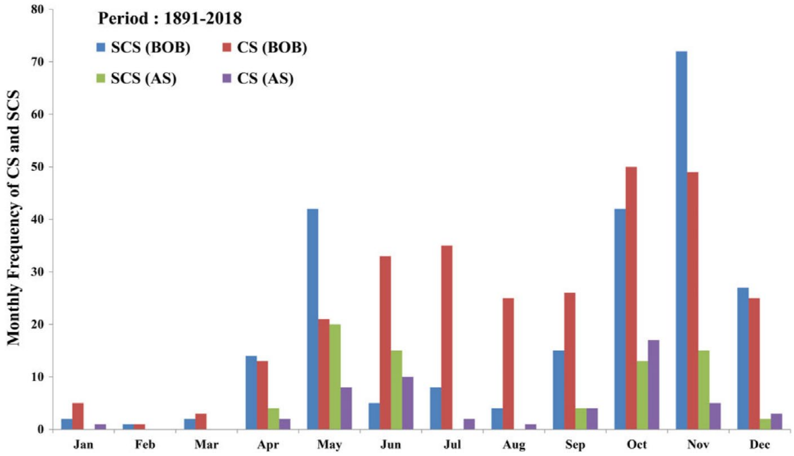

Figure 14. Observed monthly frequency of Cyclonic Storms (CS) and Serious Cyclonic Storms (SCS) in the Northern Indian Ocean basin during the 1891–2018 period. BOB = Bay of Bengal, AS = Arabian Sea (from Velore et al., 2020).

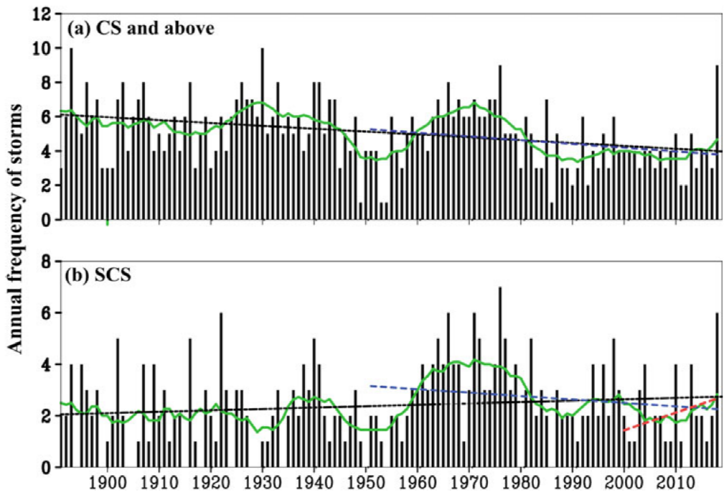

Figure 15. Observed annual frequency of Cyclonic Storms (CS) and above, and Serious Cyclonic Storms (SCS) in the Northern Indian Ocean. Linear trend lines are indicated by dashed lines: black (1891–2018), blue (1951–2018), red (2000–2018). Also, 10-year running mean is shown by a solid-green line (Vellore et al., 2020).

Expected future climate impacts

Climate models suggest that increasing levels of carbon dioxide in the atmosphere may enhance the frequency of severe/most intense cyclonic storms (e.g. Bengtsson et al., 2007; Klotzbach and Landsea, 2015). Past studies such as Danard and Murthy (1989) and Yu and Wang (2009) have pointed out that there could be an increase in both tropical cyclone frequency and tropical cyclone intensity over the Northern Indian Ocean basin, specifically in a doubled CO_2 world (Vellore et al., 2020).

Confidence on attribution of changes in tropical cyclonic activity to human influences remains low however, owing to inadequate observational evidence and physical understanding of the anthropogenic drivers of climate and cyclonic activity (IPCC, 2021; Vellore et al., 2020). The latest assessment by Knutson et al., (2019) suggests medium confidence for a projected rise in intensity of tropical cyclones and medium-to-high confidence to cyclone-associated precipitation intensity in the Northern India Ocean basin, during the 21st Century (Vellore et al., 2020).

3.1.7. Rainfall and monsoon patterns

Data sources	Levels of evidence and agreement	Confidence rating
SITE-SPECIFIC STUDIES; REGIONAL STUDIES	LOW agreement MEDIUM evidence	LOW

Current climate impacts

Sri Lanka's complex and spatially variable precipitation regime makes estimation of change over time difficult, highlighting a need to improve the evidence base in this area (Alahacoon and Edirisinghe, 2021). Many studies on rainfall trends in Sri Lanka have been conducted over the past three decades and identified different localised variabilities in the country (see Alahacoon and Edirisinghe, 2021). A recent study by Nisansala et al., (2020) showed that the eastern, southeastern, northern, and north-central parts of Sri Lanka have all been experiencing an increase in rainfall over the past 31 years (1987–2017), and that there has been a decrease in the trend of rainfall in the western, northwestern, and central parts of the country.

Although many studies have been conducted to understand the rainfall trends in Sri Lanka, they mostly focused only on data from a limited number of rainfall stations. In recent times however, satellite-based and reanalysed rainfall observations have become a better solution to gauge precipitation data for the whole country, with greater accuracy and higher spatial and temporal resolution (Alahacoon and Edirisinghe, 2021). Figure 16 shows changes in the annual rainfall on the different climatic zones of Sri Lanka between 1989 and 2019, and the discerning long-term increase especially in the wet and intermediate zones, with the maximum rainfall received in 2010, 2011, and 2014, years when the country experienced major floods.

By contrast, previous studies have suggested a decrease in annual rainfall trends in some districts (e.g. Nisansala et al., 2020). The main reason for this discrepancy is that Alahacoon and Edirisinghe (2021) used spatial data that takes into account the spatial variability of rainfall, as opposed to discrete data from individual weather stations that do not adequately consider spatial variability. Data from 1989 to 2019, show an increase in annual rainfall for every district in the country except Jaffna, Batticaloa, Kilinochchi and Ampara (Alahacoon and Edirisinghe 2021). Overall, there is a significant tendency for precipitation to increase in all climatic zones and that it is likely that there will be an increased risk of floods in the southern and western provinces in the future (Alahacoon and Edirisinghe, 2021).

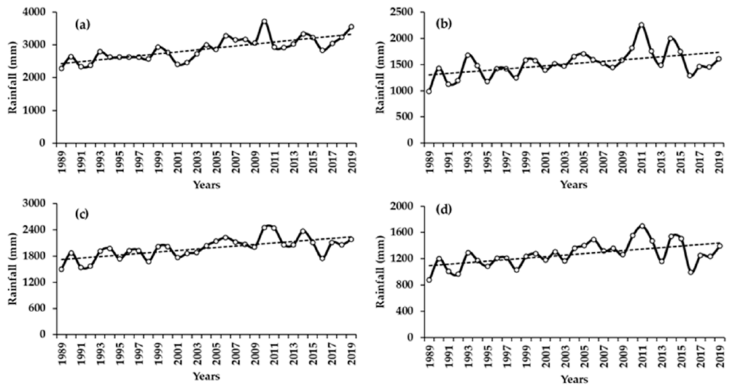

Figure 16. Rainfall trend for climate zones of Sri Lanka: (a) wet-zone; (b) dry-zone, (c) intermediate-zone, and (d) semiarid zone (Alahacoon and Edirisinghe, 2021).

Expected future climate impacts

Projected rainfall trends for Sri Lanka have a high degree of variability, but increases in heavy rainfall events are likely to increase in Sri Lanka's southern areas (World Bank, 2021). Climate model projections of future rainfall are generally less reliable than temperature projections, especially for island nations. This is due in part to coarse spatial resolution, which fails to capture local processes that drive rainfall dynamics such as convection, or the presence of land surfaces. The model ensemble used by the World Bank (2021) suggests increases in median annual rainfall under all emissions pathways, although with high uncertainty.

Precipitation changes are likely to depend on climate effects on the monsoon seasons affecting Sri Lanka. An analysis of changes in the Indian Summer Monsoon points toward a slight reduction in the frequency of light precipitation events offset by an increase in the frequency of high and extreme precipitation events, leading to a net increase in average daily monsoon precipitation of 0.74 ± 0.36 mm/day (Jayasankar et al., 2015; World Bank, 2021). Downscaling models thus far point to either increases in, or no change to, annual rainfall in Sri Lanka, alongside increased intensity of extreme rainfall events (World Bank, 2021). Further research and model downscaling work is required to constrain and localise potential changes to Sri Lanka across a wider set of global climate models.

3.2. Impacts of climate change on biodiversity

The following sections collate the evidence supporting observed climate change impacts and projected future risks to key marine species and habitats in Sri Lanka.

The types of data sources, and the levels of evidence and agreement and the overall confidence on the evidence are indicated for each biodiversity heading.

3.2.1. Plankton productivity

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES GLOBAL STUDIES	HIGH agreement ROBUST evidence	HIGH

Current climate impacts

Phytoplankton are single-celled aquatic photoautotrophs (plants and cyanobacteria) that serve as the primary food source for marine ecosystems. They regulate the availability of food for higher marine trophic levels and drive the ocean carbon cycle by converting inorganic carbon into organic carbon through photosynthesis (Modi and Roxy, 2023). Net primary productivity is the organic carbon produced by phytoplankton after subtracting the costs of metabolic processes, and exhibits variability on timescales ranging from months to years. The tropical Indian Ocean is typically characterised by two annual blooms of phytoplankton, a primary bloom during summer (June–September) and a secondary bloom during winter (December–February). Changes in physical forcing, especially related to the southwest (summer) and northeast (winter) monsoons, are linked to these seasonal bloom episodes (Modi and Roxy, 2023).

The Indian Ocean is the least studied of all the tropical basins and until recently in-situ data on indices of ocean primary production were scarce, as opposed to the Pacific and Atlantic Oceans, however satellites have made it possible to discern the impact of anthropogenic climate change on plankton productivity in this region (Modi and Roxy, 2023). Remote-sensed ocean colour provides measurements of chlorophyll, a proxy for marine phytoplankton. Chlorophyll concentrations are generally employed to discern trends in aggregate plankton (Modi and Roxy, 2023). Due to the upwelling of cold nutrient-rich water and enhanced vertical mixing provided by the periodically reversing monsoon winds, the Arabian Sea experiences enormous phytoplankton blooms in the summer and a smaller bloom in the winter. Roxy et al., (2016) reported a 30% decline in chlorophyll in the western Indian Ocean over 1998–2013 based on both satellite observations and model outputs. Another study by Prakash et al., (2012) found that chlorophyll increased during 1998–2002 but declined since 2003 in the western Arabian Sea, and suggested that the observed chlorophyll response is not governed by global warming but rather is a result of the decadal oscillations in sea-level anomaly and the thermocline. Diatoms, which are the predominant phytoplankton group in the Arabian Sea, have been reported to be declining in the region (Garrison et al., 2000; do Rosário Gomes et al., 2014). As a result, changes in the trophic interactions of the aquatic food web are to be expected (Modi and Roxy, 2023).

Analyses of changes in summer marine primary production during 1998–2022 in the western Indian Ocean suggest that chlorophyll has declined in the western Indian Ocean during the past 25 years, with isolated high-chlorophyll patches in some coastal areas such as the Sri Lankan upwelling dome (Modi and Roxy, 2023). In contrast, the Bay of Bengal is characterised as a region of low primary productivity with a consistent decrease across observed records (Modi and Roxy, 2023).

An investigation of the influence of SST and the Indian Ocean Dipole on chlorophyll concentrations around Sri Lanka in different monsoon periods, indicated a highest mean chlorophyll-a value (3.878 mg m^{-3}) coinciding with the lowest mean SST value (22.74°C) during the southwest monsoon off southern Sri Lanka, and a lowest mean chlorophyll-a (0.12 mg m^{-3}) found within the EEZ in the first inter-monsoon (Sandamali et al., 2023). Mean chlorophyll-a increase from the open ocean towards the coast in all climatic regions showing the importance of terrestrial runoff nutrients and induced upwelling during the activated monsoon patterns (Sandamali et al., 2023). In the upwelling zone off the southern coast of Sri Lanka, upwelling was prominent during the southwest monsoon, and chlorophyll-a in the upwelling zone showed a significantly ($p < 0.05$) negative correlation with SST and IOD, and a significantly positive ($p < 0.05$) correlation with wind speed. The north and equatorial Indian Ocean have witnessed a rapid drop in phytoplankton of 0.16 and 0.69 PgC year1 decade-1 since 1998 to 2015, respectively (Sandamali et al., 2023).

Expected future climate impacts

According to Bopp et al., (2013), all models forecast a decrease in net primary productivity in the tropical Indian Ocean under all emission scenarios. This decline in productivity could reach 30% under the highest carbon emission scenario, thus proving detrimental to the basin's marine biodiversity (Modi and Roxy, 2023). Similar outputs have emerged from the CMIP6 ensemble of models (see Figure 17) where particularly strong declines in chlorophyll and phytoplankton productivity are anticipated in the upwelling zone south of Sri Lanka.

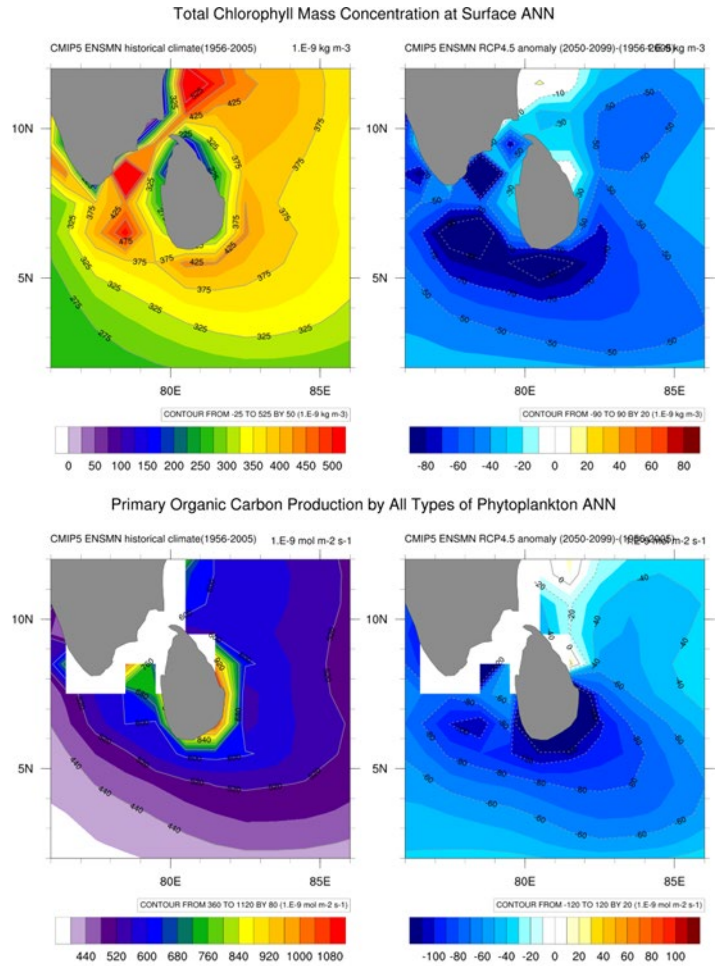

Figure 17. Average Chlorophyll mass concentration (kg per m^3) (upper left panel); and average primary organic carbon production by all types of phytoplankton (mol m^{-2} s^{-1}) (lower left panel) for the period 1985–2014 around Sri Lanka. Projected future change in Chlorophyll mass concentration by 2050–2090 assuming an SSP2-4.5 scenario (upper right panel) relative to the baseline period; projected change in phytoplankton productivity assuming an SSP2-4.5 scenario (lower right panel). From NOAA (2024).

Diatoms, which make up the majority of marine phytoplankton and represent more than 40% of the biological pump for CO_2, are also predicted to experience a rapid decline in the Indian Ocean relative to other phytoplankton types due to a stronger nitrate stress (Modi and Roxy, 2023).

Most studies argue that these model predictions of decreasing marine production in the 21st Century in low and mid-latitudes are primarily a result of the anticipated decrease in upwelling resulting in a reduced nutrient supply from bottom layers of the ocean. Under medium-to-high emission scenarios, the CMIP6 ensemble projects a further reduction of phytoplankton biomass in most parts of the tropical Indian Ocean (Roxy et al., 2022).

3.2.2. Harmful algal blooms and associated risks to humans and biodiversity

Data sources	Levels of evidence and agreement	Confidence rating
SITE-SPECIFIC STUDIES; REGIONAL STUDIES	LOW agreement LIMITED evidence	LOW

Current climate impacts

Phytoplankton blooms are natural events part of the functioning of marine and freshwater ecosystems (Thomas et al., 2023). However, in some cases, due to either the intensity and persistence of the bloom and the presence of potentially harmful species, these blooms can cause considerable nuisance, covering beaches with detritus, locally depleting inshore oxygen levels, or resulting in mass mortality events of fish, seabirds, and even marine mammals. Such blooms are commonly termed as harmful algal blooms (HABs). Over the years, the frequency of HABs has been on the rise globally. Decadal studies on HABs in the Indian EEZ have suggested an increase in the number of HAB events, and several hotspots have been identified within the region (Thomas et al., 2023).

Thomas et al. (2023) provide an analysis of bloom reports from 1908 to 2021 from the Indian EEZ encompassing nearly 59 phytoplankton species. Among these, 29 species were regarded as harmful and were responsible for 162 HAB events around the Indian peninsula. A marked increase in the frequency of HABs along the Indian EEZ has been recorded from 1950 to 2020. Two HAB incidents were documented from 1900 to 1940, 27 incidents from 1941 to 1980, and 133 incidents from 1981 to 2020 (although 'reporting bias' may be an issue for the earlier periods; Thomas et al., 2023). The biannually reversing monsoon seasons have a pivotal role in HAB events of the Indian EEZ. Seasonally, occurrences of HABs were more pronounced during spring inter-monsoon, followed by summer monsoon. A total of 111 cases of HAB occurrence were reported along the west coast of India and 51 from the east coast during the observational period (Thomas et al., 2023). The apparent increase in HAB events occurring in recent years, especially on the West coast of India are probably more related to increased nutrient run-off than to climate change, but attribution of individual events can be difficult (Thomas et al., 2023).

HABs studies in Sri Lanka are less developed and mostly focused on Colombo Harbour (e.g. Senanayake et al., 2010; Jayasiri et al., 2015). A study conducted by Wijethilake and Ranatunga (2015) reported cysts belonging to *Scrippsiella* spp. that cause fish mortalities. Dissanayake et al., (2021) investigated diatoms and dinoflagellates in five Sri Lankan Southern coast locations, focusing on potentially harmful species. A total of twenty-seven diatom species and ten dinoflagellate species were identified during the study. Among them, eight diatom species (*Asterionellopsis glacialis, Chaetoceros curvisetus, Chaetoceros lorenzianus, Guinardia flaccida, Leptocylindrus minimus, Nitzschia sp., Proboscia alata* and *Pseudonitzschia fraudulenta*) and three dinoflagellate species (*Ceratium fusus, Ceratium furca,* and *Dinophysis caudata*) were identified as potentially harmful species (Dissanayake et al., 2021).

Dinoflagellates of the genus *Gambierdiscus* are found in almost all oceans and seas between the Latitudes 35°N and 35°S. *Gambierdiscus* and *Fukuyoa* are producers of ciguatoxins, which are well described in the Pacific and the Caribbean and known to cause serious human health problems associated with contaminated seafood (Habibi et al., 2021). However, historically, their properties and presence have been poorly documented in the Indian Ocean (including the Bay of Bengal, Andaman Sea, and the Gulf). The rapid alert system for food and feed created in 1979 by the European Union successively warned in 2012, 2015, and 2016 about imported ciguatoxic fishes originating from India and Sri Lanka (Habibi et al., 2021). Ciguatera fish poisoning is the most common non-bacterial cause of human illness associated with seafood consumption globally and is associated with bioaccumulation of toxins in predatory fish species such as groupers, barracuda and snappers. Distribution and abundance of the organisms that ultimately produce these toxins, are reported to correlate positively with seawater temperature (Kibler et al., 2017). Consequently, there is growing concern that increasing temperatures associated with climate change could result in higher incidence of ciguatoxic events (Habibi et al., 2021).

Expected future climate impacts

Ralston and Moore (2020) have reviewed recent studies focussed on modelling HABs, and suggest that climate change is expected to affect the frequency, magnitude, biogeography, phenology, and toxicity of HABs. Directly linking changes in observed HAB distribution, frequency, or intensity to shifts in climatic forcing remains difficult, although examples are starting to emerge as time series of observations accumulate (e.g. Kibler et al., 2015; Townhill et al., 2018). As far as can be discerned, no future modelling studies of HABs have yet been performed for the Indian Ocean.

3.2.3. Fish

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES GLOBAL STUDIES	MEDIUM agreement LIMITED evidence	LOW

Current climate impacts

More than 1000 species of marine fish have been reported in Sri Lankan waters, occupying important ecosystems such as coral reefs, mangroves, sea grass beds, lagoons, salt marsh as well as open ocean environments. Kumara and Dalpathadu (2012) provided a systematic checklist of marine fish occurring in Sri Lanka, stating that De Bruin et al. (1994) listed about 800 marine and brackish water fishes, whereas the Fisher Country Profile of Sri Lanka reports around 975 species of marine and brackish water fish (610 coastal fish, 60 sharks, 90 oceanic pelagic fish and 215 demersal fish; FAO, 2006). Öhman et al. (1993) have listed over 300 species of reef and reef-associated fish belonging to 62 families. Thus, the actual number of marine and brackish water fishes existing in Sri Lankan Waters could be in excess of 1800 species (Kumara and Dalpathadu, 2012).

Survey data of trawl samples on the continental shelf of Sri Lanka from 2018, covering fish density and diversity by region (East and West) and depth (20–50 m and 50–100 m) have identified 620 species from 137 different families recorded, with the family Myctophidae being the most dominant in terms of the highest number of individuals caught from all stations (24.61% out of the total number of individuals) while the most represented family by density was the Carangidae (jacks, 8.01%) (Athukoorala et al., 2021). A total of 440 species were found in the East region compared to 385 species in the West region; the density of fish was 1.3 times higher in the East region (9.00 ± 1.08 t/NM2) compared to the West region (6.85 ± 1.40 t/NM2; Athukoorala et al., 2021). Similarly, biodiversity in the East region was reported 1.3 higher than the West region, and shallow-water habitats (20–50 m) more diverse and hosting denser populations than deep-water habitats (50–100 m) habitats (Athukoorala et al., 2021). There was a positive association of fish density with oxygen and a negative association with temperature and salinity (Athukoorala et al., 2021).

An investigation of patterns of reef fish abundance and diversity at five major coral reef ecosystems on the eastern coast of Sri Lanka recorded 272 reef fish species and 101 coral species (Thilakarathne et al., 2024). The highest and lowest abundance of fish were recorded at Kayankerni and Adukkuparu Reefs respectively. However, Pigeon Island Reef had the highest fish diversity, evenness and species richness followed by Parrot Rock Reef. By contrast, Passikudah Reef had the lowest fish diversity, but Kayankerni Reef had the lowest fish evenness (Thilakarathne et al., 2024). Coral cover and reef complexity is an important factor in determining the abundance and diversity of reef fish. A loss of 10% of coral cover may reduce associated reef fish species by 60% (Wilson et al., 2006). According to Sheppard (2003), in 1998, more than 90% of shallow corals on Indian Ocean reefs died as a result of elevated SST, leading to wide-scale coral bleaching. In Sri Lanka, 54% of live corals bleached at Passikudha Reef during 2015–2016, significantly affecting reef fish abundance (Ellepola et al., 2016).

Apart from these few studies, very little is known about climate change impacts on fish or fisheries around Sri Lanka. Elsewhere in the world, there is evidence of degradation of key nursery habitats or reduced feeding opportunities for fish larvae associated with overall declines in plankton productivity. Other evidence includes shifts in distribution or migration patterns, as well as changes to fish growth rates, activity levels, breeding success and survival (see Rijnsdorp et al., 2009).

The spatial distribution of large pelagic fishes including tunas is greatly influenced by oceanographic conditions (mainly SST and dissolved oxygen) that vary greatly in space and time. Where water temperature exceeds species-specific thermal tolerance, or oxygen concentration is insufficient for physiological needs, tunas are known to move to different latitudes, longitudes and depths (Dueri, 2017). Tuna abundance also depends on good spawning and feeding conditions, which can be influenced by temperature, currents, and primary production (Dueri, 2017).

Skipjack tuna (*Katsuwonus pelamis*) is a relatively small, highly migratory species, that inhabits the surface waters of the tropical and subtropical oceans, and is a vitally important fishery in Sri Lanka. The spatial distribution of skipjack tuna is strongly influenced by ENSO (El Niño-Southern Oscillation) and IOD climatic events (Lehodey et al., 1997). In the Indian Ocean the conjunction of an IOD and a strong ENSO event in 1997–1998 led to environmental anomalies with significant consequences for fishing activities (Marsac and Le Blanc, 1998; Ménard et al., 2007). Abnormal easterly wind stress along the equator caused a reversal of the east–west thermocline slope and an increase (decrease) of primary productivity in the east (west). The catchability of skipjack tuna for purse seine gears increased in the east, due to the shallower thermocline and the higher surface biological productivity. Conversely, catchability decreased in the west, with the deepening of the thermocline and the reduction in surface schools available to the fishery. This led to a massive displacement of fishing fleets from their common fishing grounds in the Western Indian Ocean to the eastern equatorial area (Dueri et al., 2012).

Skipjack tuna is not the only species responding to climatic oscillations. During the 1997–1998 ENSO/IOD event, the catchability of yellowfin tuna *(Thunnus albacares*) increased for purse seine gears in the eastern Indian Ocean (Ménard et al., 2007; Marsac and Leblanc, 1998). On the other hand, positive IOD events have been correlated to a decrease in catch per unit effort for longline fisheries and to reduced catch areas, to the northern and western margins of the western Indian Ocean (Lan et al., 2013). Catchability of bigeye tuna (*Thunnus obesus*) for longline fisheries in the Indian Ocean was found to increase during positive IOD events with low Indian Ocean Index value (1972–73, 1977–78, and 1982–83) (Ménard et al., 2007).

Expected future climate impacts

Climate change projections with the RCP8.5 scenario show important changes in skipjack tuna habitat suitability (Dueri et al., 2014). Simulations project a decline of habitat suitability in the equatorial waters of the Indian Ocean between 2010 and 2050, that progressively intensifies from 2050 to 2095. At latitudes higher than 10°N or 10°S, simulations project an increase in habitat suitability in the first half of the century, followed by a decrease in the northern part of the Indian Ocean (Dueri et al., 2014). Climate change projections with the RCP8.5 scenario show that yellowfin tuna reaches the upper limit of its current favourable spawning temperature range in many places (Senina et al., 2015). Moreover, the anticipated decrease in primary production has negative consequences for the feeding habitat of this species.

Cheung et al., (2009) provided projections of future distributional ranges for a sample of 1066 commercially exploited marine fish and invertebrates worldwide. Projections suggested that climate change will lead to numerous local extinctions in the tropics, as well as dramatic species turnovers of over 60% of the present biodiversity, implying ecological disturbances that could potentially disrupt ecosystem services. Fish populations in the central Indian Ocean, to the south of Sri Lanka, will decline significantly by 2050 under a high emissions climate change scenario (Cheung et al., 2009). More recently, future projections of fisheries catches based on two ecosystem models suggest decreasing total maximum catch potential in the world's EEZs by 16.2 to 25.2% under climate change by the end of the 21st Century (Cheung et al., 2018). For Sri Lanka specifically, fisheries catches are projected to decline by as much as 24–55% by 2050 under a high emissions climate change scenario and by 32–69% by the end of the twenty-first century (Cheung et al., 2018).

3.2.4. Seabirds and waterbirds

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES, GLOBAL STUDIES	MEDIUM agreement LIMITED evidence	LOW

Ornithologically, Sri Lanka can be considered an oceanic island, thus a fair proportion of the offshore bird species recorded are oceanic species (Kotagama and De Silva, 2020). The 54 seabird species represented belong to the Order Ciconiiformes (herons and storks etc.), but only 7 (possibly 8) species are breeding residents, while 13 are winter visitors from northern regions (Kotagama and De Silva, 2020) and 6 are summer visitors (Kotagama and De Silva, 2020). Sri Lanka has no endemic seabird species (Kotagama and De Silva, 2020). Several seabird species from the Antarctic and sub-Antarctic regions visit Sri Lanka, including brown skua (*Stercorarius antarcticus* also known as *Catharacta lonnbergi*), south polar skua (*Stercorarius maccormicki* also known as *C. maccormicki*), and Wilson's storm petrel (*Oceanites oceanicus*), while another southern seabird, the soft-plumaged petrel (*Pterodroma mollis*) recorded recently from Sri Lanka, was the first of its species to be recorded from the tropical Indian Ocean (Kotagama and De Silva, 2020). Another of its congeners from the sub-Antarctic regions, white-headed petrel (*P. lessonii*) was the first of the species to be recorded from any tropical ocean (Kotagama and De Silva, 2020).

Seabirds and waterbirds play a fundamental role in marine and coastal ecosystems, for example seabirds enhance coral reef productivity and functioning by cycling nutrients between the sea and land, so that on reefs around islands with abundant seabirds, damselfish and other reef fish grow faster and there is a greater biomass of reef-fish overall than on islands where seabird abundance is low (BirdLife International, 2022a).

Seabirds are one of the world's most threatened groups of birds, with 30% of species considered globally threatened (19 Critically Endangered, 34 Endangered and 58 Vulnerable), a further 11% listed as Near Threatened, and 57% of species known to be in decline (BirdLife International, 2022a, based on data from the IUCN Red List). Bycatch from fisheries is one of the greatest threats to seabirds, and while mitigation measures can be effective, lack of compliance with regulations particularly in the High Seas, means that many birds are still under threat (BirdLife International, 2022a).

Longline fishing vessels operating in High Seas areas overlapping with areas of high seabird abundance must set their lines during the night to prevent bycatch, as most seabirds tend to only feed during the day, but vessels do not always obey and those operating in the High Seas in the Indian Ocean have a higher proportion of non-compliant daylight line-setting compared to data from the Atlantic and Pacific Oceans (according to BirdLife International, 2022a with sources from Carneiro et al., 2022; Clay et al., 2019; Dias et al., 2019; Pardo et al., 2017; Winnard et al., 2018). In Sri Lanka, seabirds are known to become accidentally entangled and drowned in fishing nets or hooked on trawling lines, as it has been reported for *Sterna bergii* and *Sula leucogaster* (Kotagama and De Silva, 2020). There is no data regarding impacts of climate change, or even marine pollution (Kotagama and De Silva, 2020) in Sri Lanka. The Caspian tern (*Sterna caspia*), little tern (*Sterna albifrons*), and large crested tern (*Sterna bergii*) are breeding residents present throughout the year and nesting areas of these species include small islets off the coast, the shallow banks known as 'Adam's Bridge' in the north-west, as well as the margins of larger artificial irrigation reservoirs and lagoons (De Silva, 1997). A major setback to some species of ground-nesting breeding terns in Sri Lanka is the loss of breeding habitat due to the degradation of the suitable littoral lagoons on which they nest, due to conversion into ponds for shrimp farming or salt pans (Kotagama and De Silva, 2020).

While the top disturbances to birds from human pressures such as bycatch and overfishing, have known and tested solutions, climate change and severe weather have a limited prospect of direct mitigation of most of the main known or potential impacts such as changes in oceanographic processes (resulting in declining in food availability around colonies), increased frequency of extreme weather events, inundation of colonies due to sea level rise or severe rainfall storms (Dias et al., 2019).

Current climate impacts

Climate change and severe weather impact seabirds mostly owing to habitat shifting and alteration (or that of their food), and temperature extremes, followed by storms and coastal flooding Dias et al., 2019). Analysis of terrestrial bird population trends shows that declines are greatest in areas that have experienced rapid warming, while one recent study estimated that almost one in four threatened bird species may have already been negatively impacted by climate change in at least part of their range (BirdLife International, 2022a). It appears that warming temperatures may be the main factor driving long-term declines of birds, but for seabirds, extreme weather impacts can also have rapid and catastrophic impacts on populations, particularly where it affects nesting colonies on coastal areas (Burton et al., 2023; BirdLife International, 2022a). Other indirect effects include climate change disruptions to the distribution and abundance of favoured fish prey species (Burton et al., 2023). For example, it has been demonstrated that climate-related oceanographic factors such as the timing of onset and strength of stratification (Carroll et al., 2015), affects the timing of fish availability or abundance of lower trophic levels (Jensen et al., 2003; Scott et al., 2006), which in turns manifests in poorer breeding success and, eventually population decline, for seabirds that forage on those fish (Burton et al., 2023).

Sea level rise poses a major threat to coastal ecosystems, and the species that depend on low-lying coastal habitats including islands are particularly at risk (BirdLife International, 2015). Sea level rise is likely to cause widespread flooding and accelerated coastal erosion resulting in loss or irreversible changes to many habitats such as mudflats and marshes, which are critical for wildfowl and wader species (BirdLife International, 2015; Galbraith et al., 2002; Hughes, 2004; Le V. dit Durell et al., 2006). Rising sea levels, in combination with more frequent and intense storm surges, will prove particularly catastrophic to shore-nesting birds (BirdLife International, 2015; Bennett et al., 2007). Small islands, reefs and atolls are particularly vulnerable to sea level rise and islands also tend to be important hotspots for biodiversity, for instance, a disproportionately high number of threatened birds occur on islands (BirdLife International, 2008), and populations of many Critically Endangered species are entirely restricted to low-lying islands (BirdLife International, 2015).

Extreme natural events such as floods and cyclones can have catastrophic human, environmental and economic impacts (BirdLife International, 2012). Tsunamis in particular are a natural disaster risk across the Indian Ocean including Sri Lanka, and even though not a climatic hazard *per se*, they do offer an example of the potential environmental impact of extreme water levels on coastlines. For instance, the tsunami of December 2004 off Indonesia, had a huge human and environmental impact, affecting ecosystems across the entire Indian Ocean basin including the destruction of seabird colonies thousands of miles away from the epicentre (Viera et al., 2006; Lay et al., 2005). Similarly, the powerful tsunami that originated off Japan in March 2011 reached the Midway Atoll near Hawaii, home to over three million nesting seabirds (BirdLife International, 2012). The tsunami completely over-washed the fringing reef and the smaller island and inundated most of other islands washing away many thousands of young, including 110,000 albatross chicks, as well as at least 2,000 adult albatross (FWS 2011; BirdLife International, 2012).

Climate change can be a factor in the spread and invasion of non-native species (Keller et al., 2009; Kularatne, 2023), and similarly it can also drive increased occurrence and virulence of avian pathogens (Dias et al., 2019; Grémillet and Boulinier, 2009; Sydeman et al., 2012) which can spread very rapidly and have devastating consequences for bird populations, particularly migrating seabirds and waterbirds. In the UK for example, the Royal Society for the Protection of Birds[1] reported that the most recent avian flu outbreaks detected in 2021/22 have been unprecedented and the largest ever in the UK and worldwide – killing tens of

[1] https://www.rspb.org.uk/birds-and-wildlife/advice/how-you-can-help-birds/disease-and-garden-wildlife/avian-influenza-updates/

thousands of birds and affecting around 70 species of birds in the country in total, including 20 of the 25 seabird species that regularly breed in the UK, as well as other waterfowl including geese, ducks and swans. No official information from Sri Lanka could be found but during the same outbreak in 2021 in India, the federal government issued a high alert and reported mass deaths of migratory birds, mostly bar-headed geese in the northern state of Himachal Pradesh[2]. Avian flu can have a particularly catastrophic impact on seabirds as most species are long-lived and take several years to reach breeding age, rearing only one or two chicks a year. This means that it takes far longer for populations to recover from declines following disease mortality[3]. The link between climate change and avian influenza specifically is not fully understood as yet, but it is thought that its main effect in the epidemiology of avian influenza will be through changes in the distribution, composition and migration behaviour of wild waterbirds, which form the natural reservoir of all avian influenza viruses (Gilbert et al., 2008).

Expected future climate impacts

Climate change poses a serious challenge to migratory waterbirds because of the changes in the suitability of habitat sites, particularly wetlands along their flyways and at each stage of the annual cycle, to feed, rest and breed, by altering environmental conditions and species composition at each site (BirdLife International, 2022b; Breiner et al., 2021; Nagy et al., 2021). Birds can seek cooler climates at higher latitudes or altitudes (though not seabirds) if suitable habitat is available, or they can change the timing of migration or breeding to coincide with more favorable climatic conditions, but there is a limit to how far distributions can shift, and changes in migratory and breeding cycles potentially lead to disrupted relationships between predators, prey and competitors, often resulting in reduced survival (BirdLife International, 2022a).

In a global assessment of future threats to seabirds, Dias et al., (2019) found that storms and flooding appear to be the most salient threats, followed by habitat shifts and alteration (Dias et al., 2019). For some species, the loss of suitable historic sites may be compensated for by other, new sites becoming suitable for the first time, while for other species climate change alterations to their habitat may result in net losses across their entire range, increasing the risk of local or even global extinction (BirdLife International, 2022b; Nagy et al., 2021). Coastal areas on mainland Sri Lanka as well as the numerous small offshore islands represent important breeding grounds for seabird and waterbird species, such as the tern colonies in Ambalangoda Godawaya islet, the rocky coastline at Hikkaduwa Wawalagala Rock, and the Adam’s Bridge Islands in the Gulf of Mannar region[4]. Many of these areas have been designated as

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2 Bird flu: India to cull poultry amid fears of virus - BBC News

3 https://www.rspb.org.uk/birds-and-wildlife/advice/how-you-can-help-birds/disease-and-garden-wildlife/avian-influenza-updates/

4 Seeing Scenic Seabirds - Ceylon Today

marine sanctuaries and granted protection, however they could still be exposed to the impacts of extreme sea level events and storms.

In the case of seabirds, any changes in the abundance or distribution of their prey will also have knock-on effects for survival, fitness and reproductive success, and evidence suggests that these effects will vary depending on the species (Bindoff et al., 2019). Changes in prey availability may be advantageous to some species, and many will be able to adapt by changing their target prey as oceanic seabirds often have broad diets (Spear et al., 2007). However, there is concern about the potential mismatch between the timing of prey abundance near to the coast and timing of the seabird breeding season, as seabirds generally have limited plasticity in their reproductive phenology, which would make seabird populations highly vulnerable to future mismatch with their marine fish or invertebrate prey species (Keogan et al., 2018).

3.2.5. Marine mammals: cetaceans and dugong

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES; REGIONAL STUDIES; GLOBAL STUDIES	MEDIUM agreement MEDIUM evidence	MEDIUM

Current climate impacts

Cetaceans

The near-shore and off-shore waters of the Indian Ocean surrounding Sri Lanka are inhabited by around 37 cetacean species including Sperm whale (*Physeter macrocephalus*), Blue whale (*Balaenoptera musculus*) and over 20 species of dolphins (Gunatilleke et a., 2008). Scientific data regarding the diversity and distribution of cetaceans around Sri Lanka is still lacking, although during the last decade the expanding marine tourism sector is motivating further studies to help understand and manage dolphin and whale watching activities. In 2012, a survey off Mirissa in the south coast of Sri Lanka, between the winter and less dry seasons (January to May), was used to map and document the distribution, pod size and behavioural patterns of cetaceans across an area of ca. 1000 km^2. A total of 8 species of cetaceans were reported: spinner dolphin (*Stenella longirostris*), bottlenose dolphin (*Tursiops truncates*), melon headed whale (*Peponocephala electra*), fin whale (*Balaenoptera physalus*), killer whale (*Orcinus orca*), short-finned pilot whale (*Globicephala melas*), sperm whale and blue whale (Thilakarathne et al., 2015). Of a total of 6675 sightings recorded during the survey, the most sighted species were spinner dolphins (80%), followed by bottlenose dolphins (12%; Thilakarathne et al., 2015). Spinner dolphins, bottlenose dolphins and melon headed whales were observed in shallower areas between the shore and 100 m depth, whereas fin whales, killer whales and short-finned pilot whales were observed in areas between 500–650 m depth, and sperm whales and blue whales were observed further offshore around 1000 m depth areas and beyond (Thilakarathne et al., 2015). For example, Kalpitiya in the northern marine zone has been identified as a marine mammal hotspot and is known for large seasonal gatherings of spinner dolphin and sperm whale along with small groups of killer whales (MoMD&E, 2019).

Blue whales are present in the Northern Indian Ocean waters around India and Sri Lanka during all months of the year (Ilangakoon and Sathasivam, 2012). Strandings in both countries occur throughout the year, but peaks in sightings in certain months may not reflect annual changes in abundance of blue whales, but they are rather an indication of the frequency of opportunistic observations when sea conditions are suitable for tourism (Ilangakoon and Sathasivam, 2012). The infrequent sightings between May – October coincide with the prevailing south-west monsoon making cetacean surveys difficult to nearly impossible off the west and south coasts of Sri Lanka. It is assumed that Antarctic blue whales (*Balaenoptera musculus ssp. intermedia)* remain south of 55°S in the austral summer and venture northwards into temperate waters, e.g. around southern Africa, in winter, while pygmy blue whale (*Balaenoptera musculus ssp. brevicauda*) do not migrate to Antarctic waters but generally remain north of 54°S (Ichihara, 1966; Kato et al., 1995). Accordingly, it has been assumed that the Northern Indian Ocean population are pygmy blue whales (Alling et al., 1991; Mikhalev, 2000; Yochem and Leatherwood, 1985) but their taxonomic status remains as yet uncertain (Ilangakoon and Sathasivam, 2012).

Marine mammals have a higher tolerance and adaptive capacity to environmental changes than some other species such as turtles, and climate change remains a threat, however, the pressures from other human activities can be just as, or more, important to the future of marine mammals in Sri Lankan waters. As evidence from studies from across the world shows, these pressures are causing direct mortality and population declines, as well as heightening vulnerability to future climate change for these species (Wabnitz et al., 2018; Abdulqader et al., 2020).

Since the final moratorium on commercial whaling in 1985, whale populations have increased in abundance throughout much of its global range, although they still face threats from entanglement, vessel strikes and harassment, pollution, habitat degradation, and underwater noise (IWC, 2023a,b; NOAA Fisheries, 2023; Thomas et al., 2015), and the significance of these threats is greater for those populations that are small or that have a restricted range (IWC, 2023a). Furthermore, while global baleen whales have increased in numbers since the whaling moratory, changes have been observed in their behaviour that are in some cases attributed to climate change, raising concerns over their successful recovery (Meynecke et al., 2020).

Cetaceans are capable of shifting location or diet to cope with environmental change (Askin et al., 2017; Barendse et al., 2010; Witteveen et al., 2008). Under specific conditions, whales have been reported to alter migration routes and even skip it altogether (Schall et al., 2021). For instance, across the South Atlantic and the Atlantic sector of the Southern Ocean, female and juvenile humpback whales are known to prolong their stay in the Southern Ocean feeding grounds to fuel growth, pregnancy, or lactation with additional winter feeding (Craig et al., 2003; Brown et al., 1995). Whales are known to exploit new feeding grounds in response to either changes in prey availability or increases in whale numbers, resulting in pods staying on in low latitude regions to feed and mate rather than migrating south (Schall et al., 2021; Askin et al., 2017; Findlay et al., 2017).

Dugong

Dugong (*Dugong dugon*) are migratory, herbivorous marine mammals found in coastal waters ranging from East Africa to Vanuatu in the South Pacific Ocean (IUCN Sri Lanka, 2023b; UNEP, 2002). The global population status of dugong has been assessed as Vulnerable by the IUCN Red List of Species (Marsh and Sobtzick, 2019) although the local dugong population of Sri Lanka is now confirmed as depleted and has been granted a Critically Endangered status and is strictly protected under the fauna and flora protection ordinance (IUCN Sri Lanka, 2023b). The dugong's historic distribution is believed to have been broadly coincident with the distribution of its food, seagrass. Apart from the largest surviving populations of Northern Australian and the Arabian Gulf, elsewhere, populations are small and fragmented (Marsh and Sobtzick, 2019). In Sri Lanka, from a much wider distribution range, dugong are now only found around the northwestern part of Sri Lanka with a scattered population on the East coast, and sightings are mostly restricted to the Palk Bay and Gulf of Mannar areas (Dilmah Conservation, 2023; Ilangakoon and Sutaria, 2008; Karunarathna et al., 2011).

Expected future climate impacts

Climate-related changes in spatial distribution and abundance of plankton and commercially important fish stocks have been documented or predicted, including poleward and depth shifts (Nye et al., 2009; Pinsky et al., 2013; Poloczanska et al., 2013; Grieve et al., 2017; Morley et al., 2018). These changes are also expected to cascade through to cetaceans, but the evidence is scarce (MacLeod 2009; Sousa et al., 2019). Some baleen whales are largely opportunistic foragers that feed on krill as well as small schooling fish (e.g., sardine, anchovy, sand lance and herring) (NOAA Fisheries, 2023; Clapham et al., 1997; Geraci et al., 1989; Baker et al., 1985). Given the high metabolic costs associated with rorqual feeding behaviour, whales may target alternative prey depending on prey density thresholds, below which feeding is not energetically beneficial as they need to build up enough fat in their blubber tissue to sustain them throughout the winter (Goldbogen et al., 2008; NOAA Fisheries, 2023). For example, in the North Pacific, humpback whale diet along the California Current has been shown to echo two major shifts in oceanographic and ecological conditions. Diet was dominated by krill during periods characterized by positive phases of the North Pacific Gyre Oscillation, cool sea surface temperature and strong upwelling, which fuels high krill biomass, while the whales fed mostly on schooling fish during negative NPGO, when surface temperature was warmer and the seasonal upwelling was delayed, so anchovy and sardine populations displayed increased biomass and range expansion (Fleming et al., 2016).

Whales are considered a sentinel species, that will show alterations to key life-history traits such as calving or reproductive rates can be linked to wider environmental changes (Kershaw et al., 2021; Cartwright et al., 2019; Bengtson Nash et al., 2018; Moore and Huntington, 2008). The impacts of climate change on whales are so far unclear (NOAA Fisheries, 2023). At least for the more cosmopolitan species, it is unlikely that climate change alone will directly affect their global population levels or result in direct implications for conservation, although where some species adapt to a changing climate by shifting their distribution, this may force them into new areas with new threats, for example shipping lanes or fishing activity (IWC, 2023a; MacLeod, 2009). Additionally, climate change may also displace or disrupt certain marine activities, resulting in a higher risk of negative encounters and other impacts (NOAA Fisheries, 2023). Overall, climate change still poses an indirect threat through changes in where many whales forage throut the year (NOAA Fisheries, 2023). As Antarctic sea ice coverage is changing, cascading changes in prey distribution could lead to alterations to whales' foraging behaviour and result in nutritional stress (NOAA Fisheries, 2023). Krill abundance is decreasing, and distribution is shifting due to climate-driven processes, both in the Antarctic and the Arctic, and it is essential to assess how whales will respond to future changes (Atkinson et al., 2019; Zerbini et al., 2019; Flores, 2012). Changing water temperature and currents could also impact the timing of environmental cues that are important for the navigation and migration (NOAA Fisheries, 2023).

Some dolphin species are primarily oceanic and warmer water-limited, preferring temperature ranges from sub-tropical to tropical waters, so future increases in water temperature are likely to result in a polewards range expansion for these species (MacLeod, 2009). Furthermore, with sufficient increases in water temperature, it is possible that mixing will occur between populations currently separated by land masses, such as that of southern Africa (MacLeod, 2009).

In the case of dugong in particular, the main threats in Sri Lanka are not necessarily climate-related, as dugong continue to be hunted for their meat, or exposed to accidental and deliberate killing by blast fishing, and entanglement in fishing nets (Rodrigo, 2021). Because of its highly specialised diet, it is expected that the condition of seagrass meadows will strongly determine the future distribution of dugong (AGEDI, 2015; Wabnitz et al., 2018; Preen, 2004). The dugong population of Sri Lanka is declining rapidly (Plön et al., 2019), and therefore, future changes to the abundance, extent and species composition of seagrass habitats, as well as any other human pressures, will strongly determine its future persistence and distribution.

3.2.6. Marine reptiles: sea turtles, saltwater crocodile, sea snakes and water monitors

Data sources	Levels of evidence and agreement	Confidence rating	
SITE-SPECIFIC STUDIES, LOCAL STUDIES, REGIONAL STUDIES	LOW-MEDIUM agreement LIMITED-MEDIUM evidence	LOW	MEDIUM

Sea turtles

There are five species of sea turtles known to nest in Sri Lanka, according to information from the Sri Lanka Sea Turtle Conservation Project (TCP, 2023): hawksbill turtle (*Eretmochelys imbricata*), green turtle (*Chelonia mydas*), olive ridley turtle (*Lepidochelys olivacea*), loggerhead turtle (*Caretta caretta*) and leatherback turtle (*Dermochelys coriacea*).

The south and southwest coastlines of Sri Lanka comprise the largest marine turtle rookeries, with all five species still recorded at the locations of Kosgoda, Induruwa, Rekawa and Bundala (Jayathilaka et al., 2017; Ekanayake et al., 2002). Other rookeries cited in the literature include: hawksbill turtle nests in the Pigeon Islands National Park, Swami Rock, Koneshwaram (Munasinghe and Waduge, 2021); green turtle nests in Sinnapaduwa, Mirissa and Polhena (Munasinghe and Waduge, 2021); olive ridley nests in Goyambokka beach, Tangalle (Ediriweera and Bandara, 2021); and leatherback nests in Godavaya (TCP, 2023).

A survey in 2014 revealed that the highest nesting density (298 nests per km in a year) was recorded at Kosgoda beach, followed by Ahungalla (105 nests per km in a year) and Induruwa (94 nests per km in a year; Jayathilaka et al., 2017). Approximately 68% of the total nesting turtles were Hawksbill and 30% olive ridley turtles, with the rest of the nests belonging to the other three species (Jayathilaka et al., 2017). The highest nesting frequency of green turtle was recorded between February to April whereas the nesting frequency of olive ridley turtle peaked during November to March (Jayathilaka et al., 2017).

Incidental by-catch, illegal poaching of eggs, natural predation on eggs and hatchlings and habitat change and destruction are the main threats faced by marine turtles in Sri Lanka (Jayathilaka et al., 2017).

Male turtles spend all their time at sea, and little is known about their habits, while females come ashore to nest on the same beach they were born, and in some areas, they can be seen having a ‘‘sunbathe’’ on beaches or rocks (TCP, 2023). Most species are highly migratory, moving between nesting and feeding grounds, often 1000s of kilometres apart. Sea turtles are generally assumed to have a life span greater than 80 years, and timing of sexual maturity depends on species. Olive ridley turtles, the smallest in size, take 7 to 15 years, green turtle might take 50 years, and the remaining 3 species including the largest leatherback turtle takes 20 to 30 years (TCP, 2023;

Ahungalla Sea Turtles, 2023). Once the eggs are laid the female turtle leaves them to incubate in sand warmed by the sun, which takes about 60 days before hatching.

Current climate impacts

Climate change can greatly impact species with temperature-dependent sex determination such as sea turtles and specifically green sea turtles. A study of a green turtle population from Great Barrier Reef nesting beaches near Australia, combining genetic and endocrine techniques, showed that those rookeries have been producing primarily females for two decades, suggesting that complete feminization is possible in the near future (Jensen et al., 2018). These findings suggest that increased sand temperatures affect the sex ratios of this population of green turtle in the Great Barrier Reef, such that virtually no male turtles are now being produced from these nesting beaches (Jensen et al., 2018). Furthermore, surveys revealed that increased sea surface temperatures causing coral bleaching are correlated with increased beach sand temperatures, and thereby the incubation environment of sea turtle nests (Fuentes et al., 2009; Girondot and Kaska, 2015).

In Sri Lanka, some of the main threats to sea turtles include natural predation of adults, hatchlings or eggs by other species such as feral dogs and jackals, monitor lizards, wild boar, mongoose as well as ants and crabs on land, and killer whales, sharks and other fish or seabirds in the sea (TCP, 2023). Slaughter of marine turtles for their meat or shell (in the case of hawksbills) is still a traditional practice in many coastal areas, either by targeting nesting females or those trapped in fishing gears.

Degradation and destruction of marine turtle habitats such as coral reefs, seagrass beds, mangroves, sand dunes and beach vegetation are also putting sea turtle populations at risk (MoMD&E, 2019). Unsustainable coral harvesting and mining of both coral and sand are leading to the loss of important feeding and sheltering turtle habitat and accelerating the erosion rate on nesting beaches (MoMD&E, 2019). Increasing noise and light pollution from coastal development causes disturbance to normal nesting behaviour and disorientates hatchlings resulting in higher mortality (MoMD&E, 2019). Finally, marine pollution and particularly marine litter is responsible for injury, disease, starvation and mortality of numerous sea turtles (MoMD&E, 2019), particularly leatherbacks as they tend to ingest plastic film objects mistaken by their natural jellyfish prey (TCP, 2023). All sea turtles in Sri Lanka are under threat from anthropogenic and climatic factors (Ediriweera and Bandara, 2021; Munasinghe and Waduge, 2021).

Expected future climate impacts

Climate change represents an immediate threat to global sea turtle populations. The impacts of rising temperature are particularly pertinent in species with temperature-dependent sex determination, where the sex of an individual is determined by incubation temperature during embryonic development (Jensen et al., 2018). In sea turtles, the proportion of female hatchlings increases with the incubation temperature, and with the predicted average global temperature increases, many sea turtle populations are in danger of high egg mortality and female-only offspring production (Jensen et al., 2018). Rising temperatures may initially result in increased female-biased populations, but the lack of male turtles will eventually impact the overall population persistence (Jensen et al., 2018). The presence of plastic litter on nesting beaches can then aggravate this risk as the accumulation of plastic can further raise the circadian temperature within the sand (Lincoln et al., 2022; Lavers et al., 2021).

Additionally, future changes to the seagrass meadows in Sri Lanka is likely to have an effect on the local sea turtle numbers. Some sea turtle species are omnivores, whereas the hawksbill and the leatherback are specialists, subsisting primarily of sponges (hawksbills) and jellyfish (leatherbacks). Green turtles feed on seagrass shoots (see Turtles, 2024). Recent research demonstrates that in addition to their famously strong fidelity to their natal rookery where they return to nest, sea turtles also exhibit strong foraging-ground fidelity – to the extent where individuals imprint on a specific feeding area instead of feeding in potentially riskier unknown habitats, and this can be passed on to the next generations for the long-term (de Kock et al., 2023).

Extreme weather such as such as storms, cyclones, heavy precipitation and extreme draughts and heatwaves, that lead to damaging effects on the coastline can have negative impacts to laid turtle nests or the hatchlings and can destroy rookery habitats through erosion or debris accumulation (TCP, 2023). This risk is expected to increase in future due to climate change.

Other marine reptiles: estuarine or saltwater crocodile, sea snakes and water monitors

Sri Lanka is home to around 2,500 to 3,500 saltwater crocodiles (*Crocodylus porosus*), the largest living reptile, more than half of which are found in national parks particularly in estuarine systems on the western, southern and eastern coasts of the island (Welikala, 2020; MoMD&E, 2019). Other marine reptiles in Sri Lanka comprise sea snakes and monitor lizards, such as the South Asian Bockadam (*Cerberus rhynchops*; Least Concern: Murphy, 2010) common in mangroves, mudflats and tidal pools; Gerard water snake (*Gerarda prevostiana*; Least Concern: Murphy, 2010) and the common water monitor (*Varanus salvator*; Least Concern: Quah et al., 2021; MoMD&E, 2019). Very little work has been carried out concerning climate change impacts on these 'other' reptile species.

Like sea turtles, saltwater crocodiles, are also highly dependent on key habitats such as estuarine wetlands, mangroves, seagrass beds, intertidal areas and coral reefs, and are therefore vulnerable to their decline, whether that is driven by climate change or through other human pressures such as coastal development, as well as to mortality from bycatch by fishing nets (MoMD&E, 2019). Despite the adaptation to the saline environment, saltwater crocodiles, requires constant or regular access to freshwater for breeding (Fukuda et al., 2022). Climate change threatens this species by destroying their habitat, in particular the freshwater swamps or floodplains where they nest, through saltwater inundation as a result of the sea level rise (Fukuda et al., 2022). A study of the impacts of climate change on *C. porosus*, to quantify the potential loss of nesting habitat through saltwater inundation and sea level rise in the Northern Territory, Australia, found that sea level rise-driven by continuing global warming can be the major threat to mound-nest-building crocodilians, including *C. porosus*, rather than direct impacts from changes in temperature and rainfall (Fukuda et al., 2022). The degree of impact on saltwater crocodiles will be determined by the interplay between the loss of nesting habitat under current global warming, and the ability to expand into new areas (Fukuda et al., 2022).

3.2.7. Offshore and deep-sea environments

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES; GLOBAL STUDIES	LOW agreement LIMITED evidence	LOW

The pelagic marine zone of Sri Lanka extends from the edge of the continental shelf to the boundary of the EEZ and consists of deep-sea, pelagic and mesopelagic environments and harbour a large number of migratory species (MoMD&E, 2019).

The Northern Marine Zone covers the continental shelf in the northern part of the island from Pulmoddai to Talawila (MoMD&E, 2019). The Eastern Marine Zone extends from Pulmoddai to Arugam Bay along the continental shelf (MoMD&E, 2019). A key feature is the Trincomalee canyon, a multiple submarine canyon complex and the largest in the country, which is known to be an important area for cetaceans (MoMD&E, 2019). The South-eastern Marine Zone extends from Arugambay to Ambalantota and is characterized by high energy seas with high waves and swells and strong currents and includes some offshore rocky and boulder reef habitats, rather than fringing reefs, such as Great and Little Basses reefs (MoMD&E, 2019). The Southern Marine Zone from Ambalangoda to Ambalantota contains deep rocky reefs and rock habitats as well as fringing reefs (MoMD&E, 2019). The Southern Zone, particularly offshore from Mirissa, is important for residential and transient populations of blue whale and sperm whale (MoMD&E, 2019). The Western Marine Zone extends from Ambalangoda to Talawila and include some offshore deep patchy reefs at depths of 15 to 30 m (MoMD&E, 2019).

Current climate impacts

The deep ocean provides a critical buffer to climate change, helping to lock away both greenhouse gasses and heat for considerable periods of time, but climate change exposes vulnerable ecosystems to combined stresses of warming, ocean acidification, deoxygenation, and altered food inputs (Levin and Le Bris, 2015). For example, measurements in some deep basins globally have shown that waters have warmed by 0.01°C per year (Purkey and Johnson, 2010). It has also been demonstrated that food supply to the deep seafloor has been impacted by declines in oceanic plankton productivity at certain localities, which could affect the productivity of deep-sea benthic food-webs (Levin et al., 2020). These alterations may therefore threaten biodiversity and compromise key ocean services (Levin and Le Bris, 2015). The Indian Ocean has relatively few seamounts and islands, although it contains numerous submarine plateaus and rises (Ingole and Koslow, 2005). Earlier biological studies in the central Indian Ocean basin reported diverse abyssal benthic communities (Ingole and Koslow, 2005). However, the deep-sea fauna in the central Indian Ocean basin is the least studied among the three oceans (Pavithran et al., 2007). Some of the deep-sea features of the Sri Lankan EEZ such as the Trincomalee canyon system are associated to aggregation sites for cetaceans (MoMD&E, 2019). Overall, however, the extent of the offshore and deep-sea regions within the Sri Lankan EEZ has not yet been fully explored or even characterised, making it difficult to understand what specific risks or changes to expect.

Expected future climate impacts

There exist large gaps in understanding of the physical and ecological feedbacks that will occur in the deep-sea as a result of global climate change (Levin and Le Bris, 2015), particularly in poorly studied basins such as the central North Indian Ocean where Sri Lanka is located, making it very difficult to predict future risks of climate change.

3.2.8. Coral reefs

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES, REGIONAL STUDIES, GLOBAL STUDIES	HIGH agreement ROBUST evidence	HIGH

There are fringing and offshore reefs of varying conditions around the island, but generally true coral habitats are limited to areas with lower levels of sedimentation in the north-western and eastern coastal areas (Rajasuriya, 1997). Elsewhere sandstone and rocky habitats extend from near-shore areas to offshore areas to depths more than 50 m, and although living corals colonize them to varying levels, live coral cover on these habitats is generally below 10% (Rajasuriya, 1997).

A total of 183 species of stony corals from 68 genera have been recorded from Sri Lanka, with Acropora, Montipora, Porites, Favia, Favites, Pocillopora, Goniastrea, Platygyra and Leptoria being the dominant reef-building coral families (Gunatilleke et al., 2008; Rajasuriya, 1997). Around 120 species of coral have been identified within the Gulf of Mannar and Palk Bay areas alone (BirdLife International, 2023).

The growth of coral reefs around Sri Lanka is influenced mainly by exposure to monsoons, which has a major impact on the level of turbidity and freshwater input into the coastal waters and limits the true, larger coral reefs to the north-western and eastern coastal areas and to fringing reefs around the Jaffna Peninsula, where run-off and sedimentation is low due to the semi-dry climate (Miththapala, 2008; Wilkinson, 2008; Rajasuriya, 1997; De Silva and Rajasuriya, 1989; Rajasuriya 1991). Coral reefs are also found along the southern coastline (Wilkinson, 2008). Nearly all of Sri Lanka's reefs are located within 40 km from the coast and they contribute significantly to the marine fish production (Rajasuriya and White, 1995). Other reef-like habitats of sandstone and rock are extensive and widespread in near-shore to offshore areas and can reach to depths of more than 50 m, but live coral cover in these hard substrates is generally below 10% (Rajasuriya, 1997), see Figure 18.

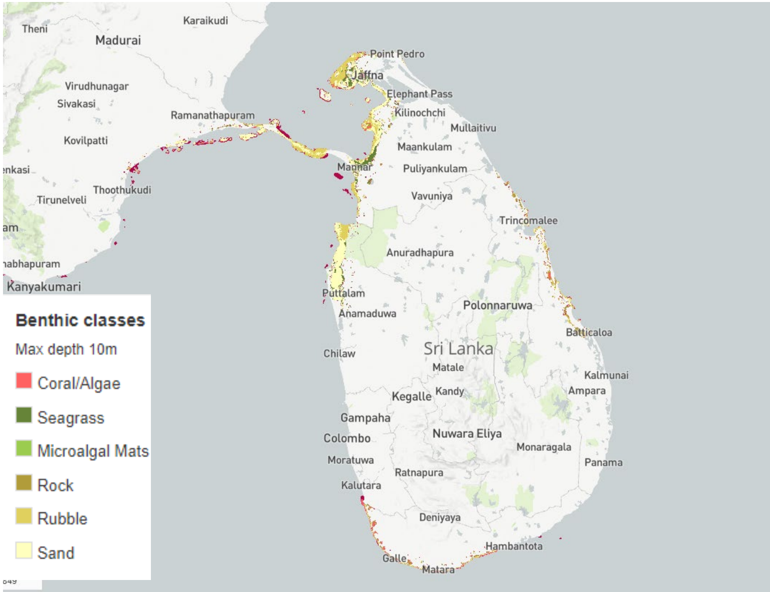

Figure 18. Distribution of key coastal substrates around Sri Lanka (Allen Coral Atlas, 2022).

Current climate impacts

During the El Nino event in 1998, high sea surface temperatures (3–5°C above normal) bleached extensive sections of some of Sri Lanka's coral reefs; Bar Reef marine sanctuary (95%); Hikkaduwa marine sanctuary (90%); Weligama (60%) and Rumassala (80%) (Rajasuriya, 2005). Figure 19 shows how surveys of coral reefs before, during and after the El Niño event of April-May 1998, reflected an extensive bleaching of corals down to 8 m depth and the drastic reduction of associated fish populations (IUCN Sri Lanka, 2023a). Recovery was slow and variable due to overgrowth of calcareous *Halimeda* sp. and other algal species (Gunatilleke et al., 2008; Rajasuriya, 2002; Lindon et al., 2002). Following the 1998 event, global coral reefs decreased by 16%, with up to 50% loses in the Indian Ocean (Wilkinson, 2004), which combined with damage as a result of other local destructive human activities caused more damage to Indian Ocean reefs than the Tsunami of 2004 (Wilkinson, 2008). In Sri Lanka, the impact of the 1998 bleaching event was very severe, with live coral cover in the Bar Reef and Hikkaduwa marine parks plummeting to less than 10% (Wilkinson, 2008).

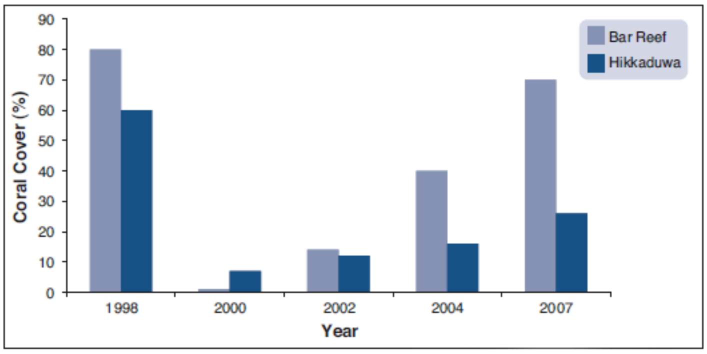

Figure 19. Extensive bleaching of corals during and after the El Niño event of April-May 1998, from IUCN Sri Lanka (2023a). Original source: Data obtained from Arjan Rajasuriya/NARA, CORDIO, and GCRMN, extracted from Wilkinson (2008).

Over 65 percent of reefs in the Indian Ocean are at risk from local threats, with one-third rated at high or very high risk (Burke et al., 2011). The single biggest threat is overfishing, especially on the densely populated coastline of Sri Lanka (Burke et al., 2011).

Ocean acidification represents another climate change-driven threat to coral reefs (IUCN Sri Lanka, 2023a). Since the 1980s especially, the global oceans have absorbed more than 93% of the greenhouse gases emitted by human activities (Laffoley and Baxter, 2016), leading to an increase of dissolved carbon dioxide in the ocean that forms carbonic acid and results in a decrease in carbonate ions available for corals to form calcium carbonate (Miththapala, 2018) (see section 3.1.4 of this report).

Intensive and poorly managed dredging, deforestation and land reclamation from coastal development activities can remove the coastal vegetated habitats that help protect coral reefs (IUCN Sri Lanka, 2023a). The result is increased sedimentation and turbidity, which can potentially smother the coral reefs and deprive coral polyps and their symbiotic algae of sunlight, leading to coral die-offs (IUCN Sri Lanka, 2023a). Run-off from agricultural land also increases the level of nutrients flowing into the ocean, which can promote macroalgae growth and reef smothering (Burke et al., 2011; Miththapala, 2018). Other forms of marine pollution from both land-based industries and marine spills are also having a negative impact on corals (IUCN Sri Lanka, 2023a).

Coral predation by invasive corallivorous predators, such as the crown-of-thorns (COT) starfish, is an additional increasing risk (IUCN Sri Lanka, 2023a). The increase in the frequency of COT outbreaks is linked to overfishing of the starfish's natural predators such as humphead wrasse and giant triton, as well as eutrophication of coastal waters, with South and Southeast Asia been amongst the most affected regions (Miththapala, 2018).

Finally, other threats to coral reefs include harmful, unregulated and careless tourism practices (IUCN Sri Lanka, 2023a).

Expected future climate impacts

Coral reefs are expected to decline significantly as oceans become warmer and with a reduced pH. By 2030, projections suggest that climate change will increase overall threat levels beyond 80 percent (IUCN Sri Lanka, 2023a). By 2050 all areas will be considered threatened from the combination of local and climate-related threats, and most will fall under high risk from thermal stress and moderate risk from acidification (Burke et al., 2011). A modelling study of the environmental tolerances of over 650 Scleractinian coral species, based on present-day conditions and distribution ranges, forecasted potential coral species richness under two emission scenarios representing the Paris Agreement target (SSP1-2.6) and high levels of emissions (SSP5-8.5) (Couce et al., 2023). Predictions indicated considerable declines in coral species richness for the majority of tropical coral reefs, with a net loss in average local richness of 73% (Paris Agreement) to 91% (High Emissions) by 2080–2090 and particularly large declines across sites in the western Indian Ocean (comparable to Great Barrier Reef, Coral Sea, and Caribbean) (Couce et al., 2023). The same study also suggested that at regional scales, the Western Indian Ocean is likely to experience dramatic reductions of average local coral richness (80.6% loss) even under the Paris Agreement scenario by 2080–2090 (Couce et al., 2023), while environmental suitability could be largely maintained (limited to 30% loss) under the Paris Agreement target in the central Indian Ocean. These projections of coral decline highlight the importance of mitigating climate change to avoid potential massive extinctions of coral species (Couce et al., 2023).

In terms of aragonite saturation, which is one of the ocean acidification parameters directly relevant to coral calcification, it is known to have a positive relationship with sea surface temperature warming (Jiang et al., 2015). Couce et al., (2023) conclude that regions experiencing the greatest warming (such as the central Indian Ocean) are expected to maintain high levels of aragonite saturation.

3.2.9. Mangroves

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES, GLOBAL STUDIES	HIGH agreement ROBUST evidence	HIGH

The Southern Marine Zone includes estuaries and major wetland habitats including mangroves (MoMD&E, 2019). Similarly, the Eastern Marine Zone hosts some of the largest mangrove stands in Sri Lanka, nested within estuaries and lagoons, such as in the Mahaweli River estuary (MoMD&E, 2019). The Western Marine Zone features extensive mangroves along the Bolgoda estuary, Kalu Ganga estuary, the Bentota river estuary and Negombo lagoon (MoMD&E, 2019). In addition to providing a cost-effective natural disaster risk reduction, mangroves deliver many other valuable socioeconomic benefits to Sri Lankans, particularly in areas of poor living standards where they are used for timber, housing constructions materials, tannins and fishing materials (Veettil et al., 2023). Some mangrove products, such as the mangrove apple, are also used for making edible products, and a number of chemical substances were recently extracted from microorganisms associated with mangroves in Sri Lanka that have valuable medicinal value, such as antibacterial and anti-obesity properties (Veettil et al., 2023).

Mangroves are adapted to grow under saline conditions and a fluctuating water table (Gunatilleke et al., 2008). A total of 32 mangrove species are reported for Sri Lanka including rare species as well as 21 of the true mangrove species mostly from the main families of Rhizophoraceae, Acanthaceae and Avicenniaceae, and dominated by *Rhizophora apiculata*, *Rhizophora mucronata, Ceriops tagal, Bruguiera gymnorhiza, Acanthus illicifolius, Lumnitzera racemosa, Avicennia officinalis* and *Avicennia marina*, which together represent one third of the world's mangrove species diversity. *Pemphis acidula* is also reported, which is endemic to the Gulf of Mannar (BirdLife International, 2023). The extent of mangrove forests in Sri Lanka is yet to be mapped in detail (Veettil et al., 2023; MoMD&E, 2019; Gunatilleke et al., 2008; Arulchelvam, 1968).

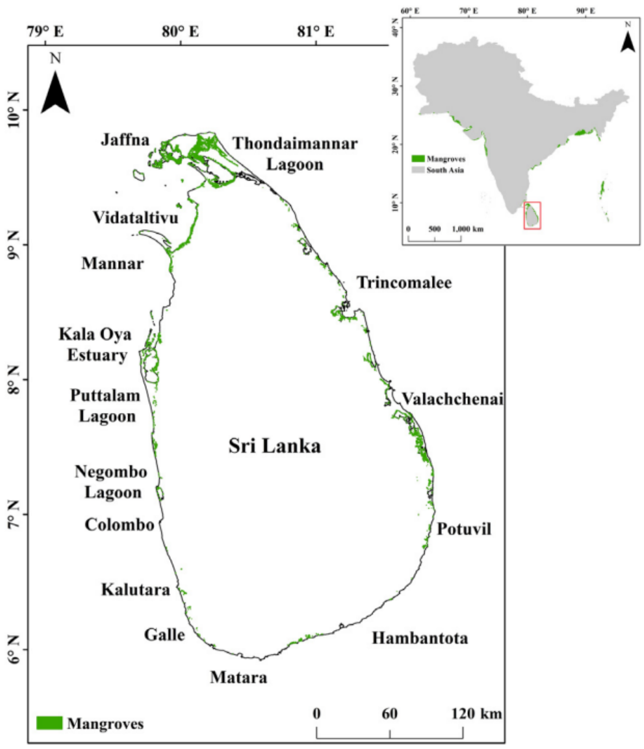

Figure 20. Mangrove forests along the coast of Sri Lanka. From Veettil et al., (2023). Original source Spalding et al., (2010) and Giri et al., (2011).

Figure 20 shows the estimated distribution of mangrove forests along the coast of Sri Lanka. A relatively recent inventory by the Department of Forest has suggested a total area of 19,726 ha consisting mostly of scattered and disconnected stands, but they are generally in sub-optimal condition with a few exceptions in the north-western (Gangewadiya), northern (Vidaththalaithiv Nature Reserve) and north-eastern (Gangi, Upparu in Mahawali river mouth) coastal belts (MoMD&E, 2019), and best preserved examples in Jaffna, Batticaloa, Kalpitiya, Rekawa and Trincomalee (Gunatilleke et al., 2008). In addition to fragmentation due to deforestation for coastal developments particularly along estuarine and lagoonal areas, the low tidal amplitude along much of the Sri Lankan coastline limits the landward distribution of mangroves to less than 3 km in most instances (MoMD&E, 2019; Gunatilleke et al., 2008).

In Sri Lanka, mangrove habitats are highly connected, physico-chemically and ecologically, to salt marsh, seagrass and sand dune ecosystems, but this interconnection is under increasing threat by a rapid development of aquaculture in the country (MoMD&E, 2019). The growth of the shrimp farming industry between 1986-2016 propelled by the aquaculture of tiger shrimp (*Penaeus monodon*) and crabs is a cause for concern, especially for the mangroves in the Northwestern and Eastern provinces, in addition to the continued encroachment and alteration of mangroves and salt marshes for settlements in the Western and Southern provinces (MoMD&E, 2019).

Current climate impacts

Natural threats to coastal mangrove forests include storms, salinity changes and floods (Veettil et al., 2020a,b). For example, climate change and ocean climate anomalies such as La Niña and El Niño can enhance rainfall as well as river discharge levels (Veettil et al., 2020a). Climate-driven, long-term sea level rise combined with the effect of the reversing monsoon typical of the Indian Ocean can also significantly increase seasonal sea surface heights in the region aggravating coastal flooding, erosion and drastically altering sediment transport and accretion in some exposed locations as shown by studies in Vietnam (Veettil et al., 2020a) and the Andaman and Nicobar Islands (Veettil et al., 2020b).

In Sri Lanka, alterations in river hydrology in southern coastal areas have resulted in changes in mangrove habitats and floristic composition, including loss of mangroves and growth/dominance of new species (Veettil et al., 2023; Dahdouh-Guebas et al., 2005). For example, following the increased freshwater inflow to Kalametiya Lagoon as part of an irrigation project, an overall expansion of *Sonneratia caseolaris* and *Typha angustifolia* mangroves was observed, which have a low saline preference, together with an overall reduction in mangrove diversity (Veettil et al., 2023; Madarasinghe et al., 2020).

Certain natural disasters such as tsunamis can offer insights when considering potential long-term and large-scale climate change impacts. On 26th December 2004, the world's fifth-largest earthquake in a century caused a tsunami that propagated across South and Southeast Asia including Sri Lanka and caused a tsunami that affected coastal and marine habitat areas including mangroves through direct wave damage, saltwater inundation and sand deposition (Gunatilleke et al., 2008). Over the years following, there were signs of recovery and regeneration of the coastal vegetation (Fernando et al., 2006; Gunatilleke et al., 2008). In the particular case of

Sri Lankan coastal mangroves directly affected by the tsunami, human activity exacerbated the damage inflicted on the coastal zone by the tsunami (Dahdouh-Guebas et al., 2005). Fringing mangroves near the water edge took all the energy and were damaged, showing for instance leaf loss on creek-fringing *N. fruticans*, but the anchoring system of the rhizomatous stems withstood the tsunami impact and new young leaves emerged less than a month later (Dahdouh-Guebas et al., 2005). Other true mangrove representatives such as *Sonneratia* spp., the stem of which can measure several meters in circumference, or *Rhizophora* spp. and *Bruguiera* spp., which have wide roots, also stood up well against the surge (Dahdouh-Guebas et al., 2005). Forests dominated by less typical mangrove associates however were severely damaged demonstrating that mangroves play a critical role in storm protection, but this depends on the quality, size and structure of the mangrove forest (Dahdouh-Guebas et al., 2005). Dahdouh-Guebas et al., (2005) concluded that conversion of mangrove land into shrimp farms, tourist resorts, agricultural or urban land over the past decades (Foell et al., 1999), as well as destruction of coral reefs off the coast, likely contributed significantly to the damage and loss of life during the tsunami event. This and other similar studies have prompted a realisation of the vital importance of coastal mangroves and launch of the Sri Lanka Mangrove Conservation Project in 2015, a joint programme between the Sri Lankan government, the fisheries federation National Coordinating Body member Sudeesa, and US based NGO Seacology, that has made Sri Lanka the first nation in the world to comprehensively protect all its mangrove forests[5] (Seacology, 2024).

Expected future climate impacts

The dense system of above-ground roots in healthy coastal mangroves that helps the trees survive in waterlogged and tidal conditions also create habitat for many animal species and contributes to stabilising sediments and mitigating erosion by buffering against waves, wind, and excess water during surges, flooding, or storms, thus acting as a natural barrier and protecting coastal communities and infrastructure (IPCC, 2012; Das and Vincent, 2009). Sea-level rise, storm damage, warming temperatures and changes in precipitation are all likely to impact mangroves globally in the future (Lincoln et al., 2021a; IPCC, 2013; Lelieveld et al., 2012; Ward et al., 2016; Li et al., 2019; Clough, 2013; Ranasinghe, 2012) due to negative effects on forest health and productivity, photosynthesis, respiration, recruitment, biomass allocation, inundation periods, sediment input, accretion rates and ground-water levels (Ellison, 2015). Sea level rise is a particular concern for mangroves, but it is not clear how mangroves will respond. In Sri Lanka, mangrove reductions (up to 66%) due to sea level rise have been predicted in the Negombo estuary by the year 2100 (Veettil et al., 2023; Perera et al., 2018). For some mangrove species such as *R. mucronata*, prolonged

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[5] Sri Lanka announces nationwide protection for mangrove forests | Mangroves for the Future - Investing in coastal ecosystems

submerged conditions may lead to restricted photosynthesis and long-term carbon starvation (Veettil et al., 2023; Arachchilage et al., 2020). While some studies suggest that mangrove growth may not be able to keep pace or accrete sediment as fast as rising sea levels this century, other studies suggest that if sea level rise was to be limited or slowed down, this might be possible (Wilson et al., 2017). High mangrove density has been underlined as critically important in coastal areas susceptible to sea level rise in Sri Lanka (Veettil et al., 2023; Kumara et al., (2011). Given the space and time and assuming that inputs of freshwater and sediments are suitable, coastal mangroves may be able to persist and retreat landwards as sea levels rise, and the aftermath of the 2004 tsunami in Sri Lanka demonstrates how these habitats are able to recover even after devastating natural disaster impacts (Dahdouh-Guebas et al., 2005). However, coastal squeeze and other human pressures may undermine resilience of mangroves, and threaten many of the important resources and ecosystem services of these wetlands, including fisheries, coastal protection, water quality and carbon sequestration (see for example Lincoln et al., 2021a). The impact of climate change on coastal mangroves is undermining and the coastal protection function provided by these ecosystems against storms and tides (MoE, 2021).

It is expected that changes in rainfall patterns as well as rising atmospheric and sea surface temperatures will shape future mangrove distribution in Sri Lanka (Veettil et al., 2023). These climatic pressures are compounded with those from other activities such as deforestation, coastal development, runoff, pollution including plastic litter (Lincoln et al., 2023), sand mining and land reclamation, which are having a particularly acute impact and in many places are accelerating the decline of coastal mangroves in countries (Biju Kumar et al., 2017). In the case of Sri Lanka, major threats to mangrove ecosystems include urbanization and pollution although it is the expansion of shrimp ponds and agriculture what has been as advocated as presenting the biggest threat to mangroves in the country (Veettil et al., 2023). Finally, over-grazing has been recognized as one of the causes of mangrove habitat loss to some extent in Sri Lanka, including propagule predation by grapsid crabs and snails that may be linked to rainfall and water level (Veettil et al., 2023; Dahdouh-Guebas et al., 2011; Cannicci et al., 2008a,b).

Some studies on *Avicennia marina* have shown small increases of photosynthesis in response to higher CO2 concentrations (Alongi, 2015), however overall, mangroves along with coral reefs, are one of the most vulnerable habitats to climate change and are expected to witness severe impacts (IPCC, 2014). It will be necessary to determine the baseline extent and condition of mangrove forests in Sri Lanka in order to ascertain long-term changes and the risk presented by climate change into the future (MoMD&E, 2019; Gunatilleke et al., 2008; Arulchelvam, 1968).

3.2.10. Seagrass meadows

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES, GLOBAL STUDIES	MEDIUM agreement MEDIUM evidence	MEDIUM

The Northern Marine Zone is characterized by low wave energy and flat, shallow seabed areas dominated by soft bottom benthic communities, seagrass meadows and fringed by coastal mangroves (MoMD&E, 2019). There are seagrass beds that extend to the northwest towards Rameswaram Island in India and from Mannar to Jafnna and around the Jafnna lagoons (MoMD&E, 2019). The Eastern Marine Zone includes extensive seagrass habitat in Batticaloa, Valachchenai and Vakarai, and along the coast (MoMD&E, 2019). The coastline of the Western Marine Zone features significant seagrass habitats (MoMD&E, 2019). The Southern Marine Zone includes only patchy seagrass meadows such as those in lagoon areas at Hikkaduwa, Weligama, Dondra, Ahangama and Rekawa (MoMD&E, 2019).

Sri Lanka is part of the Indo-Pacific seagrass bioregion, with a total of 15 confirmed seagrass species (Udagedara and Dahanayaka, 2020). Extensive seagrass meadows have been recorded off the northern coast of Sri Lanka, specially between Dutch Bay and the Jaffna peninsula, and between Mannar across Palk Bay and to Rameswaram Island on the Indian coast (BirdLife International, 2023; MoMD&E, 2019). The extent of seagrasses in Sri Lanka is estimated to be 37,137 ha., although there are inconsistencies with reported values ranging from 23,819 to 293,400 ha (Gunatilleke et al., 2017; SLCZCRMP, 2018; Vanderklift et al., 2019; Udagedara and Dahanayaka, 2020) highlighting the need for detailed ground-truthing and standardized methods (Udagedara and Dahanayaka, 2020). *Halophila beccarii* is a rare species and it has only been recorded in a few localities in Sri Lanka (Udagedara and Dahanayaka, 2020). *H. beccarii* harbors molluscs and calcifying leaf epiphytes (Meeran et al., 2018), and therefore it can provide refuge to these calcifying organisms from ocean acidification (Bergstrom et al., 2019; Mishra and Apte, 2021)

Seagrass meadows contribute to coastal protection and act as nursery or feeding grounds for marine animal species, including commercially targeted species (Libin et al., 2017). These meadows are also a critical habitat for conservation significant species including sea turtles, dugong, finless porpoise *Neophocaena phocaenoides*, humpback dolphin *Sousa plumbea* and saw-fish rays (BirdLife International, 2023; MoMD&E, 2019; Gunatilleke et al., 2008). Seagrass ecosystems contribute to climate change mitigation through their carbon sequestration and long-term storage capacity (Macreadie et al., 2019; Serrano et al., 2020).

There are many anthropogenic activities that negatively impact seagrasses, and decline was recorded at around 96% in the Northern, Eastern and Western parts of Negombo Lagoon from 1997 to 2004 (Silva et al., 2013; Udagedara and Dahanayaka, 2020). Seagrass beds have been badly affected by destructive fishing practices, especially the continuing of bottom-set trawling in the north-western coast and Gulf of Mannar area, as well as the use of drag and push nets to catch fish for ornamental industry, as well as illegal dynamite fishing (MoMD&E, 2019; Joseph, 2011; Udagedara and Dahanayaka, 2020). Flash floods and increasing levels of nutrients and suspended solids due to soil erosion threaten seagrass species that are sensitive to excessive siltation (MoMD&E, 2019). Studies have estimated a 20% loss in Negombo Lagoon alone due to micro-algal proliferation resulting from eutrophication, and in Negombo, Puttalam and Mannar, waste dumping has also led to extensive decline (MoMD&E, 2019). High loading of dissolved nutrients, concentrations of heavy metals such as mercury, cadmium, lead and arsenic have been reported from seagrass sediments from Gulf of Mannar and Palk Bay, that have been linked to waste dumping and addition of untreated effluents, as well as runoff of agricultural chemicals during monsoon rains, which is a concern for the seagrass and the marine biota that depends on these habitats (Libin et al., 2017).

Current climate impacts

Since the 1990s, global annual rate of loss for seagrasses has been estimated to range from 0.4 to 16% (Erftemeijer and Lewis, 2007; Waycott et al., 2009; Pendleton et al., 2012). This decline is attributed to the combined effect of human pressures in coastal areas, mainly driven by poor water quality and direct damage, despite the implementation of a range of conservation and restoration efforts (Short et al., 2011; Cullen-Unsworth and Unsworth, 2016; Greening and Janicki, 2006; Roca et al., 2015; Demers et al., 2013; Orth et al., 2017; Marion and Orth, 2010; Evans et al., 2018). Scouring, siltation and increased turbidity, resulting from strong storms and wave action can also damage seagrasses causing leaf decay and in extreme cases burial and die backs (Lincoln et al., 2021a; Björk et al., 2008; Green and Short, 2003; Vermaat et al., 1997; Edwards, 1995; Marbà and Duarte, 1994). However, seagrasses may be able to keep up with rising sea levels by colonizing new areas, and maintaining their optimal depth (Björk et al., 2008; Edwards, 1995; Lincoln et al., 2021a).

The seagrass meadow of Kapparathota in Weligama Bay, is considered one of the largest and diverse meadows of southern Sri Lanka, however, detailed ecological surveys between 2009 and 2010 indicated a gradual decline in the seagrass abundance, ground cover and species composition, including the disappearance of two of the five species, *C. rotundata* and *H. pinifolia* (Iroshanie et al., 2021). The causes for these shifts are still uncertain but there were indications of increased sedimentation through erosion and runoff, which could have a climate-related cause, as well as clear signs of macroalgal invasion and increased nutrient influx (Iroshanie et al., 2021). A decade later in 2020, a follow-up survey reported further shifts in the meadow, which is now formed of only two species, *T. hemprichii* and *Syringodium isoetifolium*, while macroalgae had proliferated and taken over 75% of the canopy cover within the meadow, likely due to excess nutrient inputs from coastal settlements, fish landing centres and tourist resorts (Iroshanie et al., 2021).

Expected future climate impacts

It is expected that in Sri Lanka, seagrass meadows will be increasingly exposed to the risks of future warming temperatures, rising sea levels, and extreme weather events, which threaten to worsen the current decline of seagrass habitats globally (Waycott et al., 2007; Waycott et al., 2011). Where seagrasses are already exposed to challenging local conditions of water quality, this can undermine their resilience and exacerbate their vulnerability to climate change stressors (Lincoln et al., 2021b).

On the other hand, it has been suggested that seagrasses productivity might be stimulated under higher CO_2 conditions (Manzello et al., 2012; Lincoln et al., 2021a).

3.2.11. Sandy shorelines

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES REGIONAL STUDIES	MEDIUM agreement LIMITED evidence	LOW

Sri Lanka has a coastline of 1,585 km, and many of the beaches fringing the island are wide and sandy, providing ideal habitats for nesting turtles (Gunatilleke et al., 2008) but the extent of these habitats does not appear to have been fully quantified. The Eastern Marine Zone comprises some stretches of sandy shorelines, and the South-eastern Marine Zone includes some barrier beaches and sand dunes facing high energy seas (MoMD&E, 2019). The Southern Marine Zone also features sandy beaches along with several important estuaries (MoMD&E, 2019).

Current climate impacts

Beach habitats in Sri Lanka are disappearing rapidly mainly due to settlement, sand mining and tourism developments. In addition, accelerated erosion is a concern along the entire southern coastline (MoMD&E, 2019). Some of the sandy beaches are backed by important sand dune formations, although in areas such as Pooneryn in the north and in Bundala National Park, sand dunes have been destroyed or flattened for sand mining and tourism and recreation or due to wind erosion after loss of dune vegetation (MoMD&E, 2019).

While there is limited information available on the impacts of climate change on these sandy shorelines of Sri Lanka, unregulated uses of these habitats undermines their resilience and increases their vulnerability to climate impacts. Across the globe, future climate change-related rising sea levels, increased rainfall, higher wind speeds, larger waves, and changes to oceanic currents are predicted to increase the risk of coastal erosion (Browne et al., 2015). Increases in wave height and changes to wave period together with mean sea-level rise are important contributing factors to erosion on sandy and sedimentary coastlines, and there are indications that that significant wave height and wave period are increasing for most of the Indian coastline for example (Chowdhury et al., 2020).

Expected future climate impacts

Into the future, for the region of Sri Lanka and India, there is a higher probability of swell waves and erosion, and wave penetration into estuaries and harbours, particularly under the effect of Southern Ocean swells (Chowdhury et al., 2020). Significant increases in extreme waves are projected for the wider Indian Ocean (IPCC, 2012), so it is possible to expect this to be the case for Sri Lanka as well.

A coastal vulnerability study of the Indian district of Thoothukudi in the Gulf of Mannar highlighted that sea-level rise is accelerating coastal erosion and loss of beach width and slope and increasing the risk of inundation from the sea (Parthasarathy and Natesan, 2015). In the Indian state of Tamil Nadu, across the Gulf of Mannar from Sri Lanka, beach erosion is continuing at high rates (Chowdhury et al., 2020), exacerbated by improper practices related to sand mining, urban development, and the industrialisation of the coastal zone (Parthasarathy and Natesan, 2015). Acute flooding and erosion events are more likely during the seasonal monsoon, therefore any climate-driven changes to the strength of rain and wind and the likelihood of extreme weather or sea levels events, such as storm surges, combined with improper management of sandy shorelines, will accentuate the risk of beach and dune erosion and loss in Sri Lanka (Lincoln et al., 2023; MoMD&E, 2019).

It would be necessary to survey and characterise the extent of sandy shoreline habitats in Sri Lanka, and to understand any local pressures, particularly extractive activities, in order to quantify and qualify future climate risks (Gunatilleke et al., 2008).

3.2.12. Saltmarshes, mudflats and estuaries

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES, REGIONAL STUDIES, GLOBAL STUDIES	MEDIUM agreement LIMITED evidence	LOW

Research studies on coastal saltmarshes in South Asian countries are scarce, including in Sri Lanka (Patro et al., 2017). An earlier estimate of saltmarsh extent in Sri Lanka provided by Gunatilleke et al., (2008) indicates a total area of 33,573 ha, although the extent of these habitats has not been mapped accurately since (MoMD&E, 2019). Saltmarshes are confined to the intertidal flats in the northwestern and southeastern arid zones of Sri Lanka (see Gunatilleke et al., 2008 and references within). They are dominated by the halophytic or salt-loving plants *Halosarcia indicum*, *Salicornia brachiata*, *Sueda maritima*, and *S. monoica*, and provide habitats for waterfowl and milkfish (Gunatilleke et al., 2008). An estimate of estuarine and lagoonal habitats in Gunatilleke et al., (2008) indicates a total area of 158,017 ha, while the extent of mudflats is unknown.

The Eastern and South-eastern Marine Zones include important riverine estuaries and lagoons (MoMD&E, 2019). The Southern Marine Zone includes the Madu River, Gin

Ganga, Nilwala River, Walawe River and Kalametiya, and major wetland habitats spread along these estuaries (MoMD&E, 2019). In certain parts of the country river diversions have resulted in an influx of freshwater changing the salinity levels and decreasing water quality such as in Bundala, while barrage construction to stop saltwater intrusion into lagoons in the Northern Province is a threat to mangroves as well as saltmarshes (MoMD&E, 2019). In recent years saltmarshes as well as mangroves have become threatened by clearance for salterns in areas such as Puttalam (MoMD&E, 2019).

Extensive areas of saltmarsh, as well as other coastal wetland habitats and sand dunes, were affected by the December 2004 tsunami, with vegetation destroyed by the force of the wave, saltwater inundation and sand deposition (Gunatilleke et al., 2008). Most vegetation types have shown recovery and regeneration with time but the impact on individual species has not been assessed fully (Fernando et al., 2006).

The accumulation of solid waste and substantial levels of pollution of brackish water in estuaries is a critical concern that also threatens all interconnected coastal habitats (MoMD&E, 2019). The estuaries in Negombo and Chilaw are reported to be especially polluted, with long shore currents periodically bringing in solid waste from transboundary countries, further worsening the situation (MoMD&E, 2019).

Current climate impacts

Coastal saltmarshes, estuaries and mudflats are exposed to rises in mean sea-level rise as well as extreme sea surges and storm damage, but they are also increasingly exposed to desiccation during prolonged hot and arid conditions, as well as agricultural conversion, reclamation for development, excessive siltation, reduced water quality, changes in water regimes, excessive biomass removal, loss of biodiversity and introduction of exotic species (ENVIS, 2014). Reports on the risks and status of saltmarshes from tropical regions are few but overgrazing by cattle, conversion to saltpans and conversion to aquaculture ponds have been highlighted as major threats to the saltmarsh habitats of Sri Lanka (Patro et al., 2017; Lowry and Wickremeratne, 1987). Other threats like pollution and eutrophication also affect saltmarshes, though specific studies have not been undertaken in South Asian countries (Patro et al., 2017).

The response of these wetland habitats to a changing climate may be especially complex, more so than that of either fully terrestrial or fully marine ecosystems because they exist at the interface of land and sea (Poppe and Rybczyk, 2021). While wetland plants and animals have typically evolved to withstand highly variable environmental conditions as part of tidal and seasonal cycles, they are sensitive to both extreme and chronic stressors such as changes to temperature, salinity, freshwater flows, and input of sediment or nutrients from runoff, which can in-turn affect the resilience of saltmarsh plants and animals to climate change impacts (Poppe and Rybczyk, 2021). For example, changes in plant productivity and decomposition rates, above ground and below ground biomass, and stem density will determine the effects on a larger scale, with implications for species composition, elevation change, nutrient cycling, carbon sequestration, food webs, and ultimately marsh survival (Poppe and Rybczyk, 2021).

According to a NASA-led study, the world has witnessed a net loss of saltmarsh globally, equivalent to an area double the size of Singapore (719 km^2), with a loss rate of 0.28% per year from 2000 to 2019 (Campbell et al., 2022). Russia and the USA accounted for 64% of saltmarsh losses, driven by hurricanes and coastal erosion, highlighting the vulnerability of saltmarsh systems to sea level rise and storminess (Campbell et al., 2022).

Expected future climate impacts

Changes in land-use and inland catchment-management, together with changes to precipitation patterns, will also affect freshwater flows and sediment supply to the coastal zone from river networks (Burden et al., 2020). Changes in seasonal extremes will also affect timing, quantity and potentially source of sediment (Burden et al., 2020). On the other hand, sea-level rise will affect saltmarshes in different ways depending on local context. Marshes with higher tidal ranges and higher sediment loads will be more resilient, as they will remain able to keep pace with sea-level rise by accreting vertically (Burden et al., 2020). However, the lateral extent of marsh could be reduced as deeper water and larger waves cause erosion to the seaward edge, which could also be exacerbated by an increase in storminess (Burden et al., 2020). Landward migration of saltmarsh could compensate for these losses, but only in places without hard-built sea defences and away from coastal squeeze (Burden et al., 2020). With changes in temperature, vegetation communities are likely to shift, favouring the spread of drought-tolerant plants, which sometimes will invade and out-compete native species (Loebl, 2006; Burden et al., 2020). As plant diversity is key for soil stability however (Ford et al., 2016), large-scale changes to marsh vegetation could eventually result in increased erosion and loss of saltmarsh (Burden et al., 2020).

3.2.13. Endemic marine species

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES GLOBAL STUDIES	HIGH agreement LIMITED evidence	LOW

Sri Lanka is considered as part of the West and South Indian Shelf marine ecoregion (Spalding et al., 2007) and is connected to the wider Indo-Pacific. As such, there is a low level of marine endemicity (Spalding et al., 2007). This contrasts with high levels of terrestrial endemicity including a quarter of all angiosperms, along with 43% of indigenous land vertebrates, and the highest rates recorded among amphibians, freshwater fishes and reptiles[6,7].

To our knowledge, marine endemics include only two species of sea slugs[8], *Goniobranchus fidelis* or faithful sea slug, and *Goniobranchus precious*, as well as nine fish species, according to the Checklist of Endemic Marine Fish Species[9] and FishBase (2004):

- Scolecenchelys vermiformis (Ophichthidae)
- *Pseudochromis dilectus* (Pseudochromidae) Sri Lankan Dottyback
- *Helcogramma* billi (Tripterygiidae)
- Antennablennius ceylonensis (Blenniidae)
- Alionematichthys ceylonensis (Dinematichthyidae) 2008
- *Pempheris pathirana* (Pempheridae) Trincomalee Sweeper 2015
- *Pempheris trinco* (Pempheridae) Sri Lanka Sweeper 2015
- *Thysanophrys tricaudata* (Platycephalidae) Sri Lankan Flathead 2013
- *Helcogramma serendip* (Tripterygiidae) 2007

In addition, the coral species *Porites desilveri* is found only in shallow reef areas and lagoons of Sri Lanka, although presence is also strongly predicted along the east coast of India within the Bay of Bengal (Veron et al., 2016). *Acropora elegantula* is also noted as probably endemic to Sri Lanka, although the taxonomy is currently unresolved (Veron et al., 2016).

Depending on the particular species, biogeographic ranges typically include the southwest of the Indian shelf, but also extend as far as the Andaman Sea, including the Andaman Islands, Thailand, Maldives and Sumatra.

Current climate impacts

There is no information on current climate impacts on endemic marine species in Sri Lanka. Nevertheless, anecdotal notes and evidence from elsewhere suggests that climate-driven environmental changes can affect negatively the quality and extent of core habitats, and the risk of displacement or even local extirpation is disproportionally higher for endemic species compared to native or introduced species (i.e. Hodapp et al., 2023; Manes et al., 2021).

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6 Convention on Biological Diversity Sri Lanka - Country Profile: https://www.cbd.int/countries/profile/?country=lk
7 The National Red List of Sri Lanka: Assessment of the Threat Status of the Freshwater Fishes of Sri Lanka 2020: https://lk.chm-cbd.net/documents/national-red-list-sri-lanka-assessment-threat-status-freshwater-fishes-sri-lanka-2020
8 Animalia 2023, Endemic Animals of Sri Lanka: https://animalia.bio/endemic-lists/country/endemic-animals-of-sri-lanka
9 Living National Treasures, Sri Lanka: https://lntreasures.com/srilankamf.html

Expected future climate impacts

There is no information on future climate impacts on endemic marine species in Sri Lanka. However, meta-analysis and modelling approaches agree that while climate change is projected to negatively impact biodiversity across all terrestrial and marine environments, endemic species will be more adversely impacted, with a 46% high risk of extinction for marine endemics, which become a 100% in island environments (Manes et al., 2021). Extirpation rates are expected to increase regionally, for example, in the Indo-Pacific, particularly under RCP8.5, leading to strong decreases in richness and the anticipated formation of no-analogue communities where invasions by non-native species are common (García Molinos et al., 2016).

3.2.14. Marine invasive non-native species

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES REGIONAL STUDIES	MEDIUM agreement MEDIUM evidence	MEDIUM

The marine biodiversity of Sri Lanka, is reported to comprise 1713 species of invertebrates and 2142 species of vertebrates (Kularatne, 2023), but is also vulnerable to marine bio-invasions due to its unique central location in the Indian Ocean, and specifically its connection to the East-West shipping route (Kularatne, 2023; Chandrasekara and Fernando, 2009; Kumara et al., 2017; Marasinghe et al., 2018; Ranatunga, 2013). Common with other economically developing tropical island nations, data regarding the occurrence of marine invasive non-native species and their impacts and management is scarce (Kularatne, 2023; Bailey, 2015) despite their array of critically important marine habitats such as coral reefs.

Current climate impacts

Red tide-forming and toxic dinoflagellates, and the European green crab (*Carcinus maenas*) have already been detected in the marine environment of Sri Lanka (Kularatne, 2023). Those species are included in the list of the International Maritime Organisation's "most unwanted" species that can be spread through ballast water operations (Lakshmi et al., 2021; Senanayake et al., 2010). The European green crab, for example, predates on molluscs and on the North American east coast has been linked to collapse of bivalve shellfisheries (Anil et al., 2002; Bax et al., 2003). Given the position of Sri Lanka, within the trans-oceanic shipping route connecting east and west, the likelihood of introduction of invasive non-native species through ballast water disposal and vessel fouling is considered high (Kularatne, 2023). Colombo Harbour is the busiest port, receiving over 5,000 ships (or 80% of all vessel arrivals in Sri Lanka) every year and an estimated million tonnes of ballast water are released into the harbour annually, which presents a high risk of introduction of non-native species (Chandrasekara and Fernando, 2009; Ranatunga, 2013; Senanayake et al., 2010; SLPA, 2021; Kularatne, 2023).

Many of the commercial harbours, ports and anchorages owned by the Ceylon Fisheries Harbours Corporation are located near sensitive marine environments which includes Marine Protected Areas (Kularatne, 2023). Once species are introduced to a particular locality, prevailing sea surface currents linked by local monsoon wind regimes will govern their spread (Pattiaratchi et al., 2022), with high probability of reaching sensitive coastal areas (Kularatne, 2023). A detailed assessment of the risk of marine non-native species in Sri Lanka highlights the extremely sensitive fringing coral reefs in Kankesanthurai and Point Pedro and reef-associated biota in the Northern Coast (Kularatne, 2014) as especially vulnerable to bio-invasions, which may also drift down to other areas in the Northern and North-eastern coastal areas during the north-east monsoon when sea surface currents, stronger in the eastern than the western coast, reverse and flow southwards (Kularatne, 2023). The strong water mixing between the Bay of Bengal and Palk Bay during the north-east monsoon when surface currents flow south (Kularatne, 2014) could also increase the risk of spread to reefs around Delft and Paraitivu Islands within Palk Bay (Kularatne, 2023). On the other hand, non-native species introduced within the Trincomalee Harbour could impact the marine communities of Shell Bay within the Trincomalee Bay (Berg et al., 1989; Kularatne, 2023). Galle Harbour in the Southern Province is located close to the extensive (1707 ha) coral reefs within the Rumassala Marine Sanctuary (Kularatne, 2023). While the sanctuary harbours a rich variety of coral communities, the reefs are already stressed due to sedimentation, excess growth of calcareous green algae *Halimeda* sp., destructive fishing practices, coral trampling and poor coastal management practices (Kularatne, 2023). The consequences of any bio-invasions would be further aggravated by the impact of climate change (Kularatne, 2023).

Expected future climate impacts

Climate change can be a contributing factor to the arrival, establishment and spread of non-native invasive species. Sri Lanka is identified as a hotspot of climate change (Kottawa-Arachchi and Wijeratne, 2017) with sea surface temperatures projected to rise during the course of the 21st Century (Kularatne, 2023), which will place additional stress on native species and exacerbate bio-invasion impacts through competitive exclusion, predation and extinction (Przeslawski et al., 2008; Sorte et al., 2010; Kularatne, 2023). Invasive species are often opportunistic, with comparatively faster growth and survival rates, and therefore they are better adapted to changing and extreme environmental conditions than more sensitive native species (Przeslawski et al., 2008; Sorte et al., 2010; Kularatne, 2023). Warming seawater temperatures for instance may facilitate earlier and longer spawning periods for non-native species, thus increasing population growth rates and simultaneously expanding their distribution range (Keller et al., 2009; Kularatne, 2023).

The projected future rise of global mean sea level threatens native freshwater and brackish biota due to saline water intrusion (Kularatne, 2023; Kottawa-Arachchi and Wijeratne, 2017). In addition to the sensitive marine areas, Sri Lanka has an extensive network of estuarine and lagoonal habitats many of which are fringed by mangrove forests (Kularatne, 2023; Kottawa-Arachchi and Wijeratne, 2017) and are connected with backwater and freshwater systems across the coastal plains (Kularatne, 2023). These wetlands areas are an additional conduit for non-native invasive species of marine origin to spread further inland, as in the case of invasive Chinese mitten crabs (*Eriocheir sinensis*) in Europe (Raheel and Olden, 2008; Kularatne, 2023). The relevance of Chinese mitten crab, which is native to eastern Asia and has become highly problematic throughout Europe and parts of North America, is that the free-swimming planktonic larvae develop predominantly in saline water while adult crabs spend much of their life in fresh water (Raheel and Olden, 2008). Therefore, salinity changes in coastal regions associated with climate change may open the landscape to greater survival and invasion risk of propagules of similar brackish water species, often introduced by ballast water discharges (Raheel and Olden, 2008).

Climate change will alter abiotic filters that determine the success of invasive species in aquatic environments and will mediate the impact of bio-invasions (Raheel and Olden, 2008). Overall, predictions as to how climate change will influence aquatic invasive species are hampered by uncertainty in climate-change scenarios and by inadequate knowledge of how factors, such as transportation vectors influence the distribution and abundance of aquatic organisms (Raheel and Olden, 2008).

3.3. Impacts of climate change on societal and economic sectors

The concept of 'ecosystem services' encompass all the benefits to humans provided by the natural environment and healthy ecosystems. In the following sections a categorisation for ecosystem services has been adopted, based on the Environmental Benefits Assessment approach suggested by Hooper *et al.,* (2014). *Environmental benefits* are identified where a direct gain in human welfare is provided by environmental goods and services. For the purposes of this report, benefits are analysed from an anthropocentric perspective and include not only goods, but also intangible gains (e.g. health and wellbeing). Environmental benefits to society have been grouped into four main types of services: provisioning, carrier, cultural and regulating, each of which provides different benefits or values.

As stated in Sri Lanka's NDC, the country's vast exclusive economic zone of more than 517,000 km^2 supplies over 80% of the nation's fish catch and supports the livelihoods of many thousands of citizens who engage directly or indirectly in maritime industries. In addition the coastal region underpins a major share of the industry and tourism sectors (MoE, 2021). Sri Lanka's coastal zone contributes approximately 40% to the national GDP (MoE, 2021). The Sri Lanka government recognises the severity of the projected risks of sea-level rise and other coastal hazards and has formulated a set of coastal and marine sector adaptation priorities for monitoring and responding to climate change as contained within the country's NDCs (MoE, 2021). These include establishment of accurate sea level rise forecasting systems, preparation of updated vulnerability and risk maps, strengthened shoreline management measures – including soft solutions such as mangrove restoration (MoE, 2021).

Marine resources and services that are important for the economy of Sri Lankans include coastal and reef-based fisheries, offshore tuna fisheries, catches of ornamental species for aquariums, aquaculture, salterns, offshore fossil fuels, maritime transportation, land reclamation for coastal development, coastal and marine tourism, as well as other coastal industries or infrastructure (MoMD&E, 2019). Many of these activities are causing environmental pressures that compound with the impacts of climate change.

3.3.1. Provisioning services/benefits

A provisioning service is any type of benefit to people that can be extracted from nature. Along with food, other types of provisioning services include drinking water, fuel and energy, and minerals or other raw materials.

3.3.1.1. Fisheries

Data sources	Levels of evidence and agreement	Confidence rating	
LOCAL STUDIES REGIONAL STUDIES GLOBAL STUDIES	MEDIUM-HIGH agreement MEDIUM-ROBUST evidence	MEDIUM	HIGH

The Sri Lankan fisheries sector encompasses marine, coastal, inland fisheries as well as aquaculture. Marine fisheries make use of 517,00 km^2 of sea area, while coastal and inland fisheries use 489,000 ha of lagoons, estuaries, reservoirs and riverine areas (Fisheries Statistics 2019, Ministry of Fisheries and Aquatic Resources Development, 2019). In the Western Marine Zone, from Ambalangoda to Talawila, the high nutrient input from the large rivers emptying into the coastal estuaries sustains extensive inshore fisheries (MoMD&E, 2019).

Marine and coastal fisheries contribute 80% of the total fish catch and provides 2.4 million direct and indirect jobs, as well underpinning as 70% of the animal protein intake for the populace. Fisheries contribute approximately 1.2% to Sri Lanka's GDP (Annual Report 2019, Central Bank of Sri Lanka, 2019). The Ministry of Fisheries and Aquatic Resources Development and Department of Fisheries and Aquatic Resources take charge in guiding sector development, in accordance with its National Fisheries and Aquaculture Policy, 2018 and regulations framed under the Fisheries and Aquatic Resources Act No 2 of 2016 and its amendments. Data from 2016 suggests around 276,000 people are actively engaged in the fishing and aquaculture sectors in Sri Lanka, with an additional 200,000 people indirectly employed in marketing and other ancillary services (Arulananthan, 2016). Currently, unsustainable fishery practices, over-fishing of certain species, poaching, land-based pollution from rivers, garbage dumping and habitat destruction in coastal areas (mangroves and coral reefs) are the main threats to Sri Lanka's fishery resources.

The coastal fishery is the backbone of the marine fishery sector in Sri Lanka, mainly confined to relatively narrow continental shelf area (Dissanayake, 2005). Includes stocks of small size pelagic species, small demersal species and non-fin-fish marine resources such as lobsters, crabs, shrimps and sea cucumbers. Sardinella and anchovies are dominant among the small size pelagic species while pony fish and snappers are dominant among the small demersal species found in this area. Of the variety of gear used, small-mesh gillnets and beach seins are the main gear types used to exploit the coastal fish resources of the Island (Dissanayake, 2005).

Sri Lanka is one of the oldest and most important tuna producing island nations in the Indian Ocean (Dissanayake, 2005). Over the past years, tuna fishing has undergone many changes. Tuna fishing activities are carried out both in coastal and offshore environments. Sri Lanka has a well-established offshore/oceanic tuna fishery, with a fleet of locally designed and constructed, multi-day boats sailing up to, or even beyond, the EEZ boundary (Dissanayake, 2005). The main target species are yellowfin tuna (*Thunnus albacares*), big eye tuna (*Thunnus obsesus*), skipjack tuna (*Katsuwonus pelamis*), kawakawa (*Enthynnus affinis*), frigate tuna (*Auxis thazard*) and bullet tuna (*Auxis rochei*).

Current climate impacts

Climate change will affect fisheries and aquaculture via ocean acidification, changes in sea temperatures and circulation patterns, and high frequency and severity of extreme events, as well as sea-level rise and associated ecological changes (FAO, 2016).

Arulananthan (2016) provided an overview of climate change impacts on coastal fisheries in Sri Lanka. As an island nation, Sri Lanka is bestowed with many types of coastal wetlands including marshes, mangroves, seagrass beds and mud flats that are important to maintain the coastal fishery. The impacts or effects of climate change on the fisheries sector has not been assessed or quantified widely, although it is expected to have a wide range of impacts on the production, availability and breeding patterns of aquatic life as well as on onshore and offshore fishery operations. Any damage to estuaries and lagoons, coral reefs or coastal wetlands would lead to reduced feeding, breeding and nursery habitats for commercially important coastal and marine finfish and shellfish used in the food fishery. Ocean warming may have substantial impacts on the distribution, growth and reproduction of fish stocks. Therefore, changes in the ocean circulation may lead to the loss of a certain population or the establishment of new ones, while warmer sea temperatures are associated with the spread of invasive species and marine diseases, that could lead to forced migrations and even localised species extinctions (Arulananthan, 2016).

Natural disasters such as tropical cyclones and associated storm surges will lead to considerable loss and damage in the fisheries sector (Arulananthan, 2016). The mean annual occurrence of cyclones is 0.2, indicating a return frequency of severe cyclones every five years. Cyclone, storm surges, flooding and inundation in combination with sea level rise may be adversely affect coastal infrastructure, including fishery harbours, anchorages and landing sites – most notably in the beach seine fishery, stilt fishery, boat landing sites and fisher folk settlements along the beach. Cyclone-induced storm surges can raise the sea level, as demonstrated in 1978 during the impact of cyclone Batticaloa, which raised the sea level up by 2.73 m on the eastern coast resulting in seawater penetration wave upsurge up to 800 m inland from the shoreline (Arulananthan, 2016). In marine fisheries sector Kalpitiya (Puttalam District) emerges as the fisheries community that is highly vulnerable to sea level rise exposure. Kalpitiya has 43 fisheries landing sites and 5,938 jobs in the fisheries sector, which is more than 25% of its total employment at this division. An additional 5 divisional secretary divisions within the southern province are considered moderately vulnerable, with 115 fisheries landing sites involving 10,408 individual fishers (Arulananthan, 2016).

The possible impacts of changes in rainfall regimes and prolonged drought can have varied implications affecting mainly inland fisheries (Arulananthan, 2016). It is expected that in the dry and arid zones, this would lead to increased evaporation which would impact the inland fishery including lowered yields in seasonal ponds. On the other hand, flooding will affect inland aquaculture and capture fishery due to pollution, sedimentation and any adverse changes in water quality parameters of surface water bodies. These would all have serious implications on rural nutrition and incomes for dependent communities (Arulananthan, 2016).

Allison et al., (2009) examined the vulnerability of 132 national economies to the impacts of climate change on fisheries. Countries were scored in terms of fisheries exposure, sensitivity and adaptive capacity. Overall, Sri Lanka was scored as low vulnerability (exposure = very low, fisheries sensitivity = high, adaptive capacity = low). However, a more recent re-analysis by Blasiak et al., (2017) for 147 countries, drawing on the more comprehensive data ranked Sri Lanka 35th out of 147 (within the 1st quartile) in terms of vulnerability.

Expected future climate impacts

Estimates of projected changes in fisheries catch potential based on two ecosystem models indicate an overall projected decrease of total maximum catch potential in the world's EEZs of between 16.2 and 25.2 by the end of the twenty-first century (Cheung et al., 2018).. The projected changes in maximum catch potential varied substantially across EEZs in different regions. For Sri Lanka specifically, fisheries catches were projected to decline by as much as 24–55% by 2050 under a high emissions climate change scenario and by 32–69% by the end of the twenty-first century (Cheung et al., 2018).

Although ocean warming may alter the potential fish catch over the next 50 to 100 years, changing storminess has the potential to cause more immediate and catastrophic impacts, such as that of the severe storms that hit the western coast in 2013, which claimed the lives of at least 40 people, mostly fishermen operating small vessels near the western coast (see Sainsbury et al., 2018).

3.3.1.2. Aquaculture

Data sources	Levels of evidence and agreement	Confidence rating
SITE-SPECIFIC STUDIES; REGIONAL STUDIES	HIGH agreement MEDIUM evidence	MEDIUM

Current climate impacts

The aquaculture industry in Sri Lanka started in the early 1980s when a few large multinational companies embarked on shrimp (black tiger prawn, *Penaeus monodon)* farming (Drengstig 2020). During the period 1992–1996 there was a rapid but largely unregulated development in the shrimp farming industry due to attractive public investment incentives and high economic return. In this period, farms produced 8,000–9,000 kg/ha/year in dug out ponds or lagoons. The total number of farms amounted to around 1,400 with over 70 hatcheries, and a total area of 4,500 ha. However, due to a lack of proper law enforcement and planning, the rapid development culminated in closure of 47% of all illegal farms operating without proper licenses (Drengstig 2020). From 1996 the industry started to suffer due to disease outbreaks and environmental issue, and almost all farming activities became restricted to a narrow coastal belt of approximately 120 km by 10 km in the Northwestern Province. Between 1998 and 2004, the industry was characterised by volatile boom-and-busts, with unsure conditions caused by multiple disease outbreaks. Nowadays Sri Lanka has a limited, but stable, shrimp production sector varying between 20–30,000 tonnes per year (Drengstig 2020). The export of farmed shrimp (mostly to the United States, Europe and Hong Kong) has contributed over 50% of the total export earnings from the fisheries sector with ornamental fish production contributing another 11%.

Recently, Sri Lanka has introduced Pacific white shrimp *Penaeus (Litopenaeus vannamei*) mainly to revive the shrimp farming sector, which has faced frequent crop failures of black tiger shrimp, caused by the fatal white spot disease (Jayasinghe and Amarasinghe 2021). Oyster farming (*Crassostrea madrasensis*) commenced during early 2000 at a very small scale and now exports to Hong Kong, Taiwan and China, both in live and frozen forms (Jayasinghe and Amarasinghe 2021). Climate hazards including rising sea temperature and weather extremes pose challenges for the coastal aquaculture industry, with sea level rise rendering sites unsuitable and damaging structures being especially concerning (Jayasinghe and Amarasinghe 2021).

Galappaththi et al. (2019) have provided a perspective on climate change adaptation in coastal shrimp aquaculture based on a case study from northwestern Sri Lanka, where shrimp disease spreads along an interconnected lagoon system and make it difficult to predict and control the shrimp lagoon fishery. Galappaththi et al., (2019) examine how small-scale shrimp farmers can adapt to the impacts of climate change by collectively managing shrimp disease, where inadequate rain raises the susceptibility to shrimp disease and unexpected extreme weather events such as flooding (e.g. the May 2016 floods) can damage ponds and canals (Galappaththi et al., 2019).

Expected future climate impacts

There are plans in the country to grow coastal aquaculture production from 20,000 t in 2020 to 60,000 t by 2025 (Jayasinghe and Amarasinghe 2021). Whether this is feasible and sustainable, could depend on future climate change and in particular future patterns of rainfall and cyclonic activity (see sections 3.1.7 and 3.1.6, respectively). No modelling or projection studies are available for this sector specifically in Sri Lanka, but climate change is increasing the risk of disease. Resilient small-scale shrimp aquaculture hinges on the collective action of individual owners through producers' cooperatives and collaborative multi-level management (Galappaththi et al., 2019).

3.3.1.3. Reef harvesting of ornamental trade species

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES	LOW agreement MEDIUM evidence	LOW

In addition to fishing activities for food, collection of reef fish, invertebrates and live coral for the ornamental fish export industry is of considerable importance in Sri Lanka (Rajasuriya, 1997). The export of ornamental fish is rated the third highest in volume terms, after exports of prawn and lobsters (Baldwin, 1991). Sri Lankan ornamental fish exports for the international market include locally wild caught marine, brackish-water and freshwater species as well as captive bred freshwater fish (Wijesekara and Yakupitiyage, 2001). It has been estimated that between 2005–2006 in Sri Lanka, wild-captured marine fishes represented 50–60% of the ornamental fish trade exports (Herath and Wijewardene, 2014). The ornamental fish industry in Sri Lanka is currently governed by stringent environmental laws to protect the sustainability of the industry as well the endemic fish population in the country (Sri Lanka EDB, 2024).

There have been reports however of uncontrolled collection and destructive harvesting techniques that can be damaging to the habitats (Rajasuriya and White, 1995). In addition to corals, other fisheries and aquatic products harvested around coral reefs include sea cucumber, spiny lobsters and various species of molluscs such as cowry shells (Rajasuriya and White, 1995).

Current climate impacts

No information was found regarding current climate impacts on Sri Lanka's marine ornamental species trade, although impacts on reef-associated fish species are documented in section 3.2.3.

Expected future climate impacts

Any climate impacts on Sri Lanka's reefs could affect the future of the trade in ornamental wild species, not limited to corals but other reef-associated species.

3.3.1.4. Seabed mining and sand extraction

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES	LOW agreement LIMITED evidence	LOW

According to a study from 2014, the demand for sand in Sri Lanka was about 12 million m^3 per year, with a projected increase by 10% every year, primarily for building materials (Kularatne, 2014). Sri Lanka's construction industry could face a shortage of sand unless offshore sand mining can be promoted as a viable and sustainable alternative, as over-exploitation of river sand is worsening the already significant threat of river erosion (Kularatne, 2014). Offshore areas in the north-eastern sector are being considered, while east and north-western offshore locations do not appear viable for seabed mining due to the bathymetry, as most locations in the east coast are deeper than 20 m, where suction dredging would be very difficult., In Sri Lanka mining is prohibited at depths equal or less than 15 m and within 2 km of the shore due to the occurrence of critical marine habitats (Kularatne, 2014). In the south-eastern region, in addition to depth, complex wave dynamics result in varying shoreline stability (Kularatne, 2014).

Current climate impacts

As this is an emerging activity there is no information currently available.

Expected future climate impacts

As this is an emerging activity there is no information currently available, although sea level rise may increase the demand for sand and gravel to build, maintain or repair hard sea defense structures.

3.3.1.5. Coral mining

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES	LOW agreement LIMITED evidence	LOW

Coral is traditionally mined in Sri Lanka mainly to produce lime for the construction industry, although some lime is also used for agricultural purposes to buffer the acidity of soils. Coral mining is reported to have caused degradation of some fringing reefs, particularly along the southwestern coast of Sri Lanka (CBD, 2024; Rajasuriya, 1997; Hale and Kumin, 1992). Coral mining in the bays of Kalkudah and Passikudah on the east coast has resulted in severe coastal erosion, where hard structures have since needed to be built to protect the coastline (Rajasuriya, 1997). A survey conducted in 1984 by the Coast Conservation Department in the south-western and southern coastal areas reported that 18,000 tonnes of coral were being supplied annually to the lime industry (Rajasuriya, 1997). Mining for lime production has mainly targeted ancient, fossilized coral reefs, found inland and below ground, but more recently mining has begun exploiting reefs at sea, both dead and alive (Rajasuriya, 1997). Most of the mining occurs beyond the coastal zone, while 16% is mined on land within the coastal belt, and another 30% comprises illegal harvest of coral debris from the shore (Rajasuriya, 1997). The balance 12% consists of illegal coral mining at sea (Rajasuriya, 1997; Hale and Kumin, 1992).

Current climate impacts

No information is currently available regarding climate change impacts on this activity.

Expected future climate impacts

No information is currently available regarding climate change impacts on this activity.

3.3.1.6. Offshore energy production

Data sources	Levels of evidence and agreement	Confidence rating
REGIONAL STUDIES, GLOBAL STUDIES	HIGH agreement LIMITED evidence	LOW

It has been suggested that Sri Lanka has considerable potential for ocean energy production, notably in wave and tidal energy (Nayanaranga et al., 2023). A report by the World Bank discussed the potential for exploratory deployment of offshore wind energy in Sri Lanka and identified the Gulf of Mannar in the north and Puttalam in the west, as the most favourable sites based on considerations of water depth, average wind speeds, environmental or social sensitivities, grid connection options and accessibility of port facilities (World Bank Group, 2023). Similarly, Naradda Gamage et. al. (2017) also argue that the country's location provides suitable renewable energy production sites in the form of tide and wind energy in the coastal provinces and hydro-electric projects in the central provinces.

With regards to fossil fuel extraction and energy production, Sri Lanka has only one refinery, the state-owned Ceylon Petroleum Corporation Sapugaskanda plant, and both the plant and the main, 5.8-kilometer, port-to-refinery pipeline are considered outdated and in urgent need of upgrading and expansion (ITA, 2022). The plans include a refining capacity increase from the current 50,000 barrels per day to 100,000 barrels per day expansion (ITA, 2022). Output from the Sapugaskanda oil refinery currently meets 40 percent of Sri Lanka's demand for refined fuels, while the government imports 60 percent of the refined fuels consumed domestically (ITA, 2022).

Current climate impacts

No information in terms of climate risks to the offshore energy sector in Sri Lanka was found, however studies from other countries may serve as guidance. For example, a recent review of climate change impacts to coastal and offshore infrastructure in the UK highlighted that offshore and coastal assets are increasingly exposed to flood and erosion risks, driven by rising mean sea levels, while warming sea and air temperatures can impact the efficacy of industrial cooling systems (Coyle et al., 2023). Storms and associated surges are also increasing the risk to operations which are sensitive to weather-related disruption (Coyle et al., 2023).

Expected future climate impacts

Whilst there is no information specific to Sri Lanka. The same review by Coyle et al., (2023) on climate risks to coastal and offshore infrastructure in the UK highlighted that as sea levels continue to rise at an accelerated rate, and as the frequency and / or severity of storms also increases, the associated risk of disruption and damage to offshore and onshore assets and operations will also increase. It can be expected that this also represents an increasing risk in future in Sri Lanka, particularly in the context of projected intensification of tropical cyclones in the Northern India Ocean basin (Knutson et al., (2019).

3.3.2. Carrier services/benefits

Critical infrastructure ensures essential services and functions, and the failure or destruction of that infrastructure, such as during disaster situations, can have severe effects on the population and institutions of a country (Randeniya et al., 2022). In Sri Lanka, critical infrastructure includes emergency services, water, energy, finance, transportation, and telecommunications (Randeniya et al., 2022).

3.3.2.1. *Maritime transport (ports and shipping)*

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES REGIONAL STUDIES GLOBAL STUDIES	HIGH agreement MEDIUM evidence	MEDIUM

Sri Lanka is well positioned in the middle of a trans-oceanic shipping route connecting east and west (Kularatne, 2023). It is reported than between 300 million to 550 million megatons of oil alone per annum, almost a quarter of the world's oil transportation, crosses through Sri Lanka's EEZ, from the Middle East to the Far East (Kularatne, 2023; Gunasekara, 2011; BOBLME 2013; Prakash et al., 017). This maritime activity carries an inherent risk of collisions and incidents; within Sri Lanka's EEZ, there has been a total of 10 major accidents reported since the 1990s, up to the *X-Press Pearl* disaster in 2021 (Edirisinghe, 2021). The southern part of Sri Lanka's marine area in particular represents a major maritime trading route with around 300 vessels passing per day and hence a need for ship channeling. In addition, supply of water, fuel and crew changes for international shipping are being undertaken from the Sri Lankan ports and harbours (Kularatne, 2023; Ranasinghe, 2016).

Since 2009, Sri Lanka has experienced an economic boom coupled with an increased influx of tourists and goods (Kularatne, 2023). In response to the anticipated growth, maritime facilities and services have undergone rapid development including a rehabilitation of the commercial harbours in Colombo in the Western Province, Oluvil and Trincomalee in the Eastern Province, Galle in the Southern Province and Point Pedro and Kankesunthurai in the Northern Province, along with the opening of the new Hambantota Port in the Southern Province (Kularatne, 2023).

Galle Harbour is a natural harbour located on the southwestern coast, and is the only Sri Lankan port with facilities for pleasure yachts (Ports Authority, 2023). Some of the facilities at Galle Port were damaged during the 2004 Indian Ocean tsunami and are still subject to re-development, including upgraded berthing facilities to 300 m cruise ships and 200 m cargo vessels, and breakwater barriers (SLPA, 2023). Trincomalee is the second-best natural harbour in the world, 10 times larger than the Port of Colombo, and caters for bulk, heavy industries, tourism and agriculture (SLPA, 2023). Hambantota Port in the south is a deep-water, multi-purpose port strategically positioned nearest to the global shipping routes passing by Sri Lanka (SLPA, 2023). The Port of Oluvil is part of the economic development plans for Eastern Sri Lanka, to form a link for goods and cargo between the west and the southeastern coastal harbours (SLPA, 2023). Kankesanthurai Harbour in the north is currently undergoing rehabilitation including repairs to existing breakwaters, piers and roads, dredging to allow handling of larger cargo vessels, wreck removal, and construction of a new pier (SLPA, 2023). Finally, Colombo Harbour is the busiest port in the country, and a maritime hub for the South Asia Region (SLPA, 2023). The Port of Colombo is primarily a container port, with about 5,000 ships arriving per annum (more than 80% of all vessels arriving in Sri Lanka every year; SLPA, 2021; Kularatne, 2023). The port accommodates deep water berths and the latest generation of mainline vessels, and is served by a wide two-way channel (SLPA, 2023). The Port of Colombo is undergoing expansion and construction of new terminals (SLPA, 2023).

Current climate impacts

According to a study by the US Naval Research Laboratory (NRL, 2017), the Port of Colombo is sheltered from most of the tropical cyclones that approach Sri Lanka from the east or southeast and offers protection from storm-associated winds (NRL, 2017). In rare occasions however, intense tropical cyclones may approach from the east or southeast and track within critical distance of the port, such as in 1978, when an intense tropical cyclone approached from the west and resulted in sustained winds in excess of 90 km per hour experienced at the harbour (NRL, 2017). These rare tropical cyclones developing to the southwest of Colombo have the potential to severely damage the harbour. Entry by vessels into the harbour during winds greater than 55 km per hour or departure with winds greater than 75 km per hour is not recommended (NRL, 2017). Winds are strong in all seasons along the south coast, and high waves are a frequent occurrence, but heavy swells are rarer on the west coast except during the onset of the southwest monsoon (September-November) or during tropical storms that develop west or just north of the Port of Colombo (NRL, 2017). There is no known evidence of significant storm surges within the Port of Colombo, and no historical accounts of any storm surge associated with tropical cyclones (NRL, 2017). Tidal currents in the port are generally weak (NRL, 2017).

Although no evidence or information to this regard has been found, tropical cyclones approaching from the east or southeast could present a threat to the other main ports of Sri Lanka particularly those on the east and south costs, which face the typical seasonal storm track, such as Oluvil in the east, and Galle and the new Hambantota Port in the south (Kularatne, 2023), compared to Colombo Port.

Expected future climate impacts

Ports have a critical role in the global trading system and their potential exposure to climate related damage, disruptions and delays is strategically significant globally, but it is also crucially important for vulnerable coastal and island nations (UNCTAD, 2021), such as Sri Lanka. Island nations depend on their seaports as lifelines for external trade, food and energy security, tourism, and ports also provide vital socio-economic linkages and are key to regional and inter-island connectivity (UNCTAD, 2021). However, these critical assets are at high and growing risk of climate change impacts (UNCTAD, 2021; IPCC, 2019).

Many climatic hazards can affect seaports, such as heat waves, extreme winds and precipitation (UNCTAD, 2021). Vessels and infrastructure in around harbours and ports are exposed to damage by storms and cyclones, which can also disrupt port operations and navigation, and intensify the risk of collisions and spills (Lincoln et al., 2021a) including chemicals and other dangerous goods.

Adverse climatic conditions can interfere with supply chains and port and traffic control facilities, with knock-on effects on shipping activities (Asariotis et al., 2017; UNCTAD, 2021). Adverse wind and wave conditions make harbour conditions and berthing operations particularly difficult for large vessels (Asariotis et al., 2017; Rossow and Theron, 2012). Heatwaves may result in higher costs and loss of competitiveness for ports, as well as spoiling perishable cargo and increasing public health risks (UNECE, 2020; Asariotis et al., 2017; UNCTAD, 2021; Lincoln et al., 2021). Smaller harbours and marinas are also vulnerable, and climate change impacts can badly affect poorer coastal communities whose livelihoods depend directly on them, such as fisherfolk (Lincoln et al., 2022).

Mean sea-level rise and associated extreme sea-levels pose a particularly important threat in Sri Lanka, which is growing (UNCTAD, 2021; IPCC, 2019). Rising mean sea levels and extreme sea level events can undermine or overtop obsolete coastal protection structures and increase the risk of damage and disruption. In addition, localisedflooding or inundation can result in additional economic costs, cut off coastal transportation links around the port, and necessitate the evacuation or relocation of people and businesses (Asariotis et al., 2017; Izaguirre et al., 2021; Rahmstorf 2012; UNCTAD 2021).

3.3.2.2. Telecommunications

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES REGIONAL STUDIES GLOBAL STUDIES	HIGH agreement MEDIUM evidence	MEDIUM

Telecommunications include telephone, internet, television, radio, and postal services (Randeniya et al., 2022). Sri Lanka's telecom market includes 4 mobile operators and 2 fixed line operators serving a population of 22 million (Sri Lanka Telecoms, 2023). Sri Lanka is building a national fiber optic 45,000-kilometer network linked to numerous international cables to serve fixed broadband and mobile services, including 5G (International Trade Administration, 2023). Sri Lanka’s information technology and business services sector is the country’s fourth largest export earner, and active mobile connections have grown from just 5.4 million (or 20% penetration) in 2005 to over 28 million (or 131% mobile penetration) by the end of 2021 (International Trade Administration, 2023). Sri Lanka is also connected to the Southeast Asia-Middle East-West Europe submarine cable system, linking Asia to Europe via the Indian Sub-Continent and Middle East. This system aims to significantly increase the bandwidth and global connectivity of users along its route between Singapore and France (International Trade Administration, 2023). In July 2021, the Sri Lanka Government launched the Submarine Cable Protection and Resilience Framework to secure the integrity and functionality of fibre-optic submarine cables that cross the marine area under Sri Lanka's jurisdiction (Ministry of Foreign Affairs, 2023).

Current climate impacts

During natural disasters such as those caused by climate change or earthquakes, telecommunications infrastructure failures occur through physical destruction of network components, disruption to supporting network infrastructure such as pylons and transformers and/or network congestion (Townsend and Moss, 2005).

Physical destruction of network infrastructure is the most common and well-documented cause of telecommunications failures in recent disasters, and the disruptions tend to be more severe and last longer than those caused by disconnection or congestion (Townsend and Moss, 2005). In May 2016, torrential rain in Sri Lanka caused severe and widespread destruction to infrastructure including telecommunications, power lines and roads, as well as loss of life, requiring the government of Sri Lanka to issue an international request for assistance, and relief organisations to deploy emergency telecommunication equipment provided including satellite phones, satellite broadband terminals and accessories (ITU, 2023). Telephone systems are highly vulnerable to physical destruction during disasters, for instance severe weather and landslides can sever cables and flood underground equipment, and high winds during storms and cyclones can wreck fragile overhead telephone lines (Townsend and Moss, 2005). Newer mobile telecommunications networks are more resilient to physical destruction (Baran, 1964; Townsend and Moss, 2005). Locally, internet service for small businesses and homes is still largely delivered over old telephone wires in Sri Lanka and cable television networks, but even wireless links, which rely on electromagnetic radiation, can be disrupted by physical phenomena such as weather or debris (Townsend and Moss, 2005). Finally, centralised broadcasting facilities are typically located within metropolitan areas and are more vulnerable than antennas for cellular telephone networks that typically service smaller neighbourhoods in major cities (The Seattle Times, 1994; Townsend and Moss, 2005).

Outages caused by disruption in supporting infrastructure tend to be far more widespread and damaging, as telecommunications networks often rely upon many other local and regional, older systems (Townsend and Moss, 2005). For example, electrical power systems remain the most important supporting infrastructure for telecommunications facilities, and cooling systems are also critical, and can fail independently of power supply (Weigand, 1994; Townsend and Moss, 2005). Finally, transportation disruptions can also impact the supply of fuel for electric power generation. For example, the widespread power failures following the 2004 Indian Ocean tsunami crippled communications throughout the devastated areas (Townsend and Moss, 2005). One of the oldest technologies for telecommunications - amateur radio - remains the only one that has repeatedly demonstrated its ability to operate effectively when electrical power supplies fail[10]. Finally, network congestion or overload is the final major cause of telecommunications failures during disasters, even in the case of well-managed modern networks (Miami Herald (1994; Townsend and Moss, 2005). After the 2004 tsunami struck Phuket, Thailand, cell phone networks (as well as landlines) were congested, leaving only SMS operational (Bangkok Post, 2005; Townsend and Moss, 2005).

Expected future climate impacts

For the telecommunications sector it is important to distinguish between future impact of short-term extreme weather events and long-term incremental climate change, in the acknowledgement that the vast majority of the literature is concerned with the nature and frequency of extreme events, with less attention given to slow onset changes (Horrocks et al., 2010; Ospina et al., 2014). Some companies are already responding to the dramatic effect of extreme weather events and their potential economic cost in the near term, while the gradual climatic impacts are less prominent in their contingency plans due to the combination of associated uncertainty, failure to spot the signals, lack of risk motivation, and short-term business decision-making time frames (Adams and Steeves, 2014). Long-term climate change impacts however can lead to incremental costs and can decrease the expected lifespan of assets and infrastructure (Adams and Steeves, 2014). Incremental changes also reduce operating margins and thresholds, which may not be immediately obvious, and they reduce operating margins for handling extreme events (Adams and Steeves, 2014).

It has been suggested that it is the low-probability and high-magnitude future climate change impacts, that pose the greatest risks to the telecommunications sector, with potential risks including fires from excessive heat beyond design standards or flood damage to critical infrastructure components (Baglee et al., 2012). In comparison, there is a lack of evidence on assessments on secondary or tertiary impacts, such as climate risks to supply chains (Adams and Steeves, 2014).

Typically, the lifespan of telecommunications infrastructure is shorter, and the pace of technological development more rapid, than other infrastructure types such as energy or transport, which reduces the liability (Adams and Steeves, 2014; Horrocks et al., 2010). On the other hand, in the modern economy every sector is dependent on telecommunications, and in turn telecommunications data centres rely heavily on key functioning services notably water (for cooling server centres), energy (for cooling and operating both data centres and equipment), and transport (Defra, 2011; URS, 2010). Furthermore, disturbances to the power grids often affect telecommunications infrastructure as telecommunications and power lines often share the same poles (Jacob et al., 2011; Adams and Steeves, 2014). The reliance of telecommunications

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[10] American Red Cross Amateur Radio Service: http://www.qsl.net/arcars/

on the electricity grid means that vulnerability is exacerbated in remote and rural areas that are not well connected to the grid (Adams and Steeves, 2014). These interdependencies compound the impacts in the wake of extreme events, and it also means that the consequences of future impacts of climate change will be greater as reliance on telecommunications will only increase (Adams and Steeves, 2014; Baglee et al., 2012). For instance, during the power outages caused by Hurricane Sandy in October 2012 across the Caribbean and the eastern areas of the USA and Canada, users had trouble finding energy to charge cell phones and the backup batteries in cell towers were quickly exhausted (Kahn, 2012).

3.3.2.3. Energy, water, transport links, and other critical coastal infrastructure

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES, REGIONAL STUDIES	HIGH agreement ROBUST evidence	HIGH

In Sri Lanka, around 70% of the population and 80% of national economic infrastructure is concentrated in coastal cities, as well as disaster-prone mountainous areas (MDM, 2016). A large proportion of human settlements are located within the 1 m mean sea level contour or encroach on 50- and 1000-year flood plains, and these include substantial areas of squatter settlements and low-income, poor-quality housing (World Bank Group, 2011). However, a detailed assessment and mapping of these areas is still needed to better determine the size and vulnerability of these settlements to potential future impacts of climate change (World Bank Group, 2011).

Sri Lanka has extensive bitumen-surfaced roads, most of which skirt the coastline or low-lying areas, and also link to major tourist destinations (World Bank Group, 2011). Railway is mostly limited to a single-track line connecting the international freight container port of Colombo, which handles most of the international marine transport (World Bank Group, 2011). Given its location, transport infrastructure is highly vulnerable to climate change impacts through storm surges and sea level rise, droughts and high-intensity rain, particularly because a considerable length of the major road and railway network runs along the coast and in low-lying areas.

In 2015 it was reported that 38% of the total electricity generation in Sri Lanka is from major hydropower plants, while 51% was from thermal stations including diesel and coal and 11% from non-conventional renewable energy (mini-hydro, wind, solar and biomass energy) (MDM, 2016; World Bank Group, 2011). As of 2015, Sri Lanka's energy generation assets included 17 hydropower, 16 thermal-oil, 1 thermal-coal stations, and 1 wind energy station operating that are owned and operated by Sri Lanka's energy board, in addition to 184 other private power stations, mostly small hydroelectric but also some thermal fuel and non-conventional renewable energy (MDM, 2016). Transmission and distribution lines are also a critical element of the national power grid, and as of 2015 comprised around 3,000 km of overhead and underground transmission routes from power stations to substations, and around

170,000 km of distribution lines to consumers including low voltage lines (MDM, 2016; CEB, 2011). Rural electrification projects are underway in Sri Lanka: 12% of the population did not yet have electricity in their households according to data from 2011 (CEB, 2011).

In Sri Lanka, water sources for human use include mains pipe-borne water supplied by the National Water Supply and Drainage Board (approximately 32% of drinking water supply), and pipe-borne water managed by community-managed water schemes (approximately 10% of supply), but household and common dug wells represent the largest contribution to Sri Lanka's drinking water supply with a coverage of 51% (MDM, 2016). Dug wells are mainly categorised as protected and unprotected depending on the availability of a guard wall and/or apron around the well, and require household water treatment such as boiling or adding chlorine tablets to address microbial risks before use (MDM, 2016).

Current climate impacts

Cyclones often cause extensive damage, resulting from combined extreme conditions of rain, wind and storm surge. One of the latest cyclones to impact Sri Lanka was Cyclone Burevi, which entered Sri Lanka from the north-eastern coast on 2 December 2020, and caused high winds, heavy rainfall and flash floods in low lying areas in Northern and Eastern provinces (UNICEF Sri Lanka, 2020). District Disaster Management Centers reported that almost 10,000 people were affected in Jaffna, Mullaitivu, Kilinochchi and Mannar districts with 15 houses fully damaged and 246 houses partially damaged (UNICEF Sri Lanka, 2020). At the time of the report however only housing damage was reported while damage to infrastructure, assets, education and healthcare centres and water supply had yet to be assessed (UNICEF Sri Lanka, 2020).

Periods of intense precipitation can result in flash flooding and landslide events in Sri Lanka, leading to loss of life and livelihood as well as severe damage to critical infrastructure (USAID, 2018; World Bank Group, 2021; Asian Disaster Preparedness Center, 2018). Around a third of the nation's surface area is estimated to be exposed to landslide events, reportedly the third most frequently occurring hazard, behind flood and drought (USAID, 2018; World Bank Group, 2021; Wickramaratne et al., 2012). Shifts in the precipitation regime toward more intense extreme events have driven increased landslide risk over the late 20th and early 21st centuries (Ratnayake and Herath, 2005). Rural settlements and urban areas in low-lying coastal areas are highly vulnerable to the combined impacts of storm surge and sea-level rise (USAID, 2018; World Bank Group, 2021; Dasgupta et al., 2011). In addition to the increased risk of rapid-onset disaster events, salinity intrusions and contamination of drinking water reserves are already significant in the coastal zone of Sri Lanka and are affecting the lives of many people, including in Colombo where the water supply is protected by a Salinity Barrier (USAID, 2018; World Bank Group, 2021).

Floods and landslides often cause widespread and costly physical damage to the country's electricity distribution system, as well as electricity grievances to customers from the power outage and risk of casualties and damage due to electrocutions. One example is the floods in May 2016 which affected 19 districts in 8 provinces and caused physical damage to transformers, meters, lines and poles, which added to power supply sector losses reaching an estimated LKR 662 million(MDM, 2016). After severe flood events in Sri Lanka, the recovery and restoration of electricity supply takes a considerable time after the water level subsided, especially in the worst-affected low-lying areas that are fully submerged by the floods (MDM, 2016).

The May 2016 floods also caused damage to road and railway infrastructure. The damage to the rail network included cave-ins and dislocation of tracks, submerging of track sections in flat terrain causing signal system failures, and blockages due to fallen trees, and soil and rock debris (MDM, 2016). Damage to the road network included bridge and road surface damages, damage to culverts, and erosion of river embankments and shoulders in national roads, and lesser but widespread damage to 700 km of provincial roads (MDM, 2016) most of which in coastal and low-lying areas (World Bank Group, 2011).

In Sri Lanka, water accessibility or quality can be compromised following natural disasters (MDM, 2016). Following the severe floods in May 2016, damage and blockages were reported to water intakes built along rivers and streams and to borehole intakes due to heavy loads of mud and silt as a result of the landslides, and the floods also destabilised distribution pipe networks (MDM, 2016). Floods also put at risk pump houses and river water treatment plants (MDM, 2016). Damage to dug wells however are usually underreported during disaster situations, and either protected and unprotected dug wells immediately become unusable due to inundation of contaminated water, with guard walls and aprons destabilised by severe floods rendering many wells inaccessible (MDM, 2016).

Damage to other key public services due to climate-related events include those sustained by health and education facilities, which is of particular concern because these communal buildings are often used as shelters for people evacuated during rescue operations. During the May 2016 floods, schools and their water and sanitation facilities were of particular concern immediately following the disaster, because in addition of direct damage and loss sustained, school facilities were utilised heavily during the emergency response, as the first option to offer temporary shelter to displaced and evacuated communities (MDM, 2016). Health facilities were also damaged include central clinics, as well as maternal and child clinics and drug stores (MDM, 2016).

Bandaranaike International Airport (BIA) is the main international airport serving Sri Lanka and is located in the suburb of Negombo, 32.5 kilometres north of the nation's capital and commercial center, Colombo. In a global analysis of sea level rise risk to 1238 airports (Yesudian and Dawson, 2021), Bandaranaike International Airport was not identified as being particularly at risk of inundation although China Bay Airport near Trincomalee was identified as potentially being at risk of annual disruption in the more distant future.

Expected future climate impacts

While projections of future average annual precipitation are uncertain, there is some confidence that extremes of daily precipitation likely leading to an increase in landslide risk (USAID, 2018; World Bank Group, 2021). It is estimated that by the 2030s, approximately 230,000–400,000 people could reside in exposed floodplains, growing to up to half a million people by the 2060s (Neumann et al., 2015), even assuming modest sea-level rise of 10 cm by 2030 and 21 cm by 2060 (USAID, 2018; World Bank Group, 2021). The increasing risk is also mirrored by huge economic losses that continue to rise in recent years, for example flood-associated losses were estimated at 105 million USD in 2010, rising to 500 million USD in 2011 (MDM, 2016)

While most of the main hydroelectric plants are located inland, some of the thermal plants and primary and distribution substations are located on or near the coastline mostly along the Western and Southern provinces, exposed to marine climate impacts (CEB, 2011). On average, a one degree increase in ambient temperature can result in a 0.5%–8.5% increase in electricity demand as a result of increased demand for business and residential air-cooling systems (Santamouris et al., 2015; USAID, 2018; World Bank Group, 2021). This increase in demand will place a strain on energy generation systems as average air temperature, and the frequency of acute heat events, increase in the future, which are compounded by the heat stress on the energy generation system itself, commonly due to its own cooling requirements, which can reduce its efficiency (ADB, 2017; USAID, 2018; World Bank Group, 2021). Exposed overhead lines, transformers, switchgear and cables are vulnerable to extreme heat, as high temperatures de-rate the carrying capacity of lines and transformers and curtail their lifetime depending on equipment and peak load (Lincoln et al., 2021a). In Sri Lanka both underground lines and overhead assets are at risk, particularly in areas of unstable soils affected by floods and landslides during monsoonal heavy rains or cyclonic storms. Energy generation, transmission and distribution infrastructure located near the coast such as power stations, substations and lines, which supply some of the main urban centres including Colombo as well as a large number of rural, low-income settlements, will be at increased risk of impact from rising and extreme sea levels and extreme weather events.

Transport infrastructure is highly vulnerable to climate change impacts through storm surges, sea level rise, and heavy precipitation since a considerable length of the country's major road and railway network links run along the coast and in low-lying areas (World Bank Group, 2011). Without adaptation and network maintenance and improvement, it is likely that the climate risk to key transport links will continue to worsen in terms of severity and frequency of damages and disruption from flooding, erosion, and subsidence, and owing to blockages following landslides and debris accumulation.

A study by Nianthi and Shaw (2015) showed that future changes in climate and increased frequency of extreme events in Sri Lanka, as reported widely by the scientific community, may have significant economic impacts on various other sectors, such as, land resources (an estimated amount of 1242 million rupees), tourism (affected cost of 201 million rupees and replacement cost of 1174 million rupees), industries (152 million rupees) and rice and coconut production (64.5 million and 83 million rupees respectively). These estimates stress the importance of incorporating the dimension of economics and global climate change into national strategies of development. A comprehensive Coastal Zone Management Plan (CZMP) is required that incorporates development issues, scale issues and multi-stakeholder issues. An important element of this management plan is community participation.

3.3.2.4. Solid waste and wastewater systems

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES REGIONAL STUDIES	HIGH agreement MEDIUM evidence	MEDIUM

In Sri Lanka, piped sewerage systems are confined to the Colombo Municipal Council area, with domestic sanitation consisting mostly of household latrines elsewhere, which may have associated septic tanks, pits or cesspools for onsite disposal (MDM, 2016).

Waste disposal is an issue of national concern in Sri Lanka, due to the enormous amount of municipal solid waste; up to 7,000 megatons per day island-wide (data from 2016), 85% of which is collected in open dumps (MDM, 2016).

Current climate impacts

Climate change has the potential to aggravate the environmental impact and public health risk of solid waste and wastewater, for example through litter mobilisation and spills due to flooding and increased erosion following extreme weather events (Lincoln et al., 2023; 2022). Household toilets are vulnerable to damage during flooding events, although reports in the aftermath of the severe flood in May 2016 in Sri Lanka highlight that while the damage to latrine superstructure is visible, assessments are not systematic and damage to concealed disposal systems are less visible and more difficult to assess, which can lead to long-term hazards (MDM, 2016). The vast majority of septic tanks in Sri Lanka's household latrines are structurally weak, are not water sealed and lack a soakage pit, resulting in inundation (MDM, 2016). Inundated septic tanks became a source of pathogenic contamination as the sludge is carried away by floodwater, and once the flood recedes, due to the unseen structural damage, the septic tanks become long-term sources of groundwater pollution with the potential to cause pathogenic contamination of dug wells (MDM, 2016). Leachates from municipal waste dumps were also mixed with the floodwaters adding to health risks and causing nuisance odours. The Meethotaumulla dumpsite in the Colombo Municipal Council opened in 2000 and used to receive over 700 megatons of unsorted solid waste daily, including chemical and clinical waste, resulting in a huge expansion in size of the site (almost 7 hectares in 2016), and serious local health risks and nuisance (MDM, 2016). During the 2016 floods, some dumping sites in the Colombo and Gampaha coastal areas were submerged by the flood, while others (Meethotamulla) suffered partial collapse and 8,000 megatons of solid waste were carried away and dispersed into the surrounding area (MDM, 2016). A year later in 2017, heavy rain resulted in another, more catastrophic failure of the Meethotamulla open dump, which collapsed and slid over the immediate housing area claiming 32 fatalities, 11 missing people, and displacing more than 1541 persons from their homes (Chandrasena et al., 2020). The site was declared closed following the event (Chandrasena et al., 2020).

Discharges of industrial sludge, effluents and waste due to the inundation of factories during severe floods has also been reported, including spills of hazardous waste as it is a common practice by small sites to collect their hazardous waste within the premises until it can be sent away for disposal (MDM, 2016).

Expected future climate impacts

Future climate change is likely to lead to increased impacts in Sri Lanka, including floods and landslides and other natural disasters (MDM, 2016), and floods are a particularly pervasive vector for environmental pollution and public health emergencies through damage to sanitation and waste infrastructure and systems. Annual floods are common occurrences in Sri Lanka, but each severe flood has resulted in weakened flood protection systems, and a growing population and the rapid expansion of urban and industrial areas are contributing to further increase flood risk (MDM, 2016).

A literature review of key climate change and marine litter issues in the Indian side of the Gulf of Mannar revealed that coastal habitats along the Gulf are subject to degradation from mining, deforestation, and the disposal of waste and untreated effluents, while the ongoing coastal erosion is increasing the risk of coastal inundation from future sea-level rise (Lincoln et al., 2023). Plastic pollution is particularly severe and widespread across coral islands in the Gulf of Mannar, as several hundred tonnes of waste generated daily are either uncollected or inappropriately disposed of, which is flushed in large amounts by rainfall and flooding onto coastal areas, particularly following cyclones (Lincoln et al., 2023). Waste and litter pollution also threatens coral reefs, particularly around coral islands in the Gulf of Mannar, which combines with the future risk of recurrent yearly severe bleaching events, algal bloom hypoxia and cyclone damage (Lincoln et al., 2023).

3.3.3. Cultural services/benefits

Cultural services include both material and intangible benefits that contributes to the development and cultural advancement of people, including the role of ecosystems in local, national, and global cultures; the building of knowledge and the spreading of ideas; the historic and cultural heritage which is often deeply integrated and connected in the surrounding natural landscape; wellbeing and creativity born from interactions with nature; and recreation.

3.3.3.1. Tourism industry and infrastructure

Data sources	Levels of evidence and agreement	Confidence rating
SITE-SPECIFIC STUDIES; REGIONAL STUDIES	HIGH agreement ROBUST evidence	HIGH

Coastal areas, particularly beaches and areas with fringing reefs have become important locations for tourism development (Rajasuriya, 1997). Swimming, snorkelling, deep-sea recreational fishing, boating and sailing, marine mammal and sea turtle watching, and scuba diving especially around coral reef areas are popular activities (Rajasuriya, 1997).

Current climate impacts

A dataset for the Indian Ocean identified a clear spatial pattern in sea-level rise witnessed since the 1960s (Han et al., 2010; Palamakumbure et al., 2020). Due to thermal expansion of seawater, the average sea-level has been risen by 12.7 mm along the northern Indian Ocean coasts during the past decade (Han et al., 2010), making Sri Lanka one of the most 'at risk' countries (Palamakumbure et al., 2020). Also, past studies such as Danard and Murthy (1989) and Yu and Wang (2009) have pointed out direct impacts on the tourism sector of Sri Lanka due to an increase in tropical cyclone frequency and intensity over the Northern Indian Ocean basin (Vellore et al., 2020).

Sri Lankans are generally aware of the vulnerability of the natural environment to degradation from human action. A social impact study at a popular Sri Lankan tourism destination reported that residents were supportive of further tourism development as they believe that tourism has a positive effect on the local community, in terms of increased employment opportunities and property values, as well as benefiting the appearance, infrastructure and public perception of the city (Chandralal, 2010). However, the residents were also found to only support those tourism projects that were planned and managed sustainably (Chandralal, 2010).

The impact of the Indian Ocean tsunami in 2004 offers an example of the effect of a natural disaster on the marine tourism sector (Wickramasinghe and Takano, 2007). It affected the Northern, Eastern, and Southern regions most severely, with a marked impact on the Western coast as well, with a total economic damage of 4.5% of GDP, demanding 2.2 billion USD for recovery and reconstruction efforts (Wickramasinghe and Takano, 2007). The impact of the tsunami on Sri Lanka tourism was extremely grave, as it hit the beaches when up to 6,000 tourists occupied the affected coastal belt, and around 14,500 tourists out of 17,000 tourists who were visiting the country at the time of the disaster left the island immediately (Wickramasinghe and Takano, 2007). A total of 53 hotels out of 105 in affected areas were partially damaged and 8 were completely destroyed, damage to tourism related assets (souvenir shops, restaurants, vehicles, etc.) accounted for 50 million USD, and 27,000 people working in the tourism sector lost their livelihoods (Wickramasinghe and Takano, 2007). The disaster also affected the tourism image, which is intangible and not quantifiable, and compounded by the actual physical damage but also by the sense of insecurity created by the personal perception of the disaster (Wickramasinghe and Takano, 2007). The 2004 tsunami therefore serves as an extreme example of the effect of an acute and short-term severe natural disaster, as it was the most devastating catastrophe in the recorded history of Sri Lanka (Wickramasinghe and Takano, 2007).

Expected future climate impacts

In future, warming conditions are projected to increase risks to the tourism industry, even under 1.5°C of warming, which will threaten seasonal tourism depending on sun and beach (MoE, 2021). In common with other tropical and sub-tropical regions, the main risks for tourism activities in Sri Lanka will be due to heat extremes, storms, loss of sandy beach locations and degradation of coral reef resources (MoE, 2021). The majority (60%) of tourist destinations in Sri Lanka are in coastal areas where elevation is less than 2 m from sea-level (MoE, 2021) and therefore are highly exposed to inundation during extreme weather events as well as from long-term sea level rise. In addition, climate change impacts on the natural habitats and resources that tourism depends upon, such as the effect of droughts and heatwaves on inland water bodies, rivers, mountains, forests, and marine biodiversity including coral reefs, are significant and already visible (MoE, 2021). Long droughts will impact visitation to wildlife parks and forest reserves, while warmer temperatures and heat stress, coupled with water scarcity in drier destinations in the north, north-west and east, will expose tourists to increasing health risks, and will put tourism establishments under strain (MoE, 2021). Tourism assets and infrastructure will also face higher insurance costs against frequent disasters such as floods, particularly in the Kalutara, Ratnapura, Kegalle, Batticaloa and Ampara districts, and landslides in risk areas including the Nuwara Eliya, Ratnapura, Kandy, Matale, Badulla districts (MoE, 2021). As the evidence of escalating effects of climate change on tourism and infrastructure mounts, the need to address and minimize these impacts has become even more urgent. This is particularly crucial considering the direct implications on local businesses and overall development, and there are already examples of funding strategies based on the willingness to pay by tourists, such as at the Rekawa coastal wetland in the Hambantota district, in the southern coast of Sri Lanka (Nesha Dushani et al., 2023).

A key theoretical concept is the Environmental Kuznets Curve (EKC) hypothesis (Grossman and Krueger, 1991), which explains the relationship between environmental quality and economic growth. It shows a bell-shaped relationship between environmental degradation and income. Naradda Gamage et al., (2017) examined whether energy consumption and tourism development provide evidence to support the EKC hypothesis in Sri Lanka. The authors report that carbon emissions, income, tourism development, and energy consumption are co-integrated in the long-term scenario, however the authors estimate that the EKC hypothesis is not supported in Sri Lanka in the long term. This suggests a scenario in which environmental degradation continues irrespective of income generation, where the degradation of the environment is driven by a large energy demand and consumption and aggravated by a rapid economic growth and tourism development. Naradda Gamage et. al. (2017) recommends that Sri Lanka could mitigate environmental degradation without hindering its economic growth by focusing on renewable energy production and ecotourism.

In recognition of climate change threatening the sustainability of and the revenue from the tourism industry in Sri Lanka, The Sri Lanka Tourism Development Authority has revealed plans to introduce a Marine Tourism Master Plan for Sri Lanka by 2024, in collaboration with the Asian Development Bank (The Morning, 2023).

3.3.3.2. Marine wildlife-watching tourism and recreation

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES REGIONAL STUDIES GLOBAL STUDIES	MEDIUM agreement LIMITED evidence	MEDIUM

In Sri Lanka, coastal and marine tourism includes popular activities such as deep-sea sport fishing, observing sea mammals, turtle watching in the shallower reef waters, and numerous recreational water sports including sailing, snorkelling, scuba diving, and boating (MoE, 2021). Coastal tourism represents nearly 60% of total sector revenues and offers a broad range of value-added products (MoE, 2021).

Popular spots for scuba diving and snorkelling include:

- Hikkaduwa and Unawatuna, some of the first proper dive centres to be opened in Sri Lanka and with easy access to a good number of reef dive spots suitable to all abilities that also include some shipwrecks;
- Trincomalee, with dives launching off Nilavelli beach to visit the Pigeon Island Marine Life Sanctuary and the Irakkandy wreck nearshore;
- Mirissa, originally famous for whale watching but now gaining popularity also as a diving spot;
- Passikudah, that allows visits to a number of wrecks; and

- Kirinda, where the diving season is limited to the end of the summer in March-April while the sea is calm and clear, but allows visits to the Little and Great Basses wrecks (Culture Trip, 2023).

Dolphin and whale watching is a thriving tourist attraction in Sri Lanka, particularly in the southern coast (Thilakarathne et al., 2015). Point of Dondra, Kalpitiya and Tricomalee are popular sites for whale watching as these places have high sightings of whales and dolphins, with Mirissa standing out as the most popular spot with a rapidly growing demand for whale watching because of the resident population of blue whales (*Balaenoptera musculus*) (Vivekanandan and Jeyabaskaran 2012), which can be very easily watched (Thilakarathne et al., 2015). However, most of whale and dolphin watching sea trips are non-scientific expeditions without proper regulations, potentially exposing the local cetacean populations to disturbance and harm (Thilakarathne et al., 2015; MoMD&E, 2019).

Bird watching is growing in popularity, and the best season for seabird watching is during the southwest monsoon (usually May - October) as several species enter coastal waters at this time (De Silva, 1997). A mass-migration of bridled terns, *Sterna anaethetus*, also takes place during the southwest monsoon (De Silva, 1997). The inter-monsoonal period (October/November) brings large numbers of Wilson's storm-petrels relatively close inshore, although they are not easily seen on account of their small size and habit of keeping close to the waves, as they use Sri Lankan waters as a final staging area prior to their long return journey to breed in Antarctica (De Silva, 1997). The intermonsoon season also brings winter visitors, including some gull species mainly confined to the north-western region and remote areas of the coast, while terns are mostly winter visitors (De Silva, 1997).

Many of the commercial harbours, ports and a majority of the fishing ports and anchorages are managed by the Ceylon Fisheries Harbours Corporation and are located near sensitive marine environments which includes Marine Protected Areas (MPAs) (Kularatne, 2023). Most of the Sri Lankan MPAs belong to the Department of Wildlife Conservation, for instance, Pigeon Island Marine National Park in the East Coast, which was declared as an MPA in 2003 with an area of 471.4 ha, and the Bar Reef Marine Sanctuary in the North-western coast (Kularatne, 2023). Trincomalee Bay and the Pigeon Island MNP in the East Coast and the Gulf of Mannar cluster in the Northern Coast have been declared High Regional Priority Areas within the Central Indian Ocean region, as part of the Moreover, under the NOAA, USA and IUCN project on World Heritage Biodiversity (Rajasuriya and White, 1995; BOBLME, 2013; Kularatne, 2014; Kularatne, 2023).

Current climate impacts

There is a recognition from the Sri Lanka government that while the coastal belt has an enormous capacity for tourism, this is threatened by coastal pollution, unethical fishing practices and climate change, which are in-turn affecting the sustainability of coastal resources as well as tourism revenue (The Island Online, 2023). However, no information could be found regarding current impacts of climate change on marine recreation and wildlife tourism in Sri Lanka, although indirect information could be gleaned from the evidence collated within this report regarding impacts on key marine and coastal habitats and species such as coral reefs and marine megafauna for example.

Expected future climate impacts

Whilst the direct impacts of climate change on charismatic species such as seabirds, waterbirds, turtles, dugongs and cetaceans are difficult to predict, the widespread loss of suitable habitat is likely to cause distribution shifts that could result in population declines locally (Lincoln et al., 2021a). An additional negative effect of climate change in this sense would be the loss of scenic appeal of some of the popular spots for wildlife watching, resulting in human visitor numbers decreasing over time. In the Arabian Gulf region for example, it has been estimated that the degradation of reefs and the loss of marine biodiversity may result in a loss of revenue of up to 10% per year for tour operators and marine recreation companies (AFED, 2009).

It is likely that future changes in the typical seasonal patterns and ranges of temperature, humidity, precipitation and wind, will negatively affect marine eco-tourism and wildlife-related activities in Sri Lanka. Aside from reacting to the dramatic impact of high-energy, short-duration extreme events, the enjoyment of tourists is also influenced by their experience of prevalent environmental conditions such as temperature and humidity, as well as the frequency and duration of less favourable weather including rain and wind (Perch-Nielsen et al., 2010). Local weather determines the duration of the peak tourist season and is one of the main criteria influencing destination choice by tourists (Hassan et al., 2015). Rising sea levels and coastal erosion will also put coastal resorts at risk of losing visual appeal and spoiling the experience of visitors (Lincoln et al., 2021a). Extreme weather, nuisance or harmful marine blooms and outbreaks all contribute to spoiling the experience of the sea and create public health hazards, dissuading visitors (Agnew and Viner, 2001).

3.3.3.3. Archaeology and cultural heritage

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES GLOBAL STUDIES	MEDIUM agreement LIMITED evidence	MEDIUM

Current climate impacts

While cultural heritage is not often the focus of climate change debate and policy, it has been reported that where climate change combines with poorly framed law and policy for culture and traditions, countries vulnerable to climate change may face significant cultural loss in the future (Hee-Eun 2011). Climate change threatens archaeological and cultural sites globally, but awareness and action around cultural heritage and climate change adaptation planning has been largely focused on Europe and North America. Daly et al., (2022) investigated adaptation policy and measures for heritage sites in low- and middle-income countries, by reviewing national adaptation plans, expert survey and five case studies (Brazil, Colombia, Nepal, Palestine and Sri Lanka) and showing the varied climate change adaptation responses across these countries. In discussing these nations' strengths and weaknesses, in terms of future climate change adaptation planning, the authors found that Sri Lanka's adaptation plan proposes a role for local stakeholders in the identification of "religious, cultural and archaeological assets vulnerable to climate change impacts" to build the adaptive capacity of communities (Daly et al., 2022). The country being a tourism hot spot, the report also includes recommendations for the tourism industry to develop strategies with key stakeholders, including the national Department of Archaeology, to adjust tourism operations in different locations, based on an analysis of climate change risks.

It is now common practice to include local knowledge systems in the implementation of coping strategies to increase the resilience of rural communities against climate change by adaptation measures (Pearson et al., 2021). For example, water management plans in the rural communities of Sri Lanka must include the traditional, ancient tanks locally called 'wewas', which serve for the collection, storage and distribution of rainfall and runoff and provide for irrigation water. Bebermeier et al., (2023) studied the local knowledge associated with the management and maintenance of the tank cascade systems in Sri Lanka, highlighting the value and potential of integrating traditional water harvesting systems in strategies of coping with climate change and increase resilience for rural communities.

Expected future climate impacts

Rainforests are globally threatened by various anthropogenic activities and climate stressors, and they are often intrinsic to the cultural heritage of countries. The Sinharaja Rainforest in Sri Lanka has been designated a Biosphere Reserve and World Heritage Site by UNESCO. The extent and health of this forest is declining due to human activities and changing climates, and although not a coastal site, it is an example of the status and risks threatening other historic landscapes in the country, some of which are located nearer to the coastline. Samarasinghe et al., (2022) presented a comprehensive study on the possible impact of climate change on the Sinharaja Rainforest. Using Landsat images and measured rainfall data for 30 years to study climate impacts on this region, the authors showed that the built-up areas have drastically increased over the last decade and reclaimed a good amount of forest area Although no significant trends in rainfall were found over the study period, some cleared-up areas were found inside the Singaraja Rainforest, that could not be explained by neither climate change nor human activity (Samarasinghe et al., 2022).

3.3.4. Regulating and supporting services/benefits

Regulating services moderate natural phenomena and include water quality, erosion and flood control, and carbon storage and climate regulation, while supporting services include the underlying life-sustaining natural processes, such as photosynthesis, nutrient cycling, the creation of soils, and the water cycle. Here we also include a consideration of the direct impact of climate change on people's health, and the cost of lives.

3.3.4.1. Human health and welfare

Data sources	Levels of evidence and agreement	Confidence rating	
SITE-SPECIFIC STUDIES; REGIONAL STUDIES	HIGH agreement LIMITED-MEDIUM evidence	LOW	MEDIUM

Current climate impacts

As reported in section 3.1.6, warming of the western Indian Ocean has increased the frequency and intensity of severe weather, including tropical cyclones, with associated impacts on human health (Roxy et al., 2017). Flooding, storm surges and strong winds associated with tropical cyclones and other extreme climate events can cause direct mortality to humans. These events can affect human health either directly or indirectly, for example through disruption and damage to medical facilities, power and water supply, and sewage overflow that may increase pathogen risk. On 14 May 2016, tropical cyclone Roanu struck Sri Lanka, causing major flooding and landslides. The cyclone had serious consequences for the entire Bay of Bengal in South Asia, destroying the homes of some 125,000 people and costing an estimated USD 1.7 billion in reconstruction. In Sri Lanka the disaster caused damages and losses in excess of USD 570 million (World Bank, 2016). The storm led to the displacement of over 493,319 persons and caused over 200 casualties (Friedrich 2017). Overall, 24 out of 25 districts in Sri Lanka were affected. The district of Colombo, the country's capital and economic hub, as well as the district of Gampaha were worst-affected areas by flooding (Friedrich 2017).

As seas become warmer due to climate change, blooms of toxic microalgae are expected to increase and could present a health risk to humans (see section 3.2.2). Distribution and abundance of the organisms that produce ciguatera fish poisoning, chiefly dinoflagellates of the genus *Gambierdiscus*, are reported to correlate positively with seawater temperature (Kibler et al., 2017). Subsequently, there is growing concern that increasing temperatures associated with climate change could increase the incidence of ciguatera fish poisoning including in Sri Lanka (see section 3.2.2).

Vibrio spp. are bacteria that thrive where seawater temperatures are elevated (>18C) and salinity is moderate. At least 12 *Vibrio spp*. are known to cause infection in humans, and *Vibrio cholerae* is well documented as the causative agent of pandemic cholera (Brumfield et al., 2021). Pathogenic non-cholera *Vibrio spp*., e.g. *Vibrio* *parahaemolyticus* and *Vibrio vulnificus*, cause gastroenteritis, septicaemia, and other extra-intestinal infections. Incidence of vibriosis is rising globally, with evidence that anthropogenic factors can enhance growth of *Vibrio spp*., primarily atmospheric warming and more frequent and intense heatwaves but also release of nutrients to the ocean (Brumfield et al., 2021). As a result, the likelihood of transmission of Vibrios to humans is increased, either through drinking infected water or through eating shellfish which concentrates the organism.

Early studies estimated *V. parahaemolyticus* was responsible for up to 30% of all food-poisoning cases in Japan (Jahangir Alam et al., 2002), and similar claims have been made in other parts of Asia including Sri Lanka (Koralage et al., 2012). *V. parahaemolyticus* has also been identified as the leading cause of seafood-associated gastroenteritis in the United States (Mead et al., 1999) and China (Li et al., 2014) since the 1990s (Brumfield et al., 2021).

Shackleton et al., (2023) describes an analysis of the changing relationship between ENSO and IOD with cholera in Kolkata over recent (1999–2019) and historical (1897–1941) time periods. Findings suggest that temperature may be an important factor which determines the occurrence of cholera on a yearly basis. This theory is echoed by Pascual et al., (2000) who also suggested that the influence of ENSO on cholera in Bangladesh is ultimately mediated by increases in temperature. An association between cholera and temperature has also recently been demonstrated in Kolkata using Generalized Additive Modelling (Shackleton et al., 2023).

Expected future climate impacts

As reported in section 3.1.6 of this report, modelling studies such as Danard and Murthy (1989) and Yu and Wang (2009) have anticipated an increase in both tropical cyclone frequency and intensity over the Northern Indian Ocean basin (Vellore et al., 2020). Subsequently, increased disruption to human populations and health facilities would be expected in the future as a result of long-term climate change.

Furthermore, climate change is expected to affect the frequency, magnitude, biogeography, phenology and toxicity of harmful algal blooms (HABs) in the future (see section 3.2.2). As far as can be discerned, no future modelling studies have yet been performed for HABs in the Indian Ocean. In the ocean, the most important harmful algae and their poisoning syndromes (in parentheses) are diatoms from the genus *Pseudo-nitzschia* (amnesic shellfish poisoning), and species of dinoflagellates from the genera *Alexandrium, Pyrodinium,* and *Gymnodinium* (paralytic shellfish poisoning), *Karenia* (neurotoxic shellfish poisoning, and aerosolized Florida red tide respiratory syndrome), *Dinophysis* and *Prorocentrum* (diarrhetic shellfish poisoning), and *Gambierdiscus* (ciguatera fish poisoning).

3.3.4.2. Natural flood and erosion control

Data sources	Levels of evidence and agreement	Confidence rating
SITE-SPECIFIC STUDIES; REGIONAL STUDIES	HIGH agreement ROBUST evidence	HIGH

Current climate impacts

In a recent study, Alahacoon and Edirisinghe (2019) observed a significant increase in annual rainfall during the period 1989 to 2019 in all four climatic zones of Sri Lanka, namely, wet, dry, intermediate, and semi-arid. The maximum (and minimum) increase is recorded in the wet zone (and in the semi-arid zone). This observation indicates that there could be an increased risk of (inland) floods in the southern and western provinces in the future, whereas areas in the eastern and southeastern districts may face severe droughts during the northeastern monsoon.

Soil erosion has become a severe environmental issue and results from poor land management practices with consequences for long-term agricultural production, hydropower generation and water quality. Approaches to understand the spatial variability of erosion severity are important for improving land use management. Fayas et al., (2019) studied erosion severity in Kelani River basin, Sri Lanka using the Revised Universal Soil Loss Equation (RUSLE) model supported by a GIS system. Erosion severity across river basins was estimated using RUSLE, a Digital Elevation Model, twenty years of rainfall data at 14 rain gauge stations across the basin, land use and land cover, and soil maps and cropping factors. The estimated average annual soil loss in Kelani River basin varied from zero to 103.7 t ha^{1} yr^{1}, with a mean annual soil loss estimated at 10.9 t ha^{1} yr^{1}. About 70% of the river basin area was identified with low to moderate erosion severity.

Expected future climate impacts

In another study by de Silva et al., (2023), using same methodology the authors estimated the spatial variation of soil erosion in the Nalanda Oya catchment in Sri Lanka. The results highlighted that about 18.78% of the catchment is under moderate to high (> 5 t ha^{1} yr^{1}) erosion risk which may increase to about 20.83% to 21.58% in 2030s, for RCP 4.5 and RCP 8.5, respectively. About 32% of the land area would show an increase in soil erosion mostly owing to the climate change impacted changes in rainfall. Improving the land use to mitigate the increase in potential erosion may require reforestation and conservation practices, as a climate adaptation measure to protect sensitive ecosystems and ensure continued ecosystem services.

3.3.4.3. Carbon sequestration and storage by coastal and marine habitats

Data sources	Levels of evidence and agreement	Confidence rating
LOCAL STUDIES REGIONAL STUDIES GLOBAL STUDIES	MEDIUM agreement LIMITED evidence	LOW

Mangrove forests, coastal saltmarshes and seagrass meadows represent the three main ‘blue carbon’ habitats globally (Duarte et al., 2013; McLeod et al., 2011). Despite their comparatively small extent, the blue carbon sequestered and stored by these coastal and marine ecosystems is estimated to amount to more carbon per unit area than terrestrial forests and therefore has an important role in mitigating climate change (Herr and Landis, 2016). If these ecosystems are degraded or damaged, for example, because of climate change impacts, their carbon sink capacity is lost or adversely affected, and the carbon stored is released, resulting in additional emissions of carbon dioxide that further contribute to climate change (Herr and Landis, 2016). Alongside tropical forests and peatlands, coastal ecosystems offer opportunities for countries to achieve their emissions reduction targets and Nationally Determined Contributions under the Paris Agreement, and they provide numerous other benefits and services that are essential for climate change adaptation, including coastal protection and food security for many communities globally (Herr and Landis, 2016).

Blue carbon habitats in Sri Lanka are poorly studied (Perera et al., 2022; Prasanna et al., 2021), and a terrestrial carbon inventory has not yet been conducted. Estimates of blue carbon stocks in the mangrove forests of the Benthota River estuary reported an average total carbon stock of 995 tonnes per ha, with average above ground carbon of 404 tonnes per ha and average below ground carbon was 549 tonnes per ha (Prasanna et al., 2021). This was higher than the recorded values of the dry zone mangrove ecosystems in Sri Lanka, although the values are similar to global average carbon stocks in mangrove ecosystems (Prasanna et al., 2021). A number of studies and reviews have tried to estimate the carbon stock in Sri Lankan mangroves reporting that the carbon stock in mangrove soil is highest (581 tonnes per ha) in the intermediate climate zone, followed by the wet zone (406 tonnes per ha) and the lowest (316 tonnes per ha) in the dry zone (Veettil et al., 2023; Gunathilaka et al., 2022; Cooray et al., 2021; Wijeyaratne and Liyanage, 2020; Perera and Amarasinghe, 2019). These estimations of mangrove carbon stocks from Sri Lanka are comparable to published values for mangrove systems in different countries in the Indian Ocean region (Murdiyarso et al., 2015; Dung et al., 2016) and higher compared to global range (118–424 tonnes per ha) (Veettil et al., 2023; Atwood et al., 2017).

Tropical saltmarshes retain relatively low, yet noteworthy stocks or organic carbon compared to global saltmarsh estimates (Perera et al., 2022). A study aiming to quantify the organic carbon stocks in the saltmarsh in the Wedithalathive Nature Reserve, on the Northwest coast of Sri Lanka, indicated an average total organic carbon storage of 73 ± 14.47 tonnes of C per ha up to a depth of 50 cm, in which the aboveground vegetation accounted for about 2% (Perera et al., 2022). In total, the total carbon stock in saltmarsh habitats across Sri Lanka is estimated as 2.01 Teragrams of organic carbon, which highlights their potential for inclusion in Nationally Determined Contributions under the Paris Agreement, given their potential role in climate change mitigation (Perera et al., 2022). Finally, no reliable estimates of carbon stocks in seagrass habitats of Sri Lanka were found during the preparation of this report.

Current climate impacts

As presented in the sections of this report dedicated to the three main coastal and marine blue carbon habitats – mangroves, seagrass meadows, and saltmarshes – they are inherently adapted to cope with changes or variability in environmental conditions, and can be relatively robust to climate change impacts, assuming that they are in good condition and not affected negatively by other human pressures. It has been suggested for example that seagrasses are carbon-limited plants and consequently their productivity can be stimulated under higher CO_2 conditions, with some studies suggesting the potential for seagrasses to buffer pH changes and protect calcifying organisms such as corals (Manzello et al., 2012; Lincoln et al., 2021a). On the other hand, studies on the mangrove *Avicennia marina* have also shown small increments of photosynthesis in response to higher CO_2 concentrations (Alongi, 2015).

Wetlands are being degraded and lost a rate faster than almost any other habitat on Earth, primarily because of direct destruction or adverse effects from human activity (Herr and Landis, 2016). It has been estimated that the amount of CO_2 released annually worldwide from degraded or lost wetlands is equivalent to the annual emissions of the United Kingdom (Pendleton, 2012). A few studies have recorded the conversion of loss of mangrove areas into loss of carbon sequestration and storage services capacities in Sri Lanka, and estimated that a 34% loss of mangrove areas in Puttalam Lagoon could be converted into an estimated net carbon loss of 191,584 tonnes of carbon (Veettil et al., 2023; Bournazel et al., 2015)

Expected future climate impacts

Not enough direct information could be found on expected future impacts of climate change on carbon sequestration and storage by coastal blue carbon habitats in Sri Lanka, but a conservative appraisal, based on current fragmentation and sub-optimal condition of coastal wetlands in the country (MoMD&E, 2019; Gunatilleke et al., 2008; Libin et al., 2017) suggests that their resilience and their persistence into the future is at risk in the face of increasing pressures from climate change, especially where other human activities continue to cause adverse effects. The influence on mangrove density on surface sediment accretion, belowground biomass and biogeochemistry has also been investigated in Puttalam Lagoon, showing that areas with the highest seedling density had a higher sediment accretion rates, finer sediments, higher belowground biomass, and greatest number of fine roots, as well as crucially high concentrations of C and N and low C/N ratios (Veettil et al., 2023; Phillips et al., 2017).

The disturbance and loss of these habitats represents additional emissions of CO_2 from the stored reserves and the total loss of sequestration capacity.

3.4. Marine climate change risks in Sri Lanka

3.4.1. Confidence and severity scoring

Following the compilation of the evidence presented in this report, and ahead of the risk assessment workshop, an initial list of key risks was identified. This initial list comprised 37 risks: 18 issues linked to biodiversity, and 19 societal and economic issues. Following the approach recommended by the IPCC (Mastrandrea et al., 2011) and as adapted by Maltby et al. (2022) risks were categorised in terms of confidence based on a qualitative appraisal of the amount and level of consensus of the evidence, and an overall confidence score was assigned (see Figure 5).

This initial list of risks was then discussed and assessed in detail at a 2-day workshop held in Sri Lanka in August 2024, with contribution from stakeholders and experts with relevant involvement in the country's research, policy, marine management, and nature conservation. The workshop participants were guided through the stepwise method summarised in section 2. They were given the opportunity to review the risk scoring in terms of proximity (or urgency) and magnitude (or severity). Magnitude scores were based on the perceived significance and consequences of a particular risk happening, based on an assessment of combined environmental, economic and social impacts, that is, how many people were likely to be affected, the level of economic losses anticipated, or the spatial area impacted (see Table 4). Risks were also rationalised, and stakeholders were asked to identify potential duplication of risks within the initial list, or where any given risk could in fact be compounded of more than one risk, in order to separate them.

For example, under the "*Biodiversity: Species*" category, a risk involving seabirds and waterbirds species was split into two separate risks, one for resident species of seabirds and waders, and one for migratory waterbird species. Under the "*Societal and Economic Issues: Provisioning of raw materials and energy*", coral mining extraction activities were not included in the final risk register. Under "*Provisioning of food and water*", a new risk was added to reflect the threat to coastal freshwater resources. Finally, under that same category, an initial risk capturing all coastal fisheries was split into three separate risks: declines in coastal or inshore catch potential, risks to lagoon fisheries specifically, and disruption to traditional fish processing (sun drying) activities, respectively.

The final list resulting from this critical review by the workshop experts therefore consisted of a total of 41 key risks (19 risks to biodiversity and 22 risks to society and economy). Of those 41 key risks, 14 were scored as HIGH PRIORITY (score equal to or higher than 75, see Table 6 below). These high priority risks would require further investigation and assessment. In some cases, high priority risks were accompanied by a LOW confidence score, meaning that either very little published information exists or is available on this topic, or that the link between those issues and climate change is not clear at present. These risks would also be a priority for future research.

Table 6. Final list of key marine climate change risks facing the coastal and marine environment in Sri Lanka, grouped by categories as related to *Biodiversity* (species; habitats) and to *Societal and economic issues* (provisioning of food and water; raw materials and energy; space; recreation and tourism, cultural heritage, and wellbeing; air and water quality, coastal protection, and climate control). The level of evidence and the agreement within the evidence, and the overall evidence confidence rating, are indicated. The risk score is calculated as a function of proximity (P) and magnitude (M). Risks scoring 75 and above are considered as HIGH PRIORITY and highlighted in darker colour. See section 2 for more details on the scoring method.

Risk no. and description	Levels of evidence and agreement	Confidence rating	P	M	Risk score
BIODIVERSITY: Species					
1. Decline in phytoplankton biomass and primary productivity with negative consequences for marine food-webs.	HIGH agreement ROBUST evidence	HIGH	4	3	100
2. Increases in the occurrence of harmful algal blooms in coastal waters around Sri Lanka, with negative consequences for human and animal health.	LOW agreement LIMITED evidence	LOW	3	1	25
3. Changes to coastal and reef-associated fish assemblages	MEDIUM agreement LIMITED evidence	MEDIUM	4	2	66.7
4. Changes to the distribution, migration routes, and catchability of large pelagic fish species (e.g. tuna) around Sri Lanka.	MEDIUM agreement LIMITED evidence	LOW	4	2	66.7
5. Decline in seabirds and waders as a result of habitat disturbance and changes in food availability	MEDIUM agreement LIMITED evidence	LOW	3	2	50
6. Decline in migratory waterbirds as a result of climate related habitat modification and changes in food availability.	MEDIUM agreement LIMITED evidence	LOW	3	2	50
7. Changes in the distribution, occurrence, breeding and feeding success of cetaceans around Sri Lanka.	MEDIUM agreement MEDIUM evidence	MEDIUM	3	2	50
8. Decline in habitat availability and therefore occurrence /persistence of dugong in Sri Lanka	MEDIUM agreement MEDIUM evidence	MEDIUM	3	2	50
9. Disruption of sea turtle sex ratios, migration, nesting ecology and feeding habitats	MEDIUM agreement MEDIUM evidence	MEDIUM	4	3	100
10. Degradation of saltwater crocodile nesting and feeding habitats	LOW agreement LIMITED evidence	LOW	2	1	16.7
11. Loss or disappearance of sensitive endemic species in marine and coastal habitats of Sri Lanka.	HIGH agreement LIMITED evidence	LOW	4	2	66.7
12. Invasion and outbreaks of native and non-native marine species, with widespread consequences for other ecosystem components	MEDIUM agreement MEDIUM evidence	MEDIUM	3	2	50
BIODIVERSITY: Habitats					
13. Degradation of deep-sea habitats and communities.	LOW agreement LIMITED evidence	LOW	2	1	16.7

Risk no. and description	Levels of evidence and agreement	Confidence rating	P	M	Risk score
14. Increases in the frequency and extent of severe coral bleaching events, leading to coral death.	HIGH agreement ROBUST evidence	HIGH	4	3	100
15. Decline in the structure and effective functioning of coral reef habitats as a result of coral death, changes to community composition and invasion of coral predators/diseases.	HIGH agreement ROBUST evidence	HIGH	4	3	100
16. Reduction in the extent, productivity, recovery and resilience of coastal mangroves around Sri Lanka.	HIGH agreement ROBUST evidence	HIGH	3	3	75
17. Decline and retreat of seagrass habitats with consequences for community composition and ecosystem functioning/persistence.	MEDIUM agreement MEDIUM evidence	MEDIUM	3	3	75
18. Changes in beach and sediment dynamics, inundation and degradation of sandy shoreline habitats.	MEDIUM agreement LIMITED evidence	LOW	4	3	100
19. Reduction in the extent, productivity, recovery and resilience of saltmarsh, estuarine and mudflat habitats around Sri Lanka.	MEDIUM agreement LIMITED evidence	LOW	4	2	66.7
SOCIETAL AND ECONOMIC ISSUES: Provisioning of food and water					
20. Decline in fishery catch potential from coastal waters with consequences for local employment, food security and revenues.	MEDIUM agreement MEDIUM evidence	MEDIUM	4	3	100
21. Decline in fishery catch potential and access to lagoon waters with consequences for local employment, food security and revenues.	MEDIUM agreement MEDIUM evidence	MEDIUM	3	3	75
22. Disruption to fish processing at the coastal margin with consequences for local employment, livelihoods, food security and revenues.	HIGH agreement ROBUST evidence	HIGH	3	2	50
23. Reductions in revenues and catches from offshore fisheries/licences.	MEDIUM agreement MEDIUM evidence	MEDIUM	3	3	75
24. Disruption to aquaculture/mariculture (i.e. shrimp farming, sea cucumber, seaweed, blue crab) including consequences for disease proliferation and therefore production.	HIGH agreement MEDIUM evidence	MEDIUM	4	2	66.7
25. Disruption to freshwater supplies in the coastal zone as a result of drought, salinisation and storm events.	HIGH agreement ROBUST evidence	HIGH	4	2	66.7
SOCIETAL AND ECONOMIC ISSUES: Provisioning of raw materials and energy					
26. Increased demand for sand and gravel in order to construct, repair or rebuild hard sea defences	MEDIUM agreement LIMITED evidence	LOW	2	2	33.3

Risk no. and description	Levels of evidence and agreement	Confidence rating	P	M	Risk score
27. Disruption to and decline in the efficiency of power station cooling systems or proposed desalinisation plants	MEDIUM agreement LIMITED evidence	LOW	2	1	16.7
28. Increased damage to offshore infrastructure (e.g. wind turbines and oil rigs) and disruption of operations.	HIGH agreement LIMITED evidence	LOW	3	2	50
SOCIETAL AND ECONOMIC ISSUES: Provisioning of space					
29. Increased risk of disruption to telecommunication systems (cables, masts, inter-connectors etc.)	HIGH agreement MEDIUM evidence	MEDIUM	3	2	50
30. Damage to, and deterioration of critical coastal infrastructure assets, including roads, airports, and buildings	HIGH agreement ROBUST evidence	HIGH	4	3	100
31. Increased damage to harbours and disruption of maritime transport as a result of changes in the frequency or severity of extreme weather events	HIGH agreement MEDIUM evidence	MEDIUM	3	3	75
32. Impacts on trade and breeding of ornamental reef-associated species.	LOW agreement MEDIUM evidence	LOW	4	2	66.7
SOCIETAL AND ECONOMIC ISSUES: Recreation and tourism, cultural heritage, wellbeing					
33. Physical damage and disruption to assets important to the tourism sector – with consequences for employment, insurance costs and revenues etc	HIGH agreement ROBUST evidence	HIGH	4	2	66.7
34. Changes in the occurrence of cetaceans, turtles, reef-fish populations that are important for eco-tourism – impacts on perceived attractiveness as a destination	MEDIUM agreement LIMITED evidence	MEDIUM	4	3	100
35. Loss, damage and reduced visitation to historic sites, culture and traditions in Sri Lanka	MEDIUM agreement LIMITED evidence	MEDIUM	2	3	50
SOCIETAL AND ECONOMIC ISSUES: Air and water quality, coastal protection, climate control					
36. Adverse impacts on landfill and waste disposal systems, as a consequence of seawater inundation/intrusion and coastal erosion	HIGH agreement MEDIUM evidence	MEDIUM	4	2	66.7
37. Release of untreated liquid effluents and damage to sewerage systems with consequences for public health.	HIGH agreement MEDIUM evidence	MEDIUM	4	2	66.7
38. Physical risk to human health, lives and livelihoods as a result of heat stress, sunburn or severe weather events at the coast.	HIGH agreement MEDIUM evidence	MEDIUM	3	2	50
39. Proliferation of marine organisms that are dangerous to human health.	HIGH agreement LIMITED evidence	LOW	3	1	25
40. Damage and long-term degradation of coastal habitats with negative consequences for	HIGH agreement ROBUST evidence	HIGH	3	3	75

Risk no. and description	Levels of evidence and agreement	Confidence rating	P	M	Risk score
coastal protection, flood and erosion control.					
41. Damage to carbon sequestrating habitats, with long-term consequences for emissions reduction and climate change mitigation.	MEDIUM agreement LIMITED evidence	LOW	3	2	50

3.4.2. Final register of key risks and climate drivers

Once the risks were reviewed, rationalised and scored into a final list, the key climate drivers behind each risk were also identified. These drivers refer to the physico-chemical variables identified as the main climate change forcings in the marine and coastal environment in Sri Lanka, and include temperature (air and sea), ocean circulation and currents, salinity, sea level rise, ocean acidification and pH, seawater dissolved oxygen, extreme weather events, and rainfall and changes in monsoon patterns. They are explained in detail within section 3.1.

The main points of discussion and additional details brought forward for each of the risks by the country's experts during the workshop is organised into a final register of key climate change risk for the coastal and marine environment in Sri Lanka and is presented in Table 7 below.

Table 7. Further description of climate risks to the marine environment of Sri Lanka. Confidence rating (H = high, M = medium, L = low) and risk score (between 8.3 or lowest and 100 or highest). Risks scoring 75 and above are considered HIGH PRIORITY and highlighted in darker shade of red (■) compared to the other lower score risks (■). The climate variables most likely to be driving those changes are indicated using shading (■= principal climate driver, ■= secondary climate drivers). Climate drivers headings are as follows: SLR = Long-term sea level rise and extreme sea level events (i.e. storm surges); CURR = changes in ocean circulation and currents; TEMP = changes in air and sea temperature; STORM = changes in frequency, track and intensity of storms; OA = changes in pH and other ocean acidification effects; SAL = changes in seawater salinity levels; O2 = changes in dissolved oxygen concentration; RAIN = changes in precipitation patterns and land runoff inputs; MONS = changes to timing and strength of monsoons. More detail about the confidence categorization, or the components of the risk score as a function of proximity and magnitude can be found in Table 6.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
1. Decline in phytoplankton biomass and primary productivity with negative consequences for marine food-webs.	H	100		CURR	TEMP	STORM		SAL		RAIN	MONS
Changes in currents and wind driven upwelling, freshwater runoff inputs, and shifts in temperature and salinity in coastal areas can lead to local changes in plankton community structure, timing and distribution and a potential decrease in primary production. This risk was assessed by the workshop experts as an important one with potential large-scale impacts. Experts also indicated to have knowledge of trends in the Northern Indian Ocean, from studies carried out in the 1970s, although no documented evidence was found to substantiate this.											
2. Increases in the occurrence of harmful algal blooms in coastal waters around Sri Lanka, with negative consequences for human and animal health.	L	25		CURR	TEMP	STORM				RAIN	MONS

Risk no. and description	Conf. rating	Risk score	Key climate drivers
Changes in temperature and salinity can encourage the establishment, prevalence and spread of algal species that can develop into harmful algal blooms. The climate link of these harmful algal bloom events is not clear, as their occurrence may also be linked to poor water quality and / or pollution. Experts at the workshop indicated that there is relatively more evidence from India about this risk, while evidence from Sri Lanka specifically is lacking.			
3. Changes to coastal and reef-associated fish assemblages.	M	66.7	TEMP, STORM, RAIN, MONS
Climate change can impact the distribution, reproduction and growth of coastal reef fish. Experts at the workshop agreed that declines in the abundance reef fish species are already being observed, with some species now considered to be virtually depleted. Many local-scale inshore fisheries depend on reef species, as well as sport diving and other tourist activities, which are being impacted negatively as a consequence of the loss of species richness. The causes behind these declines are not fully clear and are likely to involve the effects of habitat degradation and / or overfishing, as well as climate change. Experts indicated knowledge of changing trends of coastal fish species, although no documented evidence could be found. Experts agreed that this is a risk with clear and direct social and economic ramifications.			
4. Changes to the distribution, migration routes, and catchability of large pelagic fish species (e.g. tuna) around Sri Lanka.	L	66.7	CURR, TEMP, STORM, O2, MONS
Climate change can impact the distribution, reproduction and growth of large pelagic commercial fish species. Experts discussed the importance of translating this risk and any observed impacts into economic losses for Sri Lanka.			
5. Decline in seabirds and waders as a result of habitat disturbance and changes in food availability.	L	50	SLR, CURR, TEMP, STORM, SAL, MONS
Climate change threatens the abundance or distribution of foraging prey of resident populations of seabirds and waders, and damage to nesting habitats (e.g. mangroves and beaches), for example during severe storms. Experts recognise observed impacts on the distribution and abundance of waders and seabird species, although they do not agree that role of climate change is clear as there are also other human pressures at play. The Indian Ocean tsunami that hit Sri Lanka in 2004 resulted in inundation and changes to the salinity levels of key coastal wetlands, which have led to long-term changes to those habitats and impacts on the local seabird populations that depend on them; although not a climate-related event, these effects highlighted the potential for extreme events to cause large-scale modifications to key bird habitats along the coastline. There is some economic value associated with resident seabirds and wader populations, linked to wildlife watching activities and tourism, however it is a difficult figure to quantify. It is difficult to assess this risk into the future.			
6. Decline in migratory waterbirds as a result of climate related habitat modification and changes in food availability.	L	50	SLR, CURR, TEMP, STORM, SAL, RAIN, MONS
Climate change threatens migrant species of waterbirds by impacting the availability of foraging prey and damaging nesting habitats (e.g. mangroves and beaches), for example during severe storms. Experts recognise observed impacts on the distribution and abundance of migrant waterbirds, although they do not agree that role of climate change is yet clear as there are also other human pressures at play. The Indian Ocean tsunami that hit Sri Lanka in 2004 resulted in inundation and changes to the salinity levels of key coastal wetlands, which have led to long-term changes to those habitats and impacts on the local seabird populations that depend on them; although not a climate-related event, these effects highlighted the potential for extreme events to cause large-scale modifications to key bird habitats along the coastline. There is some economic value associated with migrant waterbirds, linked to wildlife watching activities and tourism, however it is a difficult figure to quantify. It is difficult to assess this risk into the future.			

Risk no. and description	Conf. rating	Risk score	Key climate drivers
7. Changes in the distribution, occurrence, breeding and feeding success of cetaceans around Sri Lanka.	M	50	CURR, TEMP, STORM, RAIN, MONS

Climate change can potentially impact the availability of food resources of whales and dolphins, their distribution, migration routes and timing, and can also affect the suitability of breeding grounds. It may also have a role in mass strandings events. Feedback suggested that impacts were observable with population declines, however at present studies of cetaceans in Sri Lankan waters are incomplete and further monitoring and research is required to understand population trends and / or the role of climate change.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
8. Decline in habitat availability and therefore occurrence /persistence of dugong in Sri Lanka.	M	50	TEMP, SAL, RAIN, MONS

The main climate risk to dugong is from declines in seagrass habitat. Dugong is widely distributed across the Indian Ocean but data coverage in Sri Lanka is limited, and the necessary long-term data to assess population changes is lacking. The current population in Sri Lanka is considered to be small, however it is a highly charismatic and valued species. Experts at the workshop agreed that, in Sri Lanka, storms do not have a significant effect on dugong, whilst they may be more sensitive to seasonal variations of temperature and salinity conditions. It was also noted that the protecting of seagrass habitats is essential for dugong conservation.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
9. Disruption of sea turtle sex ratios, migration, nesting ecology and feeding habitats.	M	100	SLR, CURR, TEMP, STORM, MONS

Climate change represents a significant risk to sea turtles through a combination of erosion or disturbance of nesting beaches, the risk of feminisation of hatchlings due to rising temperature, the degradation and loss of key feeding grounds (e.g. seagrass habitat), and disruption of oceanic circulation patterns. In Sri Lanka there are records of past impacts on nesting beaches, mainly through inundation during extreme sea level events, which is now being reflected as declines in population numbers.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
10. Degradation of saltwater crocodile nesting and feeding habitats.	L	16.7	SLR, CURR, TEMP, STORM, MONS

Climate change can lead to erosion or disturbance of crocodile nesting sites, feminisation of hatchlings due to rising temperature (similar to sea turtles), and prey scarcity. Workshop attendees felt that further expert knowledge in this area could be further sought and that opinion was divided, some were not sure this risk was sufficiently justified, while others thought it was important and demanded action to protect the local population of saltwater crocodiles.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
11. Loss or disappearance of sensitive endemic species in marine and coastal habitats of Sri Lanka.	L	66.7	TEMP, STORM, OA, SAL, RAIN, MONS

It is generally accepted that climate change threatens sensitive endemic species or species with restricted distribution, through negative changes in their habitat, resulting for example in loss of feeding resources. Experts recognised however that this risk cannot be fully assessed for Sri Lanka without knowing the extent of the marine species affected. It was also recognised that some species that used to be considered restricted, are being found in other areas and therefore are no longer considered endemic.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
12. Invasion and outbreaks of native and non-native marine species, with widespread consequences for other ecosystem components.	M	50	SLR, CURR, TEMP, STORM, RAIN, MONS

Climatic change typically favours opportunistic and tolerant species, that are then more likely to spread to new areas and cause nuisance outbreaks. For example, severe storms and ocean warming are known to play a role in the mobilisation, spread and establishment of non-native invasive species. Experts discussed observations of jellyfish outbreaks around Sri Lanka and agreed that whilst currently the impact of jellyfish blooms are localised and sporadic, these events can become larger and more likely to affect coastal areas in the future, although the climate link is not yet clear. Marine litter, as well as water quality, are also known to contribute to the likelihood

Risk no. and description	Conf. rating	Risk score	Key climate drivers
and severity of these population outbreaks. This is the case in other marine regions, where jellyfish blooms can damage critical services by clogging coastal power and desalination plants. Another example given was the risk of the crown-of-thorns corallivorous starfish, which can decimate areas of reef during population outbreaks. Overall, there is a lack of data, particularly long-term series observations, which means it is difficult to detect population outbreaks of invasive marine species.			
13. Degradation of deep-sea habitats and communities.	L	16.7	CURR, TEMP, OA, O2
The influence of climate change can reach deep-sea regions and have potentially negative effects on habitat and species. It is expected that temperature and changes to deep-ocean circulation will be the principal climatic factors driving these changes. It is a challenging study area, generally inaccessible through traditional sampling and monitoring methods, and therefore data are scarce, and there is limited data resolution. Besides the risk of climate change, the deep sea is also under increasing pressure from human activities, such as shipping, marine extraction and construction, and deep-sea mining. There are rising concerns that deep-sea regions are becoming a sink for ocean litter.			
14. Increases in the frequency and extent of severe coral bleaching events, leading to coral death.	H	100	SLR, CURR, TEMP, STORM, OA, RAIN, MONS
Climate change effects on coral reef habitats is very significant, mainly driven by raising temperatures and severe marine heatwave events, extreme weather events and fluctuations of monsoon patterns. Experts highlighted that this was causing mass coral bleaching, structural damage, and increasing disease susceptibility in all areas. There is ample evidence of these effects around Sri Lanka, and experts agree that climate change is having substantial negative effects and driving reef decline.			
15. Decline in the structure and effective functioning of coral reef habitats as a result of coral death, changes to community composition and invasion of coral predators/diseases.	H	100	SLR, CURR, TEMP, STORM, OA, RAIN, MONS
Climate change effects in the form of thermal stress, extreme weather, ocean acidification, sea level rise and changes in ocean currents, are not acting in isolation but in combination with other pressures from human activities such as changes in land use on coastal and catchment areas, and coastal development, causing poor water quality, eutrophication and turbidity. The result of these cumulative pressures is widespread and faster decline of coral reefs. The experts at the workshop discussed how these cumulative effects are different from coral bleaching in what while bleaching events are widespread and the effects recognisable and to some extent predictable, the effect from these other cumulative pressures are long-term and chronic and the habitat decline they cause are much more heterogeneous and variable, with some reef areas showing recovery while others collapse. Experts also suggested that residual thermal stress may also be important, which is different to the acute, short-term extreme heatwaves causing mass coral bleaching. These combined pressures result in further debilitation of the reef calcareous structures, community composition shifts, algal encroachment, and increased susceptibility to disease and predation. These effects result in poor habitat quality and loss of species richness and ecological reef functionality, with cascading negative effects across many other reef-associated communities and species.			
16. Reduction in the extent, productivity, recovery and resilience of coastal mangroves around Sri Lanka.	H	75	SLR, TEMP, STORM, OA, SAL, RAIN, MONS
Severe storms through extreme wind and wave action and inundation, particularly during surge conditions, can significantly impact coastal mangrove forests. In the short term, storms and extreme sea levels can cause smothering, uprooting, defoliation, canopy cover reduction, and tree mortality. In the long term, they can result in community diebacks and landward retreat, as well as hydrological and environmental changes to these coastal wetlands such as ponding and hyper-salinization. These alterations affect the ability of the mangrove forest to accrete sediment and keep up with the climate-driven sea level rise. Future changes in precipitation patterns will further alter hydrology and the balance between inputs of freshwater, seawater, runoff sediments and nutrients. Activities resulting in deforestation are also a major contributor to mangrove decline.			

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
17. Decline and retreat of seagrass habitats with consequences for community composition and ecosystem functioning/persistence.	M	75	SLR	CURR	TEMP	STORM		SAL		RAIN	MONS
Severe storms lead to scarring and scouring of seagrass meadows, while prolonged heatwaves conditions can cause diebacks. Some research studies suggest that there is a potential positive effect of increasing emissions, in that higher concentration of carbon dioxide may enhance the productivity and growth rate of seagrass communities, although the net result of this potential positive feedback effect versus other effects of climate change is not yet well understood. There are important data gaps in terms of distribution and composition of seagrass habitats in Sri Lanka, which makes it difficult for this risk to be assessed. However, the experts attending the workshop agreed that climate impacts on these habitats have potentially important social and economic dimension, as they affect key ecosystem services including fisheries, key habitat for dugong and sea turtles, coastal water quality, and coastal protection.											
18. Changes in beach and sediment dynamics, inundation and degradation of sandy shoreline habitats.	L	100	SLR	CURR		STORM				RAIN	MONS
Climate change is contributing to the erosion and loss of beach and dune material due to the action of storms and sea surges, combined with improper management of sandy shorelines. The workshop experts found it difficult to agree on whether to what extent the accelerated rate of loss of sandy shorelines is due to climate impacts or caused by mismanagement of coastal urban development and construction. Coastal dynamics also mean that where sedimentary material is eroded from one place, it may be deposited in another. The experts also found it difficult to assess the wider ecological consequences of these impacts, although there are clear negative implications for sea turtle species. Sea turtles display high site fidelity, and females will return to the exact same beach where they were born to lay their eggs. Where rookery beaches become eroded and unsuitable for nest building, this may threaten the recruitment and therefore the future of local populations.											
19. Reduction in the extent, productivity, recovery and resilience of saltmarsh, estuarine and mudflat habitats around Sri Lanka.	L	66.7	SLR		TEMP	STORM	OA	SAL		RAIN	MONS
Long-term sea level rise as well as extreme sea level events during storm and surge conditions can result in erosion, burial and inundation, significantly altering these coastal landscapes. Flash floods inland can also cause extensive degradation and long-term changes to these habitats as they empty out onto the coastline. On the other hand, prolonged hot and arid conditions increase the risk of desiccation of wetlands. The experts agreed that impacts are already being observed, with changes in salinity level being a principal impact factor, along changes in sea level and precipitation. The experts also highlighted potential indirect effect of groundwater inputs from land and into coastal areas.											
20. Decline in fishery catch potential from coastal waters with consequences for local employment, food security and revenues.	M	100	SLR	CURR	TEMP	STORM	OA		O2	RAIN	MONS
Changes in climate and ocean conditions, such as sea temperature and storminess, are driving shifts in the distribution of commercial fish species and impacting fishing activities and fishing catch potential. The timing and intensity of the southwest monsoon is an important factor that modulates the productivity of coastal waters around Sri Lanka, for example through the runoff and nutrient input from rivers. Coastal fisheries are mostly a small-scale activity, with little built-in resilience to deal with these impacts.											
21. Decline in fishery catch potential and access to lagoon waters with consequences for local employment, food security and revenues.	M	75	SLR	CURR	TEMP	STORM	OA	SAL		RAIN	MONS
Many rural communities around Sri Lanka specialise on coastal lagoon fisheries, but these activities are at risk from climate change. Decreasing catches are linked to declines in the abundance of target species from a combination of warming temperatures, habitat degradation and storminess. Coastal lagoons often sustain artisanal shellfish fisheries such as a shrimp and are therefore important for the livelihood and income of these											

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
communities. Furthermore, Sri Lanka exports lagoon seafood products and therefore this is an important sector for the country’s revenue. Significant impacts are expected over the coming 20 years.											
22. Disruption to fish processing at the coastal margin with consequences for local employment, livelihoods, food security and revenues.	H	50	SLR	CURR	TEMP					RAIN	MONS
Climate changes could potentially disrupt artisanal methods of fish carried out onsite at coastal landing beaches like sun drying. This is a traditional Sri Lankan industry, predominantly a female activity carried out by women from rural communities, which accentuates their vulnerability to further gender-bias impacts, marginalisation, and loss of income. The opinion of the experts attending the workshop was relatively divided as to the risk score, although they generally agreed on a medium level of magnitude. Impacts cannot yet be demonstrated but are likely to realise over the next 20 years, with sea level rise, and changes in air temperature and precipitation or humidity being the principal factors.											
23. Reductions in revenues and catches from offshore fisheries/licences.	M	75		CURR	TEMP	STORM			O2		MONS
Climate change is linked to distribution shifts of commercial species targeted by pelagic fisheries, such as tunas, as well as worsening safety conditions at sea, resulting in catch declines and loss of export revenue. The principal drivers of these impacts are ocean warming and storm activity, as well as the occurrence of low dissolved oxygen zone events causing hypoxia.											
24. Disruption to aquaculture/mariculture (i.e. shrimp farming, sea cucumber, seaweed, blue crab) including consequences for disease proliferation and therefore production.	M	66.7			TEMP	STORM	OA	SAL	O2		MONS
The main climate change threats to aquaculture activities are inundation and salinisation of floating and fixed pens, storm damage, and disease outbreaks. In Sri Lanka aquaculture is mostly dedicated to shrimp farming, and there are concerns that the sector is not as environmentally friendly or sustainable as it could be, although there is potential for improvement and adaptation is possible to face climate change challenges. There are comparatively less seaweed farms, and although this is not a significant industry sector at national level, it is usually run by women in rural coastal areas, so any climate risks further aggravate the vulnerability of their livelihoods.											
25. Disruption to freshwater supplies in the coastal zone as a result of drought, salinisation and storm events.	H	66.7	SLR			STORM		SAL		RAIN	MONS
Climate change threatens water security in Sri Lanka because of saltwater intrusions from sea level rise and increased surface runoff during heavy precipitation, leading to contamination of groundwater and aquifers. In future, climate change may also interfere with underground water flows into coastal waters. Experts attending the workshop discussed other related cumulative issues, such as overuse of groundwater reserves during water scarcity periods particularly in rural areas, the effect of hard built coastal defence structures such as rock armour and revetment, and the effect of the monsoon enhancing the risk of saline intrusions in the coastal, estuarine and mangrove areas.											
26. Increased demand for sand and gravel in order to construct, repair or rebuild hard sea defences, and for beach nourishment.	L	33.3	SLR	CURR		STORM				RAIN	MONS
There is a growing demand for sand and gravel for beach nourishment and for maintenance, and to repair and build hard coastal defences, and there is a risk of disruption to these activities such as dredging or offshore mining due to extreme weather. In Sri Lanka, sand for beach nourishment is often mined from offshore seabed sediments, but the grain size is too fine, which means the sand is highly mobile and is lost again quickly through the action of waves and wind, particularly during the monsoon. This is also a costly activity, and there are questions about its environmental as well as economic sustainability.											

Risk no. and description	Conf. rating	Risk score	Key climate drivers
27. Disruption to and decline in the efficiency of power station cooling systems or proposed desalinisation plants.	L	16.7	SLR, TEMP, SAL, RAIN, MONS

Changing climate conditions can disrupt the activity of coastal industrial plants that rely on intake of seawater for their cooling water systems, mainly due to loss of cooling efficiency from warming seawater temperatures, but also from outbreaks of nuisance marine species such as jellyfish. Currently there is only one coastal energy plant in Sri Lanka, the coal-fired Norochcholai Power Plant. Furthermore, the thermal plume from coastal industrial plants can augment the warming of seawater locally, further affecting the livelihood of artisanal and small-scale fishers, particularly those targeting ornamental fish species.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
28. Increased damage to offshore infrastructure (e.g. wind turbines and oil rigs) and disruption of operations.	L	50	SLR, CURR, TEMP, STORM, MONS

Increasing storminess can lead to damage of man-made structures offshore, either through changes in frequency or severity of storms, which can obstruct access to and operations on and around structures including maintenance, construction and offloading. Engineering usually incorporates some level of uncertainty into structural designs; however climate adaptation may require updating designs to for example extreme wave heights, which is very costly. There are plans to build the first offshore wind farm in the Gulf of Mannar, and experts attending the workshop recommended the benefit of taking into account potential climate risks. On the other hand, climate-driven changes to marine conditions can further encourage biofouling of submerged offshore structures. Biofouling is a particular concerning issue, which is expected to potentially worsen as new species arrive and become established.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
29. Increased risk of disruption to telecommunication systems (cables, masts, inter-connectors etc.).	M	50	SLR, CURR, TEMP, STORM, MONS

Climate change is putting at risk communication systems. It can cause disruption and structural damage to overhead and underground systems on land such as cables, posts, pylons, transformers, transmission structures etc., particularly during severe high-impact weather events such as cyclones. At sea, cables and interconnectors for example can become exposed due to scouring and erosion from sustained strong wave and wind conditions during the monsoon, and even sustain significant damage during severe storms.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
30. Damage to, and deterioration of, critical coastal infrastructure assets, including roads, airports, and buildings.	H	100	SLR, CURR, TEMP, STORM, RAIN, MONS

Climate change can put significant strain on transport links and hubs such as roads and airports, and other critical coastal infrastructure and assets, due to the intensification of extreme weather. Surface road flooding is a common occurrence in low-lying coastal areas during heavy rains and storm surges. During intense southwest monsoons coastal roads regularly become unsafe or unusable due to floodwater, sand drifts, mudslides and debris, or damage to the road surface, such as in the Galle district, Hambadari and Colombo, as mean wave heights increase during that period. Coastal housing also become excessively damp from continuous sea spray and rain, while intense wind-driven waves and currents accelerate the rate of coastal erosion. The experts attending the workshop discussed these issues and agreed that considerable effort is going into preventing and mitigating these impacts, but the increasing intensity and / or frequency of the monsoon and weather events mean that repair costs escalate, and structural fatigue builds up, debilitating infrastructure and making it more unsafe. Experts also noted the risks to coastal tourism activities.

Risk no. and description	Conf. rating	Risk score	Key climate drivers
31. Increased damage to harbours and disruption of maritime transport as a result of changes in the frequency or severity of extreme weather events.	M	75	SLR, CURR, STORM, MONS

There are concerns about increasing future disruption to maritime traffic during extreme weather events, and the implications for the transport of goods, including food. The experts agreed that this risk is likely to materialise within the next 20 years.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
32. Impacts on trade and breeding of ornamental reef-associated species.	L	66.7	SLR	CURR	TEMP	STORM	OA	SAL		RAIN	MONS

Declines in the abundance of populations of fish and shellfish species targeted by independent ornamental traders are already being observed. Traders sell and export these species live for aquarium breeding and stocking. Declines are mainly driven by bleaching, pollution and degradation of coral reefs, although climate change is also directly impacting the biology and ecology of reef species, including ornamental ones, with negative consequences for their health, survival, breeding and life history. The trade of ornamental marine species is important and widespread in Sri Lanka, this activity is largely unregulated or illegal, and data is lacking on many of the targeted species making it difficult to understand the effect of climate change, the impact of overharvesting/collateral reef damage, or the status of these species.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
33. Physical damage and disruption to assets important to the tourism sector – with consequences for employment, insurance costs and revenues etc.	H	66.7	SLR		TEMP	STORM				RAIN	MONS

Climate change threatens marine and coastal recreation activities such as swimming, snorkelling, game fishing, boating and sailing, due to the damaging effects of storms, coastal erosion, sea level rise and flooding. There are numerous and important coastal tourist resorts in Sri Lanka, and this sector represents an important proportion of the country's GDP and provides a livelihood and income for many people and their families, directly and indirectly. Future climate change impacts could have potential significant social and economic repercussions.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
34. Changes in the occurrence of cetaceans, turtles, reef-fish populations that are important for eco-tourism – impacts on perceived attractiveness as a destination.	M	100	SLR	CURR	TEMP	STORM	OA	SAL	O2	RAIN	MONS

Climate change impacts can spoil the appeal of seaside tourist destinations and marine wildlife watching activities in Sri Lanka, and drive shifts in the distribution, migration patterns or seasonality of charismatic marine species such as cetaceans and sea turtles. The experts attending the workshop discussed observed declines in local whale and dolphin populations. The loss of these marine species is having a knock-on effect on the numbers of visitors and on local ecotourism activities and businesses, although the role of climate change in such shifts is not yet clear as there are likely other factors at play.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
35. Loss, damage and reduced visitation to historic sites, culture and traditions in Sri Lanka.	M	50	SLR		TEMP	STORM				RAIN	MONS

Climate change can be a threat to historic buildings and heritage sites located near the coast, through the action of accelerated weathering, erosion or subsidence, and damage sustained during extreme weather events. To the knowledge of the experts at the workshop, no coastal historic sites in Sri Lanka have yet been declared at risk from climate change, and therefore they did not score this as a high risk at present.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
36. Adverse impacts on landfill and waste disposal systems, as a consequence of seawater inundation/intrusion and coastal erosion.	M	66.7	SLR	CURR		STORM				RAIN	MONS

Climate change can significantly aggravate the risk of erosion, flooding and inundation by the sea at coastal landfills and waste dumping sites. Impacts to these sites can result in the mobilisation of large quantities of litter and legacy contaminants and produce severe pollution events and public health emergencies. The experts at the workshop discussed known issues of contamination of coastal areas from landfill leachates and specifically contamination plumes from the Kelani River during the monsoon due to the mobilisation of runoff nutrients and waste, which can produce anoxic conditions as it empties through Colombo and into the bay, particularly in sheltered shallow areas with low flushing rates.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
37. Release of untreated liquid effluents and damage to sewerage systems with consequences for public health.	M	66.7	SLR		TEMP	STORM				RAIN	MONS

Risk no. and description	Conf. rating	Risk score	Key climate drivers
Flooding and inundation of sewerage and wastewater collection and discharge pipes, pumping stations and treatment plants during heavy precipitation events can overwhelm these systems and cause leaching of runoff and contaminated effluents into the environment, riverways and coastal areas. The experts discussed how this is already happening although it is localised to sites in Colombo and Galle.			
38. Physical risk to human health, lives and livelihoods as a result of heat stress, sunburn or severe weather events at the coast.	M	50	SLR, TEMP, STORM, RAIN, MONS
Climate change represents a direct risk to human health. High-intensity extreme weather events have the potential to develop into emergency and life-threatening situations. But other long-term, gradual changes such as increasing temperature and humidity conditions, can also put people's health and safety at risk, particularly the young and elderly and those with underlying health issues.			
39. Proliferation of marine microorganisms that are dangerous to human health.	L	25	CURR, TEMP, STORM, RAIN, MONS
This risk represents a higher incidence of disease and poisoning occurrences due to the spread of potentially harmful species and waterborne pathogens. Includes increases in the abundance of microorganisms linked to Ciguatera Fish Poisoning (CFP) and *Vibrio* spp. bacteria (the causative agents of cholera, wound infections and gastroenteritis, among others). The experts discussed recent media report of a public health incident early in 2024, although the origin of the problem has not been determined and appeared related to heat exhaustion and contamination of freshwater supplies, rather than related to marine pathogens. This however remains a potential risk into the future.			
40. Damage and long-term degradation of coastal habitats with negative consequences for coastal protection, flood and erosion control.	H	75	SLR, CURR, TEMP, STORM, RAIN, MONS
The decline and loss of natural coastal protection systems including coral reefs, mangrove forests and seagrass meadows, due to climate impacts on those habitats, is also compounded by the pressure from other human activities leading to deforestation, pollution, physical disturbance etc. Extensive studies following the 2004 tsunami highlighted the importance of these natural barriers in protecting the coast, critical infrastructure, and people's lives and homes, from extreme waves and inundation from the sea.			
41. Damage to carbon sequestrating habitats, with long-term consequences for emissions reduction and climate change mitigation.	L	50	SLR, CURR, TEMP, STORM, OA, SAL, RAIN, MONS
Where blue carbon ecosystems such as mangroves, tidal saltmarshes and seagrass meadows are disturbed or lost, it can result in carbon emissions from sediment stores. The experts at the workshop agreed that the risk of increased emissions and loss of this carbon capture service is an important risk, although it is difficult to quantify for Sri Lanka at present due to lack of data. They also agreed that once these habitats are damaged, the capacity to capture and store carbon is lost for the long-term even if the habitats are restored, because it is only efficient in mature established systems. Blue carbon habitats are currently under pressure due to a combination of climate change and other human pressures (see risks 16, 17 and 19).			

A total of 14 risks were scored as HIGH PRIORITY, and they are summarised in Table 8. These risks represent threats to key species and habitats, or to key societal and economy aspects in Sri Lanka, and their severity reflects a combination of medium to high urgency and magnitude, meaning these risks can potentially have a significative impact in the near future. They are therefore recommended for further investigation and assessment. In one case, risk no. 18 - *Changes in beach and sediment dynamics, inundation and degradation of sandy shoreline habitats*, was assigned a LOW confidence rating, meaning that either very little published information exists or is available on this topic. On the other hand, this risk was scored as 100, the highest level of severity, reflecting its importance and high priority for Sri Lanka, and it is therefore recommended for urgent attention and further investigation.

Table 8. Summary of HIGH PRIORITY risks, scoring equal to or higher than 75. The risk numbering corresponds to their number on the risk register. Confidence rating and key climate drivers are also included. The climate variables most likely to be driving those changes are indicated using shading (■= principal climate driver, ■= secondary climate drivers). Climate drivers headings are as follows: SLR = Long-term sea level rise and extreme sea level events (i.e. storm surges); CURR = changes in ocean circulation and currents; TEMP = changes in air and sea temperature; STORM = changes in frequency, track and intensity of storms; OA = changes in pH and other ocean acidification effects; SAL = changes in seawater salinity levels; O2 = changes in dissolved oxygen concentration; RAIN = changes in precipitation patterns and land runoff inputs; MONS = changes to timing and strength of monsoons. More detail about the confidence categorization, or the components of the risk score as a function of proximity and magnitude can be found in Table 6.

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
1. Decline in phytoplankton biomass and primary productivity with negative consequences for marine food-webs.	H	100		CURR	TEMP	STORM		SAL		RAIN	MONS
9. Disruption of sea turtle sex ratios, migration, nesting ecology and feeding habitats.	M	100	SLR	CURR	TEMP	STORM					MONS
14. Increases in the frequency and extent of severe coral bleaching events, leading to coral death.	H	100	SLR	CURR	TEMP	STORM	OA			RAIN	MONS
15. Decline in the structure and effective functioning of coral reef habitats as a result of coral death, changes to community composition and invasion of coral predators/diseases.	H	100	SLR	CURR	TEMP	STORM	OA			RAIN	MONS
16. Reduction in the extent, productivity, recovery and resilience of coastal mangroves around Sri Lanka.	H	75	SLR		TEMP	STORM	OA	SAL		RAIN	MONS
17. Decline and retreat of seagrass habitats with consequences for community composition and ecosystem functioning/persistence.	M	75	SLR	CURR	TEMP	STORM		SAL		RAIN	MONS
18. Changes in beach and sediment dynamics, inundation and degradation of sandy shoreline habitats.	L	100	SLR	CURR		STORM				RAIN	MONS
20. Decline in fishery catch potential from coastal waters with consequences for local employment, food security and revenues.	M	100	SLR	CURR	TEMP	STORM	OA		O2	RAIN	MONS
21. Decline in fishery catch potential and access to lagoon waters with consequences for local employment, food security and revenues.	M	75	SLR	CURR	TEMP	STORM	OA	SAL		RAIN	MONS
23. Reductions in revenues and catches from offshore fisheries/licences.	M	75		CURR	TEMP	STORM			O2		MONS
30. Damage to, and deterioration of, critical coastal infrastructure assets, including roads, airports, and buildings.	H	100	SLR	CURR	TEMP	STORM				RAIN	MONS
31. Increased damage to harbours and disruption of maritime transport as a result of changes in the frequency or severity of extreme weather events.	M	75	SLR	CURR		STORM					MONS
34. Changes in the occurrence of cetaceans, turtles, reef-fish populations that are important for eco-tourism – impacts on perceived attractiveness as a destination.	M	100	SLR	CURR	TEMP	STORM	OA	SAL	O2	RAIN	MONS

Risk no. and description	Conf. rating	Risk score	Key climate drivers								
40. Damage and long-term degradation of coastal habitats with negative consequences for coastal protection, flood and erosion control.	H	75	SLR	CURR	TEMP	STORM				RAIN	MONS

4. Discussion

4.1. Climate vulnerability and preparedness in Sri Lanka

Sri Lanka is already experiencing the effects of climate change, similar to other Indian Ocean regions. However without examining and assessing what evidence and data may be available it is difficult to understand those effects, or, perhaps most importantly, address and adapt to the potential impacts on its biodiversity, as well as for its societies and economies (Lincoln et al., 2021a). Evidence-based adaptation can help countries and regions to prioritise monitoring and research and guide the use of financial resources and technical capability to better protect their marine environment and people's livelihoods from the adverse impacts of climate change (Maltby et al., 2022; Lincoln et al., 2021a). Some estimates suggest that climate change could bring economic losses across South Asia equivalent to 2% of GDP of countries by 2050, which could more than triple by the end of the 21st Century (Ahmed and Suphachalasai, 2014). In that context, projections of climate-related economic and social impacts for Sri Lanka are less compared to more populated South Asian countries, but still significant (IPCC, 2021). Furthermore, as an island country, Sri Lanka closely depends on goods and services derived from the marine environment. A third of the population live in the coastal zone, where a large part of the urban area is also located, as well as the country's main industries, road and rail links and other critical infrastructure, including commercial seaports and fishing harbours.

Sri Lanka recognises the importance and urgency of taking action against climate change, with particular attention to climate-driven impacts on the coastal and marine environment, and the country's latest NDC has a strong marine and coastal focus (MoE, 2021). The island is increasingly exposed to the effects of extreme weather, ocean warming, submergence, coastal erosion and inundation. However, there is also a recognition by Sri Lanka that more evidence is needed to tackle the climate emergency (MoE, 2021), particularly in terms of marine data. For example, there are plans to improve Sri Lanka's capabilities for ocean monitoring and forecasting. There is also a commitment to improve coastal resilience, including protection of critical defender habitats such as reefs, seagrass, mangroves and sand dunes. Sri Lanka is also developing important national climate policies and strategies, including a Coastal Zone and Coastal Resource Management Plan launched in 2018.

These are important efforts by Sri Lanka, although they are challenged by fundamental gaps in the information, including data on key marine climate variables as well as distribution and status of marine habitats and species. High-resolution climate models for Sri Lanka are also currently lacking, which makes it difficult to identify trends and limits confidence in future projections for the region.

4.2. What is currently happening

Sri Lanka hosts a rich marine biodiversity dominated by Indo-Pacific species associated with communities that are characteristic of the West and South Indian Shelf marine ecoregion or province (Spalding et al., 2007). Climate change is expected to impact most components of the marine ecosystem, either directly or indirectly. Based on the evidence, and the results of the risk assessment, warming temperatures are having the strongest effect on key biodiversity components, as well as on social and economic sectors. Increasing storminess and changes to monsoon patterns are the climate variables with the most widespread effect, followed by extreme sea level events. Changing rainfall and oceanic circulation patterns are also having a significant influence.

Overall, the evidence reviewed as part of this report as presented in detail in section 3.1 includes observations of significant ongoing trends on most climate variables, that suggest climate change effects, albeit with different levels of confidence depending on data availability and spatial and temporal resolution. The wider Indian Ocean is warming rapidly compared to other basins (Gnanaseelan et al., 2017; Beal et al., 2019) and Sri Lanka has already been experiencing accelerating warming air and sea temperatures since the end of the 20th Century (World Bank, 2021; Roxy et al., 2021; Esham and Garforth, 2013; Fernando et al., 2007; Zubair et al., 2010). In addition to long-term ocean warming, marine heatwaves have become more frequent over some areas in the Indian Ocean since the 2000s compared to the 1980s (IPCC, 2021).

There is also a strong correlation between sea surface temperature and pH, with increasing risk of acidification with surface warming, which highlights the need for monitoring of Indian Ocean pH (Madkaiker et al., 2023). Surface ocean pH across the basin has declined by about 0.1 unit; more pronouncedly over the western Indian Ocean due to strong upwelling in this region drawing up anthropogenic CO_2 embedded in the deeper ocean (Roxy et al., 2021; Sreeush et al., 2019). Furthermore, coastal ocean dynamics strongly dominate pH variability, especially in areas with high river runoff and warmer seawater temperature, where freshwater discharges influence the alkalinity (Madkaiker et al., 2023). Sri Lanka's precipitation regime is complex and spatially variable, which makes it difficult to establish long term changes, highlighting the need to improve the evidence base in this area (Alahacoon and Edirisinghe, 2021). Overall, there seem to be a significant positive tendency of precipitation and therefore flood risk in the southern and western provinces in the future (Alahacoon and Edirisinghe, 2021).

Sea-level is rising, by more than 12 mm along the northern Indian Ocean margin during the past decade, with coastlines of Sri Lanka experiencing particularly rapid and substantial sea-level rise owing to an expansion of the Indo-Pacific warm pool (Palamakumbure et al., 2020; Han et al., 2010; Unnikrishnan and Shankar, 2007). On the other hand, shifts in the reversing bi-annual monsoon winds and a strengthening of the northeast monsoon current, which govern much of the seasonal patterns at Sri Lanka, appear to be forcing changes in ocean circulation, including the location, duration and timing of the upwelling zone along the southern coast, and the influx of low salinity water to the eastern Arabian Sea (de Vos et al., 2014).

Ocean circulation can also modulate other important variables such as the concentration of dissolved oxygen, which is a major determinant of the abundance and distribution of marine organisms. The upper boundaries of the permanent hypoxic layers in the Arabian Sea and the Bay of Bengal, where they intersect the continental margins along the rim of the northern Indian Ocean and around Sri Lanka, also interact with the upwelling, which can sustain or instigate coastal hypoxia by lifting oxygen-poor and nutrient-rich waters from the oxygen minimum zone onto the continental shelf (Pearson et al., 2022; Rixen et al., 2020).

Finally, there is growing evidence that warming of the western Indian Ocean in particular is contributing to more frequent severe weather events, including tropical cyclones (Roxy et al., 2014; Murakami et al., 2017; Roxy et al., 2017). While historically moderate cyclones reaching northern Sri Lanka were relatively common, in recent years most of the severe tropical cyclonic storms that reach the island form in November and December and fall onto eastern and western coasts more often than the north or the south (Srisangeerthanan et al., 2015). As a result, surges and coastal erosion have become a major threat to main population centres.

4.3. What is likely to happen in the future

In terms of expectations into the future, climate models are consistent in showing atmospheric warming trends in the future at Sri Lanka, regardless of the emissions scenario (World Bank, 2021). Although this warming rate may be less than the global prediction, it still represents a significant threat of extreme heatwave events and a higher probability of days when the critical threshold of 35°C is surpassed (World Bank, 2021). Sea surface temperatures are also projected to increase into the future, up to +3.2°C under a high emissions scenario by the end of the 21st Century. This warming or air and ocean temperature will have significant effects on habitats and species, as well as people.

One of the direct consequences of warming temperature is sea level rise. Projected ranges of sea level rise highlight the vulnerability of Sri Lanka, particularly due to the combined impacts of surges and sea-level rise, which is likely to increase the likelihood of 1-in-100-year coastal flooding events (World Bank, 2021; IPCC, 2021). Combined with population growth, this represents an even higher risk in terms of people's lives and property exposed to severe coastal flooding, up to half a million people by 2060 (World Bank, 2021). Further effects of increasing warming will include changes to monsoon patterns and wind stress over the Indian Ocean, as well as wider shift in ocean circulation, although some of these climate forcings and their effects on ocean circulation are not yet fully understood and more research and higher resolution modelling are needed (Sabin et al., 2013; Akhiljith et al., 2019; IPCC, 2021).

Future projections of ocean pH suggest a progressive acidification around Sri Lanka, with no obvious spatial distinction, while alkalinity projections generally suggest a decline under all carbon emission scenarios. Targeted monitoring of current pH conditions, particularly around key oceanic features such as upwelling zones, and further research into the biological effects of ocean acidification (i.e. coral decalcification) will help improving modelling capabilities and support feasible mitigation and adaptation options in Sri Lanka.

While global models suggest a general decline of dissolved oxygen concentrations across all oceans, there is high uncertainty and disagreement as to what this means for the northern Indian Ocean, and in particular potential changes in the existing hypoxia layers (Rixen et al., 2020; Oschlies et al., 2017). Future decreases in dissolved oxygen in the upper mixed layer of the subtropical Indian Ocean have been suggested, which would concur with projections of a decrease in productivity from separate models (Bopp et al., 2013; Cocco et al., 2013) while small increase in oxygenation may still be plausible in the western tropical Indian Ocean (Cocco et al., 2013). Overall, however, the projected increase in the frequency of extreme positive Indian Ocean Dipole suggests a higher risk of oceanic hypoxia for Sri Lanka in the future (Pearson et al., 2022).

At present, more observational evidence and physical understanding of the anthropogenic drivers of climate and tropical cyclonic activity are needed to attribute any changes to anthropogenic climate change (IPCC, 2021; Vellore et al., 2020). While basin-scale future projections of changes in cyclonic intensity and frequency are now available for most ocean basins, the confidence in those is still low (Vellore et al., 2020). What we do know with relative certainty, is that over the Northern India Ocean basin tropical cyclones and associated rainfall are likely to become more intense over the rest of this century (Vellore et al., 2020; Knutson et al., 2019). For Sri Lanka, this projected increase in heavy rainfall still stands even when not necessarily associated with cyclonic storms, particularly in southern areas (World Bank 2021). In general, climate models usually struggle to project future rainfall as reliably as temperature, especially in the case of island nations (World Bank 2021). These potential changes in future rainfall patterns need to be further understood and constrained through further research and model downscaling.

4.4. Cumulative effects

The impact of climate change added to other human pressures also makes it difficult to understand the driving factors behind the changes observed in the marine environment, as well as to manage and adapt to these changes (Lincoln et al., 2021a). Sri Lanka is no exception, and there are growing concerns that climate impacts on marine species and habitats are exacerbated by other cumulative human pressures such as pollution, over-exploitation, and habitat degradation (IUCN Sri Lanka, 2023a; IWC, 2023a,b; NOAA Fisheries, 2023; TCP, 2023; Veettil et al., 2023; MoMD&E, 2019; Biju Kumar et al., 2017; Thomas et al., 2015). Some of the severe risks identified as part of this assessment highlight this issue, such as risk no. 40 ("Damage and long-term degradation of coastal habitats with negative consequences for coastal protection, flood and erosion control"), which captures how the loss of coastal protection through the decline of habitats such as reefs and mangroves is clearly compounded by activities causing deforestation and pollution. Another example is risk no. 15 ("Decline in the structure and effective functioning of coral reef habitats as a result of coral death, changes to community composition and invasion of coral predators/diseases"), that represents the cumulative effect of poor water quality, eutrophication and turbidity in accelerating widespread decline of coral reefs. It is important to understand these other local factors, so they can be managed and where possible mitigated to complement any climate adaptation actions (Lincoln et al., 2021a). Where necessary, a precautionary principle is advisable so as not to delay action, while more research is undertaken, to reduce the cumulative effects of the various stressors on key components of the marine ecosystem (Lincoln et al., 2021a).

4.5. Climate risks vs climate opportunities

It is worth highlighting that during the risk assessment workshop in Colombo, participants were given opportunities to examine the evidence and identify any potential beneficial opportunities that climate change might be creating for the marine environment in Sri Lanka. Whilst scientific evidence demonstrates that the observed and future impacts of climate change are overwhelmingly negative, some specific activities or sectors have identified some desirable effects. Albeit few, there are some examples from elsewhere where recreational fisheries could benefit from new species as those expand their ranges into new areas (see Pinnegar et al., 2020; Townhill et al., 2019). In the case of this assessment for Sri Lanka however, and despite wide-ranging discussions, the conclusion from the experts was that no positive opportunities were apparent in terms of climate-driven changes in the marine and coastal environments in Sri Lanka, at present or into the near future.

Strategic, targeted and coordinated research is needed to improve the confidence and resolution of future projections of key climate variables, as well as the scientific evidence of climate change impacts (Lincoln et al., 2021a). This climate risk assessment can therefore inform these decisions by helping prioritise action and direct efforts towards the most severe and urgent risks, and guide research and monitoring to target key knowledge gaps.

Finally, the findings of this climate risk assessment can support the development of climate resilience interventions directed at improving the livelihood and wellbeing of disadvantaged population groups. For example, risk 22 (*Disruption to fish processing* *at the coastal margin*, see Table 6) refers to a traditional artisanal activity which is predominantly carried out by women fisherfolk from rural coastal fishing communities, which exposes them (and by extent their households) to further gender-bias impacts, marginalisation, malnutrition, and risk of loss of income, where the landing beaches they use to sun-dry the fish become flooded or eroded, or unfavourable weather conditions become prevalent (Dried Fish Matters, 2025). Another example is risk 24 (*Disruption to mariculture*, see Table 6); while seaweed farming is not a significant industry sector at national level, it provides a vital source of income and social interaction for many women in rural coastal areas, particularly those in female-headed households. Storms and prologued hot spells can prevent activities and result in extensive crop failures and can also damage nursery areas (consisting of ropes tied to floats) and even the boats (The Sunday Times, 2024).

5. Knowledge gaps and evidence needs

5.1. General gaps

In Sri Lanka, regionally relevant information on long-term climate change impacts, particularly marine and coastal, is generally scarce. To overcome this and gain some insight into likely impacts as well as potential resilience, this report collated evidence linked to the effects of severe non-climatic events, such as the Indian Ocean tsunami in 2004.

This risk assessment exercise highlighted four overall knowledge gaps for evidence of climate risks for Sri Lanka: (i) lack of lack of localised high-resolution projections of key marine variables; (ii) understanding of ecological responses to changing environmental conditions; (iii) understanding of cumulative impacts of climate change and other human pressures; and (iv) understanding of the impact of climate change on goods and services derived from the marine environment.

5.2. Risk-associated gaps

More specifically, the assessment helped identify gaps on the following climate risks to biodiversity or to societal and economic sectors:

- Degradation of saltwater crocodile nesting and feeding habitats (risk no. 10).
- Changes in beach and sediment dynamics, inundation and degradation of sandy shoreline habitats (risk no. 18).
- Increased damage to harbours and disruption of maritime transport as a result of changes in the frequency or severity of extreme weather events (risk no. 31).
- Physical risk to human health, lives and livelihoods as a result of heat stress, sunburn or severe weather events at the coast (risk no. 38).
- Proliferation of marine organisms that are dangerous to human health (risk no. 39).

The experts attending the workshop emphasized the need for more information in relation to these risks, so that they can be reassessed more fully.

5.3. Other evidence gaps

The process of collating the evidence that underpins this assessment helped identify some fundamental gaps in the information, which currently limit the confidence in the assessment of current impacts and future risks associated with marine climate change in Sri Lanka. Among those, the following appear as important:

- pH monitoring, particularly around key oceanic features such as upwelling zones.

- Changes to precipitation regimes and trends over Sri Lanka, and high-resolution modelling of potential future changes.
- Effects of climate forcings on ocean circulation, including downscaling modelling.
- Biological effects of ocean acidification (i.e. coral decalcification) in Sri Lanka.
- Dissolved oxygen concentrations across the northern Indian Ocean, and changes to permanent oxygen minimum zones.
- Understanding of anthropogenic drivers of tropical cyclonic activity are needed to attribute any changes to anthropogenic climate.

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Ocean Country Partnership Programme

The Ocean Country Partnership Programme (OCPP) is a bilateral technical assistance and capacity building programme that provides tailored support to countries to manage the marine environment more sustainably, including by strengthening marine science expertise, developing science-based policy and management tools and creating educational resources for coastal communities. The OCPP delivers work under three thematic areas: biodiversity, marine pollution, and sustainable seafood. Funding is provided through the overarching Blue Planet Fund (BPF) by the UK Department for the Environment, Food and Rural Affairs (Defra).

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