Climate Change Vulnerability of the Canadian Maritime Environment

April 2022

About Us

Clear Seas Centre for Responsible Marine Shipping (Clear Seas) is an independent Canadian not-for-profit research centre that provides impartial and fact-based information about marine shipping.

Clear Seas' work focuses on identifying and sharing best practices for safe and sustainable marine shipping, encompassing the human, environmental and economic impacts of the shipping industry.

Clear Seas research and publications are available at clearseas.org.

About this Report

Clear Seas commissioned Dillon Consulting Limited to complete the **Climate Change Vulnerability of the Canadian Maritime Environment** project to provide an understanding of the extent of climate change threats in the Canadian maritime environment and to identify potential adaptation strategies for managing these threats. The information provided in this report is intended to support decision making organizations responsible for delivering maritime services that ensure the safety and security of the Canadian maritime environment as they conduct their own climate change vulnerability assessments.

Board of Directors
Clear Seas Centre for Responsible Marine Shipping

Message from the Executive Director

Climate Change Affects our Oceans and the People That Rely on Them

We are witnessing the effects of climate change on a near-daily basis around the world. Whether it's extreme weather events, migrating polar ice packs, thawing permafrost, or rising sea levels, the changing global climate is having a dramatic effect on ecosystems and people alike.

These changes are particularly evident in the impact on the world's oceans, rivers and waterways and play out in differing and sometimes unintuitive ways. An effect like supply chain disruption is due to the compounding effects of forest fires or floods occurring at the same time as severe storms at sea along with a surge in demand for goods. Those tasked with maintaining a safe and efficient maritime environment are therefore facing unprecedented challenges. Careful planning and adaptation measures are required to mitigate the risks the changing climate is posing on human life and the environment.

I am struck by how the story of climate change and the world's waters is becoming a personal story. Climate change has very real consequences for mariners, fishers, workers in the tourism industry and many others. Indigenous Peoples are severely impacted by climate change because they look to the ocean for their food and livelihood and a deep connection to the natural environment is an integral part of their culture. The Traditional Knowledge held by Indigenous Peoples also presents valuable potential solutions to understand and adapt to the changing climate.

Our study provides practical adaptation strategies

Through this new study on *Climate Change Vulnerability of the Canadian Maritime Environment,* Clear Seas and its research partner Dillon Consulting Limited have created a series of tools and frameworks designed to help characterize the threats posed by climate change to the maritime environment as a resource for the people and organizations that rely on our oceans and waterways. The report provides a real-world perspective and maps out practical adaptation strategies to manage the effects of a changing climate.

We hope that equipped with this common language and understanding of the threats and potential adaptation strategies, we can work together to create plans that will keep the maritime environment and the people who live, work and play in our waters safe and thriving.

Executive Summary

Clear Seas Centre for Responsible Marine Shipping (Clear Seas) retained Dillon Consulting Limited (Dillon) to provide an understanding of the extent of climate change threats, and to identify potential adaptation strategies for managing climate threats in the Canadian maritime environment. Information provided in this report serves to support decision making by the Canadian Coast Guard (CCG) and other governmental departments, port authorities, industry, non-governmental organizations (NGOs), Indigenous and coastal communities, and Indigenous governments responsible for delivering maritime services. This report will support these decision makers as they explore integrated and long-term strategic approaches to climate change adaptation planning to decision making for the management of maritime services in Canada, including to deliver safe, accessible, and sustainable waterways for Canadians.

The objectives of this report are to:

- Identify ways climate change may impact Canadian waterways and their users;
- Assess how these climate change impacts may affect the delivery of maritime services by those responsible for maritime safety and security, including the effects on marine assets, facilities and infrastructure, operations, operational programs, logistics, regulations, and policies; and
- Provide potential strategies to manage the climate change adaptation process to inform future strategic program decisions, investments, climate change adaptation and risk mitigation plans for the CCG, industry, and other governmental departments.

This report focuses on the results of a literature review assessing climate change threats and identifying potential adaptation strategies across Canada, inclusive of marine and freshwater (e.g., inland) systems. Climate change hazards included were those identified as most relevant to the Canadian maritime environment. The mechanisms in which climate change hazards have the potential to affect the Canadian marine environment are organized specific to the following themes:

- Port and coastal infrastructure;
- Commercial marine shipping;
- Marine fishing;
- Marine and coastal tourism; and
- Inland waterway transport.

The analysis identifies a series of adaptation strategies relevant to both Canadian marine operations and users of Canada's waterways, and is focused on those which are applicable to the CCG, Canadian government departments, port authorities, Indigenous and coastal communities, Indigenous governments, industry, and NGOs. Potential impacts for the Canadian marine environment based on specific climate hazards identified are presented in Table E 1.

Adaptation measures vary depending on which part of the maritime environment they apply to. Swanson et al. (2021) has previously described the five general adaptation strategy types, of which their definitions have been adapted for this report. The five adaptation strategy types are as follows (Swanson et al., 2021):

- **Procedural:** Strategies which support or inform adaptation planning processes. Examples include: climate change education programs, climate data collection and organization, planning frameworks, and regulations.
- **Avoidance:** Strategies which seek to direct developments and assets away from vulnerable areas and are especially relevant for new infrastructure and projects.
- **Accommodation:** Strategies which seek to reduce or minimize the impact of climate change. These strategies may include engineering measures or nature-based solutions to adapt to climate impacts. Examples include: implementing artificial reefs, perched beaches, living shorelines, wetlands, drainage ditches, and rain gardens into coastal planning to temper the impacts of sea level rise, erosion, extreme weather events, and numerous other hazards
- **Protection:** Strategies which focus on reducing climate impacts on infrastructure and the environment through the implementation of protective barriers or buffers. Examples include: breakwaters, retaining walls, artificial reefs, engineered revetments or gabions, shore armouring, dikes, and constructed wetlands.
- **Retreat:** Strategies which seek to relocate vulnerable assets to prevent further damage or avoid complete failure. These strategies are especially relevant for existing assets and infrastructure.

To understand how other maritime-focused agencies outside of Canada are addressing climate change vulnerability and climate adaptation, research was conducted for the jurisdictions of Norway, the United States, and the Netherlands, including a literature review and interviews with researchers working in the area of climate change adaptation and resilience specific to marine assets and operations. Table E 2 presents adaptation strategies from these jurisdictions (international examples) and also includes relevant Canadian strategies and examples for sub-sectors of the Canadian maritime environment, as identified in Canadian specific reports and literature.

Best practices and strategies were gleaned from the literature review, jurisdictional scan, and interviews specific to managing the climate change adaptation process to inform future strategic program decisions, investments, and climate change mitigation plans for the CCG, Indigenous and coastal communities, Indigenous governments, industry and other governmental departments. Best practices and strategies detailed in Table E 3 are specific to aspects of the climate assessment process and adaptation planning.

Table E 1. Impacts for the Canadian Maritime Sector Based on Climate Hazards

Sub-sector of the Canadian Maritime Environment	**Ocean Chemistry** *(changes in temperature and salinity, ocean acidification, and oxygen depletion)*	**Sea Level Rise** *(coastal inundation and flooding, erosion, and storm surges)*	**Extreme Weather Events** *(reduced visibility, storm surges, safety hazards, extreme drought, heavy precipitation, high winds)*	**Changes in the Cryosphere** *(permafrost melt, changes in sea ice, coastal erosion)*
Port and Coastal Infrastructure	• Shoreline vegetation protects shorelines from erosion, which can lead to port infrastructure damage • Increased corrosion rates of infrastructure	• Landward migration of shorelines • Flooding of protective barriers (dikes, breakwaters) • Damage to built environment, vessels and equipment, especially shoreline-anchored infrastructure	• Damage to built environment, vessels, and equipment • Port and ferry closures or delays • Reduced functionality of port processing facilities	• Permafrost areas at greater risk of coastal erosion • Need supporting infrastructure and technology (e.g., monitoring technology) for increased activity
Commercial Marine Shipping	• Impacts on shipping lane locations	• Potential port closures • Potential for a greater volume of cargo and larger vessels due to higher water levels in marine areas	• Weather-related safety hazards • Potential reduction in cargo transport capacity • Longer wait times for processing • Inefficiencies in vessel navigation	• Increase in marine shipping traffic through Arctic • Increase in strikes and sinkings, search and rescue operations • Increase in spills and pollution • Need supporting infrastructure and technology for increased activity
Marine Fishing	• Changes in species composition and abundance	• Potential port closures	• Weather-related safety hazards for commercial and recreational fisheries	• Increase in strikes and sinkings, search and rescue operations • Increased potential for illegal entry and poaching on small vessels

Sub-sector of the Canadian Maritime Environment	Ocean Chemistry *(changes in temperature and salinity, ocean acidification, and oxygen depletion)*	Sea Level Rise *(coastal inundation and flooding, erosion, and storm surges)*	Extreme Weather Events *(reduced visibility, storm surges, safety hazards, extreme drought, heavy precipitation, high winds)*	Changes in the Cryosphere *(permafrost melt, changes in sea ice, coastal erosion)*
	• Reduced Indigenous fishery access • Altered timing and availability of commercially harvested species • Physiological impairments and fish kills • Increase in invasive species			• Changes to traditional areas of hunting, fishing, and trapping for Indigenous communities • An increased risk of human health and safety concerns relating to travel on sea ice
Marine and Coastal Tourism	• Changes in composition and abundance of commercially harvested species shifts feeding locations of marine megafauna	• Impacts on important coastal tourism areas from flooding, overtopping, storm surge	• Weather-related safety hazards	• Increase in recreational marine tourism traffic through Arctic • Increase in strikes and sinkings, search and rescue operations • Increase in spills and pollution • Need supporting infrastructure and technology for increased activity
Inland Waterway Transport	--	• Potential changes in cargo and vessel navigation in the Great Lakes' channels and harbors	• Extreme swings between drought and heavy rainfall impact inland freshwater levels	• Less protection of shorelines with reduced ice cover • Increase in grounding, search and rescue and environmental response operations

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			• Sedimentation and erosion in rivers affects navigation • Weather-related safety hazards	• Need supporting infrastructure and technology (e.g., channel depth monitoring)

Table E 2. Adaptation Strategies and Examples for Sub-sectors of the Canadian Maritime Environment

Canadian Strategies	**International Examples**
Port and Coastal Infrastructure	
• Data collection: monitoring sea levels, tracking extreme weather events, designing predictive tools, assessments of foundation stability in permafrost zones and other coastal infrastructure • Coastal zoning to avoid development of new infrastructure in vulnerable areas • Implementation of regulatory requirements for foundation systems in permafrost zones that will better absorb earth shifting due to freeze/thaw cycles • Use of tools such as thermosyphons in permafrost zones • Raising crests of seawalls and retaining walls • Incorporation of hybrid infrastructure such as nearshore breakwaters and artificial reefs • Building flood protection into coastal infrastructure (e.g., elevated or floating buildings) • Addition of riprap armouring or scour protection to existing infrastructure and assets • Restoration or construction of shoreline habitat including dunes, salt marshes, marine forests, and wetlands • Incorporation of measures to stabilize shoreline vegetation • Replenishment of sand in coastal zones • Strengthening of bankside permafrost areas in coastal zones • Hard-protection measures such as riprap, seawalls, groynes (Lemmen et al., 2016) Interview Insights (D. Bolduc, Green Marine) • When analyzing climate resilience, incorporate ongoing maintenance of assets as well as initial building • Include climate change strategies in long term planning (building docks, investing in terminal expansion)	*United States* • Relocation of facilities inland after hurricane damage • The use of water resistant materials and elevated telecommunication systems for rebuilding/repairing USCG infrastructure • The implementation of design evaluation criteria for existing and new infrastructure projects • Active engagement with stakeholders and to determine a resilience strategy for a Port • Exploring infrastructural shoreline protection measures for a port terminal • Conducting engineering assessments to evaluate the vulnerabilities of facilities, including those relevant to ports • Developing guidance for considering the use of living shorelines as an adaptation measure *Netherlands* • The assessment of the insurability of infrastructure damaged by extreme weather events as a proactive measure for minimizing financial loss • Amsterdam Rainproof: creating partnerships to encourage citizens, government, industry and other stakeholders to build climate resilient infrastructure • Broadening of dunes • Insurance coverage of vulnerable buildings, and potentially new building regulations that are adaptation-focused • Reclamation of excess water from heavy rainfall events • Building climate-resilient infrastructure focused on handling heavy rainfall • Replenishment of sand in coastal zones (The Sand Engine)

Canadian Strategies	International Examples
	• Growing mudflats/meadows/salt marshes to accommodate sea level rise • Onshore adaptation measures aimed at rapid drainage of excessive water from flooding (Netherlands Ministry of Infrastructure and the Environment, 2016; Netherlands Ministry of Economic Affairs and Climate Policy, 2018; Netherlands Ministry of Infrastructure and Water Management, 2018; Rosenberg, 2020)
Commercial Marine Shipping	
• Data collection: migratory patterns of marine megafauna, extreme weather event tracking, monitoring of ice calving in Arctic • Improvement of emergency preparedness measures: incident reporting, safety systems and maritime search and rescue delivery and preparing and responding to marine pollution • Collaboration with the Canadian Armed Forces to develop procedures to improve emergency preparedness and emergency response (e.g., strategic stationing of CCG or CAF assets) (Smith, 2020) • Planning for shorter road seasons in northern regions (start supplies contracts early, modify cargo transport to accommodate more per trip) (Lemmen et al., 2016) • Increases in forecasting, planning, and permitting for vessel activities in the Arctic (Swanson et al., 2021) • Avoiding areas in the Arctic that have become more hazardous due to ice calving • The inclusion of greater endurance of vessels into future planning efforts due to the potential for greater access to the Arctic due to sea ice coverage changes, changes to multi-year ice conditions and yearly shoulder season conditions Survey Insights	*United States* • Mainstream climate change considerations in all transportation agency planning and decision making processes *Netherlands* • Crisis management efforts, including emergency, recovery and crisis management plans and the preparation of emergency facilities *Norway* • Increased search and rescue capacity in preparation for more hazardous marine navigation conditions (Norwegian Ministry of Climate and Environment, 2021) • The use of online modules (AISyRisk) to assess the risks related to shipping traffic, including ship accidents, risk of an oil spill and loss of life • The use of a maritime tracking microsatellite to understand ship locations and marine traffic for risk assessment models • Integration of climate projections into planning and design procedures

Canadian Strategies	International Examples
• Greater endurance of CCG vessels to take into consideration the potential of greater access to the Arctic due to potential reductions in ice coverage due climate change • Future fleet icebreaker hull forms resulting in a full capability spectrum (CCG) • Emergency management planning efforts	
Marine Fishing	
• Data collection: behaviour, spawning, migration and feeding patterns, catch volumes, by-catch, monitoring of invasive species occurrences • Reassessment of fishing seasons and locations based on most recent available species data • Improvement of emergency preparedness measures • Collaborate with the Canadian Armed Forces to develop procedures to improve emergency preparedness and emergency response (e.g., strategic stationing of CCG or CAF assets) (Smith, 2020) • Increases in forecasting, planning, and permitting for vessel activities in the Arctic (Swanson et al., 2021) • Modifications to vessels and fleets to accommodate larger surf • Addition of riprap armouring or scour protection to existing infrastructure and assets Survey Insights • Gear modifications to access harvest of new commercial species • Considerations relating to aquaculture siting, early warning (technological), and culture diversification • Emphasis on regional and international (transboundary management) • Inclusion of climate change data in fisheries models • Strategies to increase resiliency of current fish stocks	*United States* (Johnson, 2012; Gregg et al., 2012) • Establishing marine reserves and other schemes for improving fish stock resilience and rebuilding • Utilizing adaptive fishery management • Spreading risk through insurance, cooperatives, and alternative forms of financing • Developing programs to encourage and assist in diversifying livelihoods • Improving climate research, monitoring, and forecasting • Forming national and regional strategies to prevent habitat destruction • Protecting critical coastal infrastructure used in the fishing industry • Conducting research and assessments for fishery species *Netherlands* • Adjust fishing quota • Adaptation of target species and fishing techniques • Introduction of ecosystem management • Eco-labelling and certification of fish • Reallocation of mussel nursery plots • Aquaculture on former grassland - happening for sole and turbot (Nillesen and van Ierland, 2006)

Canadian Strategies	International Examples
• Collaboratively setting fisheries targets with other jurisdictions to facilitate fisheries resources being available for a longer period of time	
Marine and Coastal Tourism	
• Data collection: behavioural, spawning, feeding, and migratory patterns of marine megafauna; environmental spill monitoring • Regulation of development for new tourism activities in vulnerable areas • Increases in forecasting, planning, and permitting for cruise ship and other tourism-based vessel activities in the Arctic (Swanson et al., 2021) • Development of policies to restrict use and access to sensitive tourism sites (Dawson et al., 2017)	*United States* • Natural and nature-based features considered by USACE which can mitigate the impacts of climate hazards in the coastal zone, can support marine and coastal tourism and serve as coastal attractions (i.e., dunes and beaches, oyster reefs) Please note that marine and coastal tourism is closely linked to shipping and port and coastal infrastructure sub-sectors. Please see above for specific examples relating to these elements of the sector.
Inland Waterway Transport	
• Data collection: riverine water levels, extreme weather tracking, river bathymetry • Building and broadening dunes • Increases in dredging of channels • Restoration or construction of wetlands, floodplains, and riparian buffer zones in riverine ecosystems • Establishment of flood bypass zones or relief channels Interview Insights (D. Bolduc, Green Marine) • Water studies on water levels in the Great Lakes and St. Lawrence • Assessing erosion and sources of erosion from transportation activities	*United States* • Restriction of ship heights to accommodate sea level rise where bridges occur over navigable waterways (Brinckerhoff and ICF International, 2014) *Netherlands* • Excessive water from high water levels in rivers has been accommodated with the construction of dikes transforming these water intrusions into canals and lakes • Predictive tools that serve as an early warning system for flooding events • Physical alterations to width and depth of riverbeds • Reinforcement of existing protective infrastructure such as dikes • Implementation of retreat measures in areas prone to riverine flooding by relocating structures and adjusting the location of dikes (United States Department of Transportation Federal Highway Administration, 2017b)

Canadian Strategies	International Examples
Indigenous Perspectives	
The National Inuit Climate Change Strategy (Inuit Tapiriit Kanatami, 2019) aims to address climate change impacts with adaptation strategies specific to five identified priorities: knowledge and capacity; health, well-being, and the environment; food systems; infrastructure; and energy. Procedural strategies to achieve set objectives include Inuit-driven climate change research and monitoring that will be used to inform future policy development. A primary focus is placed on conducting vulnerability assessments to identify adaptation priorities, one of which is to improve marine safety for Inuit food harvesters who rely on sea ice for travel. This includes the adoption of harvester safety support and better capacity and infrastructure for search and rescue services.	

Table E 3. Best Practices and Strategies for Climate Change Assessment and Adaptation Planning

Theme	Best Practices and Strategies
Strategy	• Strategies should be system, asset, operation, or facility-specific and based on risk and vulnerability assessment frameworks (Perrs. Comm., Jan Brooke, PIANC) • Planning should account for both the short and long term and account for the lifespan of physical assets (Centre for Climate and Security, 2016) • Continuously identify and build capacity to address infrastructural, operational and strategic risks (Centre for Climate and Security, 2016) • Integrate climate impact scenarios and projections into regular planning cycles (Centre for Climate and Security, 2016) • Integrate collaboration and engagement with public and private entities into the risk and vulnerability assessment and adaptation planning process (Becker et al., 2018)
Climate Data	• Establish partnerships with organizations or agencies that develop or use climate projections (FWHA, 2017a) • Collaborate with research, government departments, industry, and other stakeholders to support the inclusion of data and the development of a climate database in the assessment processes • Continue to invest in improvements in climate data (Centre for Climate and Security, 2016) • Establish and utilize a climate database to compile climate data and information over time • Utilize long term historical data sources to inform baseline climate information (PIANC, 2020) • Include historic extreme events data to inform baseline climate information (PIANC, 2020) • Utilize climate scenarios representing possible future climates if the adaptation strategy extends beyond 10 years from the present (PIANC, 2020).
Asset Data	• Develop an inventory of infrastructure assets, operations, and systems (an annex is provided in PIANC (2020) report which can help guide assets, operations, and systems to consider in the adaptation planning process) • Engage stakeholders to help identify assets as part of an asset inventory (PIANC, 2020) • Where possible, include vulnerability specific data into asset management reporting processes (FWHA, 2017a) • Georeference asset data during the data collection process and inventory development (FWHA, 2017a)

Theme	Best Practices and Strategies
Risk and Vulnerability Assessment	• Subject matter experts, staff, and local stakeholders can support the risk assessment process and ensure alignment with the local context, especially when using indicator-based approaches (FWHA, 2017a) • Numerous risk management frameworks exist and have been applied globally. When selecting a risk assessment framework, ensure alignment with the ISO 31000 Risk Management – Principles and Guidelines, First Edition, November 15, 2009 (Government of Canada, 2019) • Employ tools and risk approaches to assess the vulnerabilities of assets based on site and location characteristics and priorities • Use a business as usual option in the risk analyses as a measure of risks if no actions occur (PIANC, 2020)
Adaptation Options	• Include operation and institutional measures alongside structural and physical measures (Perrs. Comm., Jan Brooke, PIANC) • Avoid using a 'one size fits all' approach as this can result in maladaptation (Perrs. Comm., Jan Brooke, PIANC) • Adaptation strategies for ports and waterways with a planning horizon beyond thirty years should assess a range of future climate scenarios (PIANC, 2020) • Utilize a participatory process to engage stakeholders to support the analysis of adaptation strategies (FWHA, 2017a; Becker et al., 2018)
Decision Making Process	• Ensure decision making processes account for the lifespan of physical infrastructure (PIANC, 2020) • Utilize economic analysis methods and tools that can accommodate uncertainty and support the evaluation of adaptation options (PIANC, 2020) • Consider highest risk level projections when making climate related decisions (Centre for Climate and Security, 2016)
Monitoring and Evaluation	• An adaptation strategy should be a living document that is reviewed and updated frequently (PIANC, 2020) • Establish monitoring and evaluation processes to assess the success of adaptation strategies and initiatives arising from vulnerability assessments (FWHA 2017a) • Reassess vulnerabilities as new climate science and data becomes available (FHWA 2017a)
Communication	• Climate data, risk assessments, adaptation options and reports should be easily understood and readable by decision makers and civil society. Climate data needs to be available and accessible to all levels of governments, NGOs, industry etc.

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Acronyms and Abbreviations

ACPA	Association of Canadian Port Authorities
ACRH	US Army Climate Resilience Handbook
ADAP	Adaptation Decision-Making Assessment Process
AIS	Automatic Identification System
BCCR	Bjerknes Center for Climate Research
CAF	Canadian Armed Forces
CCG	Canadian Coast Guard
CMIP	Coupled Model Intercomparison Project
DHS	Department of Homeland Security
DMAF	Disaster Mitigation and Adaptation Fund
FWHA	Federal Highway Administration
GIS	Geographic Information System
ICIP	Investing in Canada Infrastructure Program (ICIP)
IMR	Institute of Marine Research
IPCC	Intergovernmental Panel on Climate Change
MARIN	Maritime Research Institute Netherlands
MTC	Metropolitan Transportation Commission
NCA	Norwegian Coastal Administration
NCCS	Norwegian Center for Climate Services
NGO	Non-Governmental Organization
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
PANYNJ	Port Authority of New York and New Jersey

PIANC	The World Association for Waterborne Transport Infrastructure
PIEVC	Public Infrastructure Engineering Vulnerability Committee (Protocol)
PRI	Port Resilience Index
PSDS	Program for the Study of Developed Shorelines
SIVA	Shore Infrastructure Vulnerability Assessment
TARA	Transportation Asset Risk Assessment
USACE	US Army Corps of Engineers
USDoD	United States Department of Defense
US EPA	United States Environmental Protection Agency
USCG	United States Coast Guard
UNEP	United Nations Environment Programme
VAST	Vulnerability Assessment Scoring Tool
WCU	Western Carolina University
WSDOT	Washington State Department of Transportation

Glossary of Terms

This section establishes relevant terminology utilized in the report. Definitions are adopted from Canada's Changing Climate Report (CCCR) published in 2019 (Bush and Lemmen, 2019), the Intergovernmental Panel on Climate Change recent Climate Change 2022: Impacts, Adaptation, and Vulnerability Report (IPCC, 2022), and The World Association for Waterborne Transport Infrastructure (PIANC) Climate Change Adaptation Planning for Ports and Inland Waterways Report (PIANC, 2020).

Adaptation

Process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Adaptation options

The array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorised as structural, institutional, ecological or behavioural.

Adaptive capacity

The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC 2020; MA, 2005).

Exposure

The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

Hazard

The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service, provision, ecosystems and environmental resources.

Impacts

The consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.

Maladaptation

Actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas (GHG) emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence (IPCC, 2022).

Marine Asset

For the purposes of this report, marine assets are collectively defined as facilities, infrastructure, operations and systems (adopted from PIANC, 2020).

Marine Fishing

For the purposes of this report, marine fishing encompasses commercial fisheries, Indigenous fisheries, subsistence fishing, and recreational fishing.

Mitigation (of climate change)

A human intervention to reduce emissions or enhance greenhouse gases (GHG) sinks; overall efforts to reduce the concentration of GHGs in the atmosphere.

Planning Horizon

The planning horizon is the length of time into the future that is covered in a climate change adaptation strategy (adopted from PIANC, 2020).

Resilience

The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation (IPCC 2022; Arctic Council, 2016).

Risk

The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. (IPCC, 2022).

Risk assessment

The qualitative and/or quantitative scientific estimation of risks.

Sensitivity

The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change.

Storm surge

The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds).

Threat (climate change)

Climate change threats, in this report, refers to the risks and expected impacts from climate change hazards, to infrastructure, livelihoods, health and wellbeing, economy, social and cultural assets, etc.

Vulnerability

The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity and exposure to harm, and lack of capacity to cope and adapt.

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Climate Change Vulnerability of the Canadian Maritime Environment

1.0 Introduction

Clear Seas Centre for Responsible Marine Shipping (Clear Seas) commissioned Dillon Consulting Limited (Dillon) to provide an analysis of the future needs of the Canadian maritime environment with respect to climate change adaptation. Climate change and associated threats such as sea level rise and severe weather pose challenges for ocean and inland water users. Climate change vulnerability has been identified as an issue affecting marine shipping in Canada and abroad (Scott et al., 2013; Becker et al., 2018).

1.1 Purpose

The purpose of this report is to provide a clear understanding of the extent of climate change threats, and to identify potential adaptation strategies for managing climate threats in the Canadian maritime environment. Information provided in this report serves to support decision making by the Canadian Coast Guard (CCG) and other governmental departments, port authorities, industry, non-governmental organizations (NGOs), Indigenous and coastal communities, and Indigenous governments responsible for delivering maritime services. This report will support these decision makers as they explore integrated and long-term strategic approaches to climate change adaptation planning to decision making manage maritime services in Canada, including delivering safe, accessible, and sustainable waterways for Canadians.

1.2 Objectives

The objectives of this report are to:

- Identify ways climate change may impact Canadian waterways and their users; and
- Assess how these climate change impacts may affect the delivery of maritime services by the those responsible for maritime safety and security, including the effects on marine assets, facilities and infrastructure, operations, operational programs, logistics, regulations, and policies; and
- Provide potential strategies to manage the climate change adaptation process to inform future strategic program decisions, investments, climate change adaptation and risk

mitigation plans for the CCG and other governmental departments, port authorities, industry, NGOs, Indigenous and coastal communities, and Indigenous governments.

1.3 Scope

This report focuses on the results of a literature review assessing climate change threats and identifying potential adaptation strategies across Canada, inclusive of marine and freshwater (e.g., inland) systems. Included climate change hazards were those identified as most relevant to the Canadian maritime environment. The mechanisms in which climate change hazards have the potential to affect the Canadian marine environment are organized specific to the following themes:

- Port and coastal infrastructure;
- Commercial marine shipping;
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The analysis identifies a series of adaptation strategies relevant to both Canadian marine operations and users of Canada's waterways, and is focused on those which are applicable to the CCG, Canadian government departments, Indigenous and coastal communities, Indigenous governments, industry, and NGOs.

To understand how other maritime-focused agencies outside of Canada are addressing climate change vulnerability and climate adaptation, research was conducted for the jurisdictions of Norway, the United States, and the Netherlands, including a literature review and interviews with researchers working in the area of climate change adaptation and resilience specific to marine assets and operations.

1.4 Understanding Climate Risk and Impact: Terminology

Technical terms used in this report describe aspects of the climate system, climate change, and adaptation planning and are listed in the report glossary (adapted from other resources (see: IPCC, 2022; PIANC, 2020; Bush and Lemmen, 2019). This section of the report presents the core relationships between key climate change terms as a means to better understand the relationships between climate change, vulnerability assessments, and adaptation and risk mitigation efforts as it relates to the Canadian marine environment.

At a high level, to understand climate change risk, it is important to recognize that it is determined based on the interaction between three elements: the occurrence of climate hazards, the exposure of assets/operations/services that could be adversely affected by said hazards, and the vulnerability of assets to be affected by hazards as a function of sensitivity and adaptive capacity. Impacts represent the consequences of realized climate risks on assets and systems. Adaptation, collectively, represents actions which seek to manage the impacts of climate change and may include efforts to mitigate the impacts, or enhance the resiliency of assets, operations, and systems. The relationship between these climate-related terms is detailed in Risk and vulnerability assessments, which are explored in detail in this report, can take many forms and generally focus on the relationship between climate hazards and asset characteristics as a mechanism to evaluate which assets are at greatest risk to climate change. Typically, vulnerability incorporates both sensitivity and adaptive capacity. By understanding which assets are most vulnerable and potentially determining the risk level to said assets, the outcomes of vulnerability assessments can support strategic adaptation efforts into the future (PIANC, 2020).

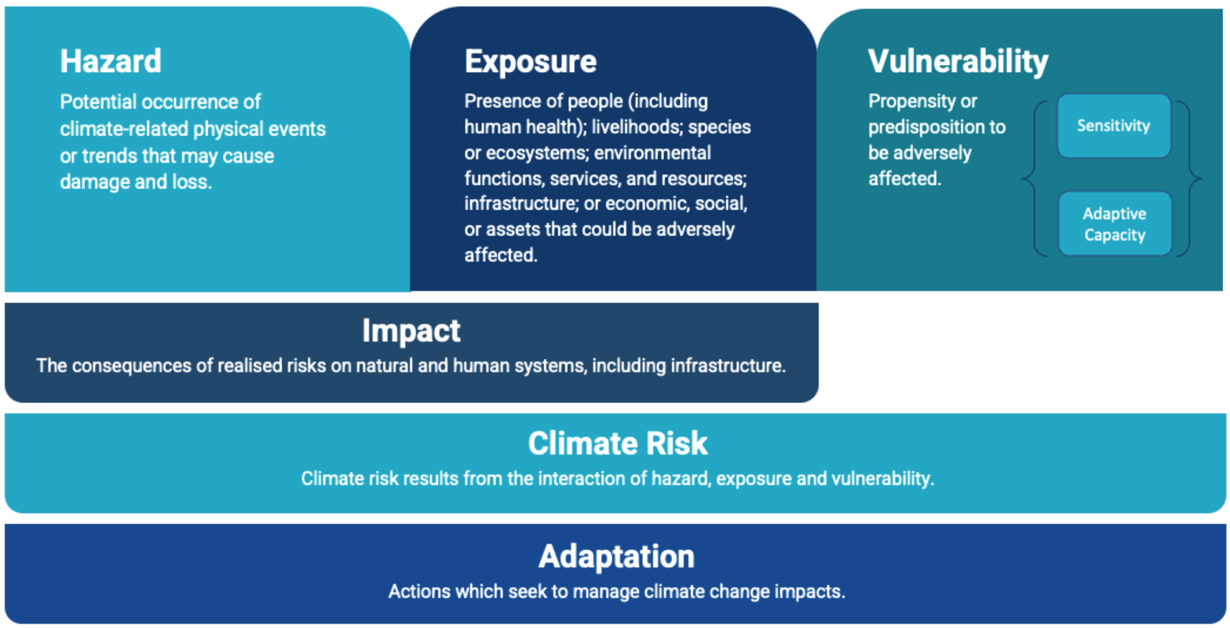

Figure 1. The Relationship Between Vulnerability, Climate Risk, Impacts, and Adaptation

1.5 Report Organization and Contents

The contents of this report are organized as follows:

Section 1: Introduction and definition of report purpose, scope, objectives, and relevant definitions

Section 2: Overview of the methodology used in the analysis

Section 3: A summary of climate impacts and hazards most relevant to the Canadian maritime environment

Section 4: Implications of climate change impacts and hazards for the Canadian maritime environment

Section 5: Exploring risk and vulnerability assessments and adaptation strategies, including those conducted within the United States, Norway, and the Netherlands

Section 6: Adaptation measures and strategies for the maritime sector

Section 7: Key themes and findings

Section 8: Recommendations and strategies: strategies to manage the climate change adaptation process to inform future strategic program decisions, investments, and climate change adaptation and risk mitigation plans

Section 9: Outlines literature and resources cited in the report

2.0 Research and Assessment Methods

This section describes the methodology applied to identify the ways in which climate change will impact Canadian waterways and their users, how these changes will affect the delivery of maritime services by the CCG and others, and presentation of potential strategies to manage the climate change adaptation process to inform future planning and decision making.

Dillon applied the following overall approach to conduct the analysis:

1. Reviewed literature focused on climate change hazards and the maritime environment in Canada
2. Identified climate hazards and their associated impacts for the Canadian marine environment
3. Analyzed climate change impacts and the ways in which they have the potential to affect the Canadian marine environment
4. Circulated an online survey with researchers, government agencies, NGOs, and industry to identify and understand climate hazards, impacts, and adaptation strategies
5. Interviewed leading researchers working in the area of climate change adaptation and resilience, specific to marine assets and operations (questions and responses can be found in Appendix A)
6. Explored approaches specific to risk and vulnerability assessments and adaptation strategies in the United States, Norway, and the Netherlands
7. Developed recommendations and strategies from the literature review and insights gleaned from interviews to inform strategic approaches to climate change adaptation planning and decision making

2.1 Literature Review

Dillon reviewed, analyzed, and synthesized information from a variety of sources, such as peer-reviewed literature, grey literature, governmental reports, and industry reports, to identify and catalogue climate change impacts that have the potential to affect the marine environment (and in what ways). Scientific and technical findings were compiled and interpreted based on their significance to the project objectives. Some of the key literature sources used in the literature review to understand climate hazards, impacts, risk and vulnerability assessments, and adaptation strategies include the following resources:

Climate Hazards

- The Government of Canada: Canada's Marine Coasts in a Changing Climate Report (Lemmen et al., 2016)
- IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability Report. Chapter 6: Ocean Systems (Pörtner, et al., 2014)

Climate Impacts

- International Institute for Sustainable Development: Advancing the climate resilience of Canadian infrastructure: A review of literature to inform the way forward (Swanson et al., 2021)
- The Government of Canada: Climate Change Impacts and Adaptation: A Canadian Perspective (Lemmen et al., 2004)

Risk and Vulnerability Assessments and Adaptation Strategies

- The World Association for Waterborne Transportation Infrastructure (PIANC): Climate Change Adaptation Planning for Ports and Inland Waterways (PIANC, 2020)
- Climate Change Adaptation Strategies and Policy Options for Arctic Shipping in Canada: Report Prepared for Transportation Canada (Dawson et al., 2017)

2.2 Gaining Perspective: Researchers, Marine Users, and Marine Operations

2.2.1 Interviews with Leading Researchers and Research Programs

A list of leading researchers and research programs were identified from around the globe (e.g., academics, NGOs, and industry professionals) working in the area of climate change adaptation and resilience, including those specific to marine assets and operations. An inventory of leading researchers and research programs contributing knowledge to the climate change resilience and adaptation of maritime services to support the safety, accessibility and sustainability of waterways was developed. A short list of eight key researchers were identified and contacted for a thirty minute virtual interview. Researchers and research programs identified as leaders in climate resilience and adaptation included the following organizations:

1. RMIT University (Australia)
2. Maritime Research Institute Netherlands (MARIN)
3. University of Rhode Island (Department of Marine Affairs)
4. Association of Canadian Port Authorities (ACPA)
5. Green Marine
6. US Army Corps of Engineers (Engineer Research and Development Center)
7. United States Coast Guard
8. Canadian Climate Institute

The interviews centred on a series of adaptation-focused questions to identify adaptation and resilience strategies, the capacity of the marine sector to adapt to climate change, emerging strategies in support of climate adaptation specific to marine assets and operations, and adaptation strategies that have been implemented and have demonstrated success. Interview questions and summaries of responses are detailed in Appendix A.

2.2.2 Climate Survey: Impacts, Risks, Adaptation, and Resilience for Waterways

Leading researchers and research programs contributing knowledge to the climate change resilience and adaptation of maritime services that were not interviewed were requested to complete an online Google survey (Appendix B). The survey was designed to identify and catalogue impacts and risks experienced or anticipated by waterways users and researchers, and to understand decision making frameworks and adaptation strategies, from both the marine sector and parallel industries, that are key to support safe, accessible, and sustainable waterways.

2.3 An Analysis of Risk and Vulnerability Assessments and Adaptation Strategies in Other Jurisdictions

An analysis of climate change vulnerability assessments and climate change risk mitigation studies were reviewed from the US, Norway and Netherlands. Each of these jurisdictions represents a nation actively prioritizing climate change adaptation, mitigation, and research. The rationale for the inclusion of each specific jurisdictions is as follows:

- The United States was included in the assessment as their marine waterways are in close proximity to Canadian waterways and as such, many similarities exist regarding climate hazards and impacts;
- Norway was included as it represents a northern country with arctic geography, similar to that of Canada; and
- The Netherlands represent a key maritime country that has been considering the impacts of climate change, especially flooding and sea level rise.

3.0 A Summary of Climate Hazards for the Canadian Maritime Environment

This section presents key climate hazards identified for the Canadian maritime environment, as informed by the literature review and insights gleaned from key researchers and maritime users. Relevant climate change hazards to the Canadian marine environment can be categorized into four main groups:

- Marine biochemistry;
- Sea level rise;
- Extreme weather events; and
- Changes in the cryosphere.

All hazards are interconnected and can influence and exacerbate one another (Bush and Lemmen, 2019). For example, the compounding effects of higher sea levels and more intense and frequent storm surges are anticipated to be more detrimental to shoreline stability than either impact on their own. This compounding effect is also represented by extreme weather-based impacts on marine fishing that can be aggravated by the altered timing and availability of commercially harvested species caused by warming ocean temperatures and shifting ecosystem dynamics (biochemistry). Each climate hazard category is discussed in further detail below.

3.1 Hazard Category 1: Changes in Marine Biochemistry

Ocean chemistry has been changing throughout the 20th century and is projected to continue changing (US EPA, 2021a; Cheng et al., 2020; NOAA, 2020; IUCN, n.d.). Changing water chemistry can have significant impacts on coastal marine environments; specifically, changes in temperature, salinity, acidification, and oxygen depletion can alter the structure and function of valuable marine resources and ecosystems. These changes have implications for Canada's coastal environments and maritime waterways as well as their users in numerous ways, including:

- Species composition and abundance are affected when warmer ocean temperatures alter the geographic distribution of marine biota, which can subsequently lead to invasive species further exacerbating this issue due to shifting ecosystem dynamics (Sorte et al., 2010; Poloczanska et al., 2016; Rockwell et al., 2009). The timing and availability of commercially important species is crucial to the success of the marine fishing industry which has impacts on both local and national economies.
- Sea surface salinity has been increasing since 1960 in oceanic regions where the salinity is higher than the global average (Cheng et al. 2020; Durack et al., 2012) which may lead to accelerated corrosion of infrastructure over time (PIANC, 2020). Fresher parts of the ocean, such as the Arctic and Antarctic, are observing decreases in salinity in response to glacial and sea ice melt (Durack et al., 2012; Haumann et al., 2016). Decreased surface salinity can have the same impacts on the fishing industry as temperature increases by changing the

spatial and temporal distribution patterns of populations (Poloczanska et al., 2016). Sensitive coastal vegetation such as salt marshes, which provide essential services to native fish and invertebrate species, can also be impaired by ocean temperature increases.

- Loss of protective vegetation limits the ability of the shoreline to resist coastal erosion, which impacts port infrastructure and marine tourism (Lapointe et al., 2021; Miller et al., 2020).
- As temperature increases and dissolved oxygen saturation decreases, hypoxic areas in the water column (i.e., "dead zones") pose a risk to aquatic life and can lead to large-scale fish kills, impaired physiological development, and loss of habitat for benthic organisms, all of which have ramifications for commercial fishing (Altieri and Gedan, 2014; NOAA, 2021).
- Increasing trends in ocean acidification have been identified as critically detrimental to multiple groups of organisms including diatoms, benthic invertebrates (including commercially harvested species such as lobster and crab), fish, seaweeds, and sea grasses (Pörtner et al., 2014).

3.2 Hazard Category 2: Sea Level Rise

Sea level is expected to continue increasing on a global scale (US EPA 2021b). Increased water levels can lead to increased flooding and overtopping, damaging port infrastructure and contributing to coastal erosion (Izaguirre et al., 2021; Swanson et al., 2021). Wave heights and the temporal duration of extreme weather seasons are expected to increase as a result of higher water levels as well, which poses a risk to both infrastructure and marine fishing, shipping, and transportation (Cohen et al., 2019). Coastal infrastructure including terminals and small craft harbours may become more exposed to wave action and flooding as protective barriers such as dikes and breakwaters become submerged. Over time, undeveloped coasts repeatedly inundated with rising sea levels drives coastal vegetation (e.g., salt marshes) landward, impacting the terrestrial shoreline with intruding saltwater (Borchert et al., 2018). The higher risk of short-term flooding and the permanent transformation of shorelines in the long-term have significant environmental, social, and economic implications (Lemmen et al., 2016).

3.3 Hazard Category 3: Extreme Weather Events

Historical data and projected trends indicate that the frequency and magnitude of extreme weather events will continue to increase as a result of climate change (Swanson et al., 2021). More intense and frequent storms, including hurricanes, will significantly increase the likelihood of storm surge flooding on all three of Canada's coasts, exacerbating the previously identified impacts of coastal erosion and infrastructure damage (Lemmen et al., 2016; Swanson et al., 2021). Coastal communities that rely on tourism may be heavily impacted by extreme weather which is economically costly to the industry (Lapointe et al., 2021). Maritime transportation services may be disrupted when residential and commercial ferries or shipping vessels are delayed by storms, or if damage to access roads and docks occur (Coll et al., 2013). Reduced visibility due to fog, blizzards, or sandstorms can further add to delays (PIANC, 2020). Increases in other extreme weather events such as hurricanes, drought, rainfall, and flooding due to increased precipitation are anticipated, all of which can cause direct and indirect damage to marine vessels and operational systems (PIANC, 2020). Road and rail accessibility to ports is crucial in maintaining the flow of people, goods, and services (Lemmen et al., 2016).

3.4 Hazard Category 4: Changes in the Cryosphere

The spatial and temporal extent of sea ice is projected to continue decreasing (Pizzolato et al., 2014). Reduced sea ice cover in Canada's northern regions is expected to increase the demand to use ice-free corridors for marine shipping, resource exploration, and tourism (Mudryk et al., 2021; Swanson et al., 2021). With increased activity, there may come a new demand for the development of Arctic ports to accommodate larger vessels more frequently (Wang et al., 2019). Although this may provide some benefit to local and global economies, it vastly increases the potential hazards and risks to the maritime sector and its users. Calving of ice shelves results in more small and medium-sized icebergs, rendering these Arctic channels significantly more hazardous to navigate. An increased number of hull strikes and sinkings are anticipated to result from the opening of the Arctic Ocean, compromising the safety of vessel personnel (Dawson et al., 2017; Schlanger, 2019). Additionally, residents of the Canadian North rely on semi-permanent trails across sea ice as a connection to essential services, but less predictable snow and ice patterns make travelling through these areas more dangerous for these users. Increases in tourism are likely to result in more environmental pollution which poses risks to ecological health (Lemmen et al., 2016).

Permafrost areas are more prone to coastal erosion than their temperate counterparts due to the compounding of several climate related impacts: warming temperatures lead to permafrost thaw which reduces the stability of frozen shorelines, and increased flooding, storm surges, and wave action rapidly degrade the coast (Jones et al., 2018).

3.5 Survey Findings: Observed and Noted Climate Hazards

To gain perspectives and knowledge on climate hazards, questions were posed in the online survey as to which specific climate hazards have been noted and observed as part of their respective operations and/or research.

Climate hazards available for selection in the survey included increased storm intensity, increased wave action and intensity, sea level rise, species migration, sea ice melt, erosion/sedimentation, changes in ocean chemistry, melting permafrost, and coastal flooding. Based on survey responses, impacts and hazards selected most frequently included increased storm intensity, sea level rise, sea ice melt and coastal flooding. Respondents noted the following additional climate hazards related to their operations and/or research in open ended survey questions:

- Increased occurrences of marine heat waves both regionally and globally
- Extreme heat, high winds, drought, winter arctic air masses moving south, increased wildfire activity, reduced winter lake ice, movement of invasive species

- Changes to multi-year ice conditions; sea ice melt is not uniform and changes may result in actually more challenging ice conditions in some areas of the Arctic

3.6 Survey Findings: Climate Change Impacts on Services

Insights were gathered in the survey as to how climate hazards impact marine services. Climate hazards available for selection in the survey included increased storm intensity, increased wave action and intensity, sea level rise, species migration, sea ice melt, erosion/sedimentation, changes in ocean chemistry, melting permafrost, and coastal flooding. When asked which climate hazards have been observed to have a high degree of impact on services, the climate hazard with the greatest frequency of selection among survey respondents was coastal flooding. Melting permafrost, erosion/sedimentation, and increased wave action and intensity were selected least often by survey respondents.

Additionally, a series of open-ended questions were posed in the survey as to how specific climate hazards have been observed/researched to have an impact on services. The following insights were shared by respondents relating to climate change hazards and subsequent impacts on the maritime environment:

- Change of spring fish migration/run
- Increased use of public water access due to extreme heat
- High winds on water reducing pleasurecraft operation
- An increase in shipping accidents
- High winds, ice storms, and snow load causing tree damage and power line outages
- Increased pavement deterioration
- Increased use of road salt and snow clearing
- Increase in insurance claims by municipalities
- Severe weather events leading to phenology shifts (e.g., marine heat waves and timing of lobster moulting)
- An increase in hurricanes along the east coast and implications for secondary, cascading impacts through the loss of critical services (e.g., power, communications, surface transportation)

The following section will further explore the potential impacts of climate change hazards on specific sub-sectors of the Canadian maritime environment.

4.0 Impacts of Climate Change Hazard on the Canadian Marine Environment

This section provides a synthesis of climate change impacts that have the potential to affect the Canadian marine environment (i.e., waterways and their users) and in what ways, based on both literature review and survey/interview responses. The impacts are grouped into seven themes:

- Port and Coastal Infrastructure
- Commercial Marine Shipping
- Marine Fishing
- Marine and Coastal Tourism
- Inland Waterway Transport
- Indigenous Perspectives and Maritime Climate Change Impacts
- Future Impacts of Climate Change on Arctic Sovereignty and Security

4.1 Theme 1: Port and Coastal Infrastructure

Ports serve a critical function in global commerce as important nodes in the supply chain, and are relied upon for most economic activity (Becker et al., 2018). Therefore, any significant impact to port infrastructure can have subsequent impacts to the local, national, and global economy (Becker et al., 2018). As the global climate continues to change, it is expected that the world will observe an increase in the frequency and intensity of extreme weather events (e.g., heavy precipitation, heat waves, storms, hurricanes) and more "slow onset" changes such as sea level rise, surface salinity, and decreasing sea ice cover.

Changes to sea level will vary across Canada during this century. Sea level rise will alter the nature of wave action along coasts and increase the severity of storm surges (Swanson et al., 2021). Consequently, this will result in various impacts to port and coastal infrastructure. Sea level rise, more severe storm surges, and wave regime changes can directly inundate and damage ports and other critical coastal infrastructure such as coastal road or railway links resulting in significant economic costs (Lemmen et al., 2016). Although some ports may find benefits in being able to accommodate deeper draft vessels as a result of sea level rise, increases in sedimentation and erosion rates in navigation channels can result in the need for more reactive dredging activities while increases in corrosion rates due to changes in water salinity will accelerate infrastructure degradation (PIANC, 2020). Furthermore, trends have been showing an increase in tropical storm frequency and intensity; especially in the Atlantic Ocean, which can elevate risks of port closures and long term damage to port infrastructure (Becker et al., 2018).

Increased precipitation and inland flooding can impact port operations through damaging cargo, equipment, and important road or rail links (Schweighofer, 2014). Increases in intensity and duration of fog can reduce visibility, which presents hazardous conditions for port operations. Increased maintenance costs of port infrastructure can incur significant monetary costs for port operators. Additionally, maintenance of coastal roads and railroads, traffic disruption and delays can incur significant monetary and opportunity costs to all marine sectors that depend on the reliability of port functions.

4.2 Theme 2: Commercial Marine Shipping

Climate change is likely to impact maritime trade routes as storms will become more intense and frequent (PIANC, 2020). To avoid or minimize heavy weather impacts, ships are often compelled to adjust their planned routes, resulting in potential delays and increases in fuel consumption. Ships without access to weather routing services can be at risk of experiencing significant delays, loss of cargo or damage to the ship (Wagner, 2021). A greater incidence of harmful algal blooms and invasive species can effect marine shipping by impairing cooling water/freshwater intakes, thus requiring more vessel maintenance (Lemmen et al., 2016). Taking into account the climate change impacts on port infrastructure, the shipping network can encounter more frequent disruptions to loading/unloading operations, resulting in supply chain disruptions.

Marine transportation plays a critical role in the movement of goods to communities across the Canadian Arctic. Although marine access to the Canadian Arctic has historically been restricted by ice conditions to a window of one to three months between July and September (i.e., summer season), climate change has started and will continue to alter sea ice conditions, thereby facilitating increasingly dynamic shipping seasons (Mudryk et al., 2021). The general consensus is that there is future opportunity for increased shipping traffic in Arctic waters due to the decreasing quantity and changed timing of sea ice formation (Swanson et al., 2021). This can present new marine transportation corridors and therefore new opportunities for shipping, natural resource development, and oil and gas exploration (Lemmen et al., 2016). However, there are still considerable risks that may factor into future patterns of marine traffic in the Canadian Arctic (Mudryk et al., 2021). Unpredictable ice conditions, limited hydrographic charts, and lack of supporting infrastructure are among those risks.

Some increased traffic is expected in the near-term future, but likelihood for rapid traffic increases is low considering that ice and other hazards in the region continue to persist. In this case, climate change serves as an enabler for Arctic shipping and not as a direct driver as other factors such as commodity prices or technological advances, can significantly contribute to changes in future trends (Dawson et al., 2017).

The potential future increase in activity in the Canadian Arctic is not only due to an increase in shipping; tourism, fishing, and exploration (discussed below) will also drive this change. More activity can bring an accompanied increase in the demand for CCG services such as search and rescue (Frost, 2021) and hydrographic services. Navigating the Canadian Arctic can still be dangerous due to the increased risks associated with shallow and uncharted waters, lack of navigational aids and uncertain weather conditions. The further north people venture, the more difficult search and rescue operations become. In addition to the complexity of operating in the arctic, other compounding factors such as potential total darkness, high winds, and long distances from supporting infrastructure can provide even more challenges for the CCG and its partners.

The reduction in sea ice cover could also be translated into a reduction in the need (and locational services requirements) for ice-breaking services from the CCG (Rompkey and Cochrane, 2009). Overall, a longer ice-free season can bring a range of opportunities and risks for multiple Arctic marine activities.

4.3 Theme 3: Marine Fishing

The anticipated changes to marine biochemistry such as changes in ocean temperature, acidity, and dissolved oxygen can have significant impacts to fish population and distribution. Shifts in ocean temperature can impact migration patterns of marine life as they move towards regions with cooler or more optimal temperatures (Poloczanska et al., 2016). In a well-documented warming event in the west coast of British Columbia from 2013 to 2015, the warming of coastal waters facilitated the growth of harmful algal blooms and influx of invasive species, damaging the local ecosystem and impacting local fisheries (Lemmen et al., 2016).

Reduced dissolved oxygen levels can create hypoxic environments for marine species. This translates to habitat loss and shifts in distribution for mobile species, increased mortality for more immobile species, altered growth rates for different animals, and overall reduced productivity (Altieri and Gedan, 2014; NOAA, 2021). Reduced productivity among marine species is expected to potentially reduce the economic potential for the fishing industry (Gregg et al., 2018). Additionally, if commercially fished species have shifts in distribution, this can cause changes in marine traffic patterns.

Ocean acidification poses significant threats to important commercial species of fish, shellfish, crustaceans and gastropods. Species such as oysters and lobsters are already experiencing events such as shell dissolution, stunted growth, and mortality (NOAA, 2020). Climate change is increasing ocean temperature and acidity and altering salinity levels while decreasing the abundance of dissolved oxygen. These shifts can impact the distribution, productivity, reproduction, and timing of growth and migratory stages for many species of commercial importance, and in turn, impact the success of fishing efforts (Gregg et al., 2018). Additionally, the marine fishing industry will face more challenging and hazardous working conditions with an increase in the severity and frequency of extreme weather events (Rezaee et al., 2016).

4.4 Theme 4: Marine and Coastal Tourism

Changes in seasonal climate patterns and decreasing sea ice cover have increased marine access to the Canadian Arctic (Dawson et al., 2017). As a result, the marine tourism sector has grown tremendously over the past few decades (Stewart et al., 2011; Dawson et al., 2014; Pizzolato et al., 2014). Private yacht and commercial cruise-ship traffic increased by 110% and 400%, respectively, between 2005 and 2015 (Lemmen et al., 2004; Lemmen et al., 2016). As the climate shifts, it can be anticipated that new passages in the Canadian Arctic will emerge, and an accompanied lengthier cruising season can result in increased tourism in the north.

Despite the potential opportunities of expanded tourism, there are significant risks related to the negative environmental, and local social and cultural impacts, the lack of supporting infrastructure to accommodate such a significant growth in Arctic tourism, as well as limited search and rescue capacity. Risks of a ship collision are especially heightened due to limited hydrographic charts and unpredictable ice conditions. Serious risks may factor into future patterns of Canadian Arctic tourism (Mudryk et al., 2021).

Another major part of the tourism industry is coastal tourism, which is defined by Tourism Development International as "the sector of the tourism industry that is based on tourists and visitors taking part in active and passive leisure and holiday pursuits or journeys on (or in) coastal waters, their shorelines and their immediate hinterlands" (Lapointe et al., 2021). As coastal tourism revolves around the sea-land interface, climate change impacts such as sea level rise, storm surges, and coastal erosion may continue to affect coastal tourism infrastructure. One example of this is evident in Quebec's Magdalen Islands, a small archipelago in the Gulf of Saint Lawrence where tourism is the second largest contributor to the islands' economy (Arseneau Bussières and Chevrier, 2008; Tourisme Québec, 2021). The Magdelen Islands are threatened by increasing erosion rates which can be attributed to sea level rise, the reduction in sea ice cover, changes in wintering processes, and changes in precipitation patterns – all of which can lead to instances of coastal squeeze, habitat loss, and retreating shorelines.

In general, many regions along the Atlantic coast are highly sensitive to sea level rise. These include the north shore of Prince Edward Island, the Gulf coast of New Brunswick, much of the Atlantic coast of Nova Scotia, and parts of Charlottetown and Saint John. The main issues observed in the regions include increases in storm surge flooding, permanent submerging of parts of the coast, accelerated erosion of beaches and coastal dunes, degradation of coastal wetlands, and saltwater intrusion into coastal aquifers (Lemmen et al., 2004; Lemmen et al., 2016). The Pacific coast has a generally low sensitivity to sea level rise, with greatest sensitivity in parts of the Queen Charlotte Islands, the Fraser Delta, and portions of Victoria and Vancouver. The main issues observed in these regions include the breaching of dykes, flooding and coastal erosion (Lemmen et al., 2016).

4.5 Theme 5: Inland Waterway Transport

The Great Lakes and the St. Lawrence River form one of the longest inland navigation systems in the world, connecting over 110 ports in Canada and the United States through a series of canals, rivers, straits, locks, and channels (International Joint Commission, n.d.).

Warmer air temperatures, increased precipitation, and more extreme swings between periods of drought and heavy precipitation in the Great Lakes Region will lead to variability in water levels that will challenge coastal infrastructure (Cohen et al., 2019; Emerging Issues Working Group of the Great Lakes Water Quality Board, 2017). Lower water levels can lead to challenges in navigation through shallow portions of the Great Lakes' channels and harbors. This can lead to the costly decision to reduce the amount of cargo being hauled in order to continue shipping operations at some capacity (Lemmen et al, 2004; Schweighofer, 2014). On the other hand, higher water levels can be beneficial for the navigation of vessels with higher volume of cargo but can also contribute to the flooding of docks and accelerate shoreline erosion (Swanson et al., 2021).

Additionally, reduced lake ice cover caused by rising temperatures could result in greater storm related flooding and erosion impacts on shore infrastructure and communities, as ice plays a critical role in protecting shoreline infrastructure from wave impacts (Swanson et al., 2021). Other extreme events (e.g., flooding, storms, blizzards, etc.) can cause direct damage, structural failure, downtime, and closure of waterborne transport assets, cargo handling activities and operational systems (PIANC, 2020). Similar implications are expected for the extensive system of locks, canals and dams which regulate the water levels and flow of traffic in the Great Lakes systems.

4.6 Theme 6: Indigenous Perspectives and Maritime Climate Change Impacts[1]

Harvesting activities such as hunting, fishing, trapping and gathering wild plants have been part of Indigenous peoples' ways of living for millennia. For many Indigenous communities, especially those in the Northern Territories, much of the hunting, gathering, and fishing activities takes place in the large bays and inlets along the coast and far inland. Therefore, many of their traditions are vulnerable to the impacts of climate change. Marine fish and invertebrates important to Indigenous communities are projected to decline by up to 64% by 2050 under IPCC high emissions scenario (Whitney et al., 2020). The five anadromous salmon species, which collectively are a staple for Indigenous communities, are projected to decline by 12.1 to 46.8% by 2050 under the same emission scenario, which may severely affect Indigenous access to essential nutrients (Marushka et al., 2018). The changes in ocean and inland waterway biochemistry are likely to disrupt fish spawning and migration patterns, as well as impact communities' ability to access harvesting/hunting/fishing grounds (Ford et al., 2008; Whitney et al., 2020).

Indigenous communities in northern territories are also vulnerable to climate change impacts on sea ice conditions. Because of the distances needed to travel from remote communities to subsistence resource areas, sea ice acts as the primary surface on which travel occurs. The sea ice system links communities to traditional areas of hunting, fishing, and trapping. The impacts that continue to be observed include reduction in ice thickness, earlier ice breakup, and later and slower ice formation. Many indigenous communities rely on the predictability of sea ice formation and characteristics, and so unpredictable sea ice conditions pose risks related to unsafe travel conditions, leading to people becoming stranded or falling into the water and restricting access to essential food sources (Lemmen et al., 2016).

A report focusing on climate change impacts and adaptation strategies borne from Indigenous knowledge, perspectives, and experiences is due to be published in 2022. This report is co-led by

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[1] Please note that insights presented from the literature have not been corroborated in discussions with Indigenous communities, governments, and industry to date. An interview with the First Nations Fisheries Council is likely to occur in the future as a means to best understand relevant climate hazards, impacts observed, and adaptation planning and resilience efforts.

Graeme Reed, Senior Policy Advisor at the Assembly of First Nations, and Shari Fox, Research Scientist with the National Snow and Ice Data Center of the University of Colorado Boulder.

4.7 Theme 7: Future Impacts of Climate Change on Arctic Sovereignty and Security

Currently, eight countries have a geographic claim in the Arctic, including Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States (Arctic Council, 2015). Canada is home to a large proportion, with just under two thirds of its land situated north of the limit of isolated permafrost (Natural ResourcesCanada, 2017). Multiple stakeholders carry political and economic power on a global scale and therefore have the ability to alter the Arctic landscape.

From a climate change perspective, increased marine access to Arctic resources and waters can allow for increased economic activity and sea traffic, including through the Northwest Passage (NWP), which connects the Atlantic and Pacific Oceans. Increased warming under climate change and reductions in sea ice cover could pose challenges for Canada's legal arguments to regulate shipping across the NWP. The untapped natural resources in the Arctic are expected to be a source of future international tension (Dawson et al. 2017). Sustained foreign use of these Arctic shipping lanes could render the NWP an international strait. Geopolitical challenges may therefore arise over the next century as an accessible Arctic (new trade routes and resources) can be expected to spark debate concerning sovereignty of the route as inland waters rather than an international strait (Dawson et al. 2017). Furthermore, improved access also increases potential for illegal entry, poaching, and human and substance trafficking on small vessels (Dawson et al., 2017).

4.8 Summary of Impacts

A summarization of potential impacts for the Canadian marine environment based on specific climate hazards is presented in Table 1.

Table 1. Impacts for the Canadian Maritime Sector Based on Climate Hazards

Sub-sector of the Canadian Maritime Environment	**Ocean Chemistry** *(changes in temperature and salinity, ocean acidification, and oxygen depletion)*	**Sea Level Rise** *(coastal inundation and flooding, erosion, and storm surges)*	**Extreme Weather Events** *(reduced visibility, storm surges, safety hazards, extreme drought, heavy precipitation, high winds)*	**Changes in the Cryosphere** *(permafrost melt, changes in sea ice, coastal erosion)*
Port and Coastal Infrastructure	• Shoreline vegetation protects shorelines from erosion, which can lead to port infrastructure damage • Increased corrosion rates of infrastructure	• Landward migration of shorelines • Flooding of protective barriers (dikes, breakwaters) • Damage to built environment, vessels and equipment, especially shoreline-anchored infrastructure	• Damage to built environment, vessels, and equipment • Port and ferry closures or delays • Reduced functionality of port processing facilities	• Permafrost areas at greater risk of coastal erosion • Need supporting infrastructure and technology (e.g., monitoring technology) for increased activity
Commercial Marine Shipping	• Impacts on shipping lane locations • Impairment of cooling water/freshwater intakes by algal blooms and invasive species	• Potential port closures • Potential for a greater volume of cargo and larger vessels due to higher water levels in marine areas	• Weather-related safety hazards • Potential reduction in cargo transport capacity • Longer wait times for processing • Inefficiencies in vessel navigation	• Increase in marine shipping traffic through Arctic • Increase in strikes and sinkings, search and rescue operations • Increase in spills and pollution • Need supporting infrastructure and technology for increased activity
Marine Fishing	• Changes in species composition and abundance	• Potential port closures resulting from storm surges	• Weather-related safety hazards for commercial and recreational fisheries	• Increase in strikes and sinkings, search and rescue operations

Sub-sector of the Canadian Maritime Environment	Ocean Chemistry *(changes in temperature and salinity, ocean acidification, and oxygen depletion)*	Sea Level Rise *(coastal inundation and flooding, erosion, and storm surges)*	Extreme Weather Events *(reduced visibility, storm surges, safety hazards, extreme drought, heavy precipitation, high winds)*	Changes in the Cryosphere *(permafrost melt, changes in sea ice, coastal erosion)*
	• Reduced Indigenous fishery access • Altered timing and availability of commercially harvested species • Physiological impairments and fish kills • Increase in invasive species			• Increased potential for illegal entry and poaching on small vessels • Changes to traditional areas of hunting, fishing, and trapping for Indigenous communities • An increased risk of human health and safety concerns relating to travel on sea ice
Marine and Coastal Tourism	• Changes in composition and abundance of commercially harvested species shifts feeding locations of marine megafauna	• Impacts on important coastal tourism areas from flooding, overtopping, storm surge	• Weather-related safety hazards	• Increase in recreational marine tourism traffic through Arctic • Increase in strikes and sinkings, search and rescue operations • Increase in spills and pollution • Need supporting infrastructure and technology for increased activity
Inland Waterway Transport	--	• Potential changes in cargo and vessel navigation in the Great Lakes' channels and harbors	• Extreme swings between drought and heavy rainfall impact inland freshwater levels	• Less protection of shorelines with reduced ice cover • Increase in grounding, search and rescue and

Sub-sector of the Canadian Maritime Environment	**Ocean Chemistry** *(changes in temperature and salinity, ocean acidification, and oxygen depletion)*	**Sea Level Rise** *(coastal inundation and flooding, erosion, and storm surges)*	**Extreme Weather Events** *(reduced visibility, storm surges, safety hazards, extreme drought, heavy precipitation, high winds)*	**Changes in the Cryosphere** *(permafrost melt, changes in sea ice, coastal erosion)*
			• Sedimentation and erosion in rivers affects navigation • Weather-related safety hazards	environmental response operations • Need supporting infrastructure and technology (e.g., channel depth monitoring)

4.9 Adaptation and Resilience Planning in Canada

In the context of adaptation and resilience planning in Canada, support for climate change adaptation is currently provided through various strategies and policies, including Canada's National Adaptation Strategy, and the Climate Lens program. The latter requires a climate change resilience assessment to be conducted on infrastructure projects receiving Infrastructure Canada's Investing in Canada Infrastructure Program (ICIP) and Disaster Mitigation and Adaptation Fund (DMAF) funding, in order to identify potential climate risks and to mitigate those risks in design and construction. Transport Canada's Transportation Asset Risk Assessment (TARA) program also provides funding to transportation asset owners to conduct climate change risk assessments and develop adaptation plans for their assets, including ports and port infrastructure.

The Canadian Centre for Climate Services and the Canadian Climate Institute represent important agencies for collecting and disseminating pertinent impact and adaptation information. An online tool with 243 Canadian climate adaptation case studies across the nation is available from Canada in a Changing Climate: Advancing Our Knowledge for Action. This interactive map (Map of Adaptation Actions) allows users to input a suite of parameters (e.g., specific climate issue, sector, stage of adaptation, type of action, type of setting, and translation priority) to hone in on examples of adaptation strategies that pertain to a scenario of choice. This tool provides valuable information that pertains directly to impacts affecting the Canadian maritime environment and associated sectors.

The following section outlines adaptation and resilience planning, including risk and vulnerability assessments, as conducted in other jurisdictions.

5.0 Risk and Vulnerability Assessments and Adaptation Strategies from Other Jurisdictions

This section provides an analysis of approaches taken by coast guards, government agencies and industry from three other jurisdictions with respect to climate change risk and vulnerability assessments, adaptation strategies and resilience efforts for marine assets and operations. Each section will present frameworks, strategies and policies, risk and vulnerability assessment examples, and adaptation strategies.

5.1 United States

5.1.1 Frameworks, Strategies, and Policies

With respect to the United States government, a variety of frameworks, strategies, and policies exist which focus on climate change, including (but not limited to) the following:

- 2022: Climate Strategy, United States Army
- 2021: Strategic Framework for Addressing Climate Change, Department of Homeland Security
- 2021: Department of Defense Climate Adaptation Plan, U.S. Department of Defense
- 2018: Climate Resilience Design Guidelines, Port Authority of New Jersey
- 2017: NAVFAC Installation Adaptation & Resilience Climate Change Planning Handbook
- 2014: U.S Department of Transportation, Climate Adaptation Plan: Ensuring Transportation
- Infrastructure and System Resilience
- 2014: Climate Change Adaptation Roadmap, U.S. Department of Defense
- 2010: U.S. Navy Climate Change Road Map: Task Force Climate Change, Department of the Navy

In support of broader climate strategies and policies, numerous applications of climate assessments and adaptation planning efforts have been conducted. A review of climate risk and vulnerability assessment frameworks, tools, and applications is provided below, with examples from governments, industry, and research in the United States. It is important to acknowledge that climate strategies, policies, and frameworks vary significantly and assessments rely on different methodologies and approaches, as evidenced by the risk and vulnerability assessments described below.

5.1.2 Risk and Vulnerability Assessment Examples

5.1.2.1 Federal Highway Administration Vulnerability Assessment Adaptation Framework

The Federal Highway Administration (FHWA) has developed a Vulnerability Assessment and Adaptation Framework, which serves as a guide and resources for analyzing climate change impacts on transportation infrastructure. The framework is oriented towards state departments, organizations, and agencies that are responsible for the planning, building, and maintenance of the transportation system in the US as a means to integrate climate adaptation considerations into transportation decision making (FHWA, 2017).

The framework relies on seven steps to conduct a vulnerability assessment. Pilot programs conducted by the FHWA from 2010-2015 have provided examples of how jurisdictions in the United States have undertaken specific steps of the vulnerability assessment framework, specific to transportation infrastructure, including marine-related assets. Examples of how different jurisdictions and associated case studies implemented steps of the FHWA framework is described in Table 2 below. When possible, examples of marine-related case studies were identified.

Table 2. Application of the FHWA Vulnerability Assessment and Adaptation Framework by United States Jurisdictions

FHWN Vulnerability Assessment and Adaptation Framework Step	Examples from Case Studies
1. Articulate objectives and define study scope	**California: San Francisco Bay Area (Bonham-Carter et al., 2014)** The Metropolitan Transportation Commission (MTC) built upon an initial study that indicated areas most susceptible to sea level rise and storm surge. The MTC developed risk profiles for transportation assets and sea level rise by focusing on three focus areas and core and adjacent assets and developed detailed adaptation strategies to protect key assets.
2. Obtain asset data	**California: San Francisco Bay Area (Bonham-Carter et al., 2014)** The Metropolitan Transportation Commission used an online questionnaire to collect data on assets and asset components from agency staff and geo-coded all information. **Washington (Washington State Department of Transportation, 2011)** Washington State Department of Transportation compiled an asset inventory and mapped asset locations in GIS for state-owned infrastructure (e.g., roadway, bridges, ferry terminals). Integrating data from many sources was identified as a challenge. **Maryland (Maryland State Highway Administration, 2014)** The Maryland State Highway Administration used a combination of qualitative and quantitative data (regional and federal data sources) relating to assets and GIS software to organize, present, and analyze data in a single, cohesive format.
3. Obtain climate data	**Arizona and Tennessee (Anderson et al., 2015; Tennessee Department of Transportation, 2015)** Arizona Department of Transportation and the Tennessee Department of Transportation utilized downscaled Coupled Model Intercomparison Project (CMIP) data for precipitation, temperature etc. and the U.S. Department of Transportation's Coupled Model Intercomparison Project

FHWN Vulnerability Assessment and Adaptation Framework Step	Examples from Case Studies
	(CMIP) Climate Data Processing Tool to obtain climate projections and historical observations.
4. Assess vulnerability	**Washington (Washington State Department of Transportation, 2011)** The Washington State Department of Transportation vulnerability assessment used a structured, stakeholder-based approach to qualitatively assess risk and included 14 workshops. The analysis considered asset criticality and the potential impacts of the state climate change scenarios and used a qualitative scoring system. **Alabama; Mobile (FHWA, 2015)** The U.S. Department of Transportation Gulf Coast Study focused on transportation modes (highways, ports, airports, rail, transit, and pipelines), used specific indicators for exposure, sensitivity and adaptive capacity to develop a vulnerability score for each asset and climate stressor.
5. Identify, analyze, and prioritize adaptation options	**California: District 1 (GHD, ESA, and Trinity Associates, 2014)** California Department of Transportation (Caltrans) used a multi-criteria analysis (including cost, flexibility of design, social and environmental considerations) and weighted criteria based on stakeholder insights to identify adaptation options. **New York: Lake Champlain Basin (FHWA, 2017)** The New York State Department of Transportation developed a benefits valuation approach, inclusive of social, economic, and environmental factors, to prioritize adaptation options for culverts.
6. Incorporate assessment results in decision making	**New York and New Jersey (PANYNJ, 2011)** The Port Authority of New York and New Jersey (PANYNJ) conducted a vulnerability and risk assessment of the agency's critical infrastructure and implemented project design evaluation criteria for existing and new infrastructure projects.
7. Monitor and revisit	**New York and New Jersey (PANYNJ, 2011)** The Port Authority of New York and New Jersey (PANYNJ)'s vulnerability assessment organized assets of lower risk as "watch" assets which will be monitored over time and re-evaluated over time.

5.1.2.2 National Park Service/West Carolina University: Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol

The National Park Service (NPS), in partnership with Western Carolina University's (WCU) Program for the Study of Developed Shorelines (PSDS), has developed a Coastal Hazards and Sea-Level Rise Asset Vulnerability Assessment Protocol which focuses on the vulnerability of physical infrastructure to climate hazards. The protocol involves four steps (NPS, 2017):

9. Exposure Analysis and Mapping - analyzes the exposure of assets to climate hazards and sea-level rise through the use of data sources and geospatial mapping. An exposure indicator score

is provided based on the spatial relationship between assets and climate hazards and sea level rise. A total exposure score is provided for each asset

10. Sensitivity Analysis - analyzes the sensitivity of assets to climate hazards and sea level rise using an asset questionnaire
11. Vulnerability Calculation - calculates vulnerability by summing exposure and sensitivity scores and binning into vulnerability ranking categories
12. Adaptation Strategies Analysis - utilizes asset data to focus strategies on assets with varying degrees of vulnerability and priority level

5.1.2.3 United States Coast Guard Shore Infrastructure Vulnerability Assessment

The US Coast Guard (USCG) has an extensive portfolio of shoreline infrastructure, facilities, and assets (GAO, 2019). Since 2015, the USCG Civil Engineering Program has been conducting a national assessment of shore infrastructure vulnerabilities to a series of natural disasters and climate hazards, referred to as the Shore Infrastructure Vulnerability Assessment (SIVA) (GAO, 2019). The USCG uses national and state sources of climate information to support the vulnerability assessment. The SIVA and resulting outcomes serve to inform the prioritization of infrastructural projects for USCG infrastructure into the future. The prioritization process and ranking of infrastructure projects for repair or other measures under this program is not apparent from resources reviewed, aside from the submission of asset information to the USCG Procurement, Construction, and Improvements Planning Board and the Regional Depot-Level Maintenance Planning Board for project prioritization purposes (GAO, 2019). The Shore Infrastructure Vulnerability Assessment (SIVA) began in 2015 and is set to be completed by 2025.

5.1.2.4 Washington State Department of Transportation Vulnerability Assessment

The Washington State Department of Transportation (WSDOT) utilized a conceptual climate risk assessment model to evaluate the vulnerability of transportation infrastructure, including ferry terminals and operations, bridges, and buildings to climate hazards including sea level rise, precipitation changes, temperature changes, and fire risk (WSDOT, 2011).

The approach followed three steps:

- Determine existing condition of assets and the environment
- Establish qualitative criteria for initial screening (for both asset criticality and climate change impact)
- Conduct qualitative screening

Fourteen stakeholder workshops were held to accomplish the qualitative portion of the assessment and used two variables to make a qualitative assessment: asset criticality (which was defined by workshop participants using a 1-10 rating scale) and potential impacts of climate change scenarios. Qualitative ratings for impacts and asset criticality were used to create GIS layers and maps of projected climate impacts. Information from this assessment provided insights as to the vulnerability of assets and climate change impacts on assets as a starting point to support future adaptation strategies.

5.1.2.5 Port Authority of New York and New Jersey (PANYNJ) Vulnerability and Risk Assessment

The Port Authority of New York and New Jersey (PANYNJ) conducted a vulnerability and risk assessment of the agency's critical infrastructure to climate hazards, including sea-level rise, storm surge, precipitation, and temperatures (PANYNJ, 2011). A risk analysis was used to prioritize the assets at greatest risk of climate hazards and determine adaptation strategies for those assets. The risk level for assets was assessed using quantitative and qualitative approaches for the likelihood of climate hazards occurring in the asset's lifetime and the magnitude of the consequences for the asset. A risk matrix was used to determine which assets were prioritized for adaptation and assets which were identified as highest risk were prioritized. Adaptation strategies developed by PANYNJ were organized into maintenance and operational strategies, capital investments, or regulatory strategies (PANYNJ, 2011).

5.1.3 United States Risk and Vulnerability Assessment Tools and Resources

Identified tools and resources that have been used in the climate risk and vulnerability assessment process are presented below in Table 3 below.

Table 3. Vulnerability Assessment Tools and Resources in the United States

Agency or Organization	Resource	Description
The U.S. Department of Transportation	Vulnerability Assessment Scoring Tool (VAST)	Microsoft Excel®-based spreadsheet file that supports a quantitative, indicator-based vulnerability screen of transportation assets. Includes numerous asset types and climate stressors, including ports and waterways, increased temperature and extreme heat, precipitation-driven inland flooding, sea level rise/extreme high tides, storm surge, wind, drought, dust storms, wildfires, winter storms, changes in freeze/thaw, and permafrost thaw.
United States Department of Defense	Defense Climate Assessment Tool	An online tool that helps to identify which DoD installations are most exposed to climate hazards. The Tool uses historical climate data and future changes in climate and supports a screening-level assessment of installation vulnerability expressed as a combination of exposure (designated by the tool) and sensitivity. It is expected that the DCAT will be used to conduct climate exposure assessments on all major U.S. DoD installations by 2022.
Ports Resilience Expert Committee	Port Resilience Index (PRI)	A Port Resilience Index (PRI) was developed by industry leaders in the United States as a tool to consider the level of preparedness of ports to natural hazards and weather events and seeks to identify strengths and weaknesses in management and operations (Morris et al., 2016). The Port Resilience Index (PRI) is a question-based tool that is targeted to port authorities and management to assess their own vulnerabilities as it relates to climate change and natural hazards (Becker et al., 2018).

Agency or Organization	Resource	Description
Santa Clara County	Silicon Valley 2.0. Climate Change Preparedness Decision Support Tool	To support and automate conducting vulnerability assessments and determining the economic consequences for assets in the county, a climate change preparedness decision support tool was developed and applied to understand, identify, and prioritize climate change vulnerabilities within Santa Clara County and support adaptation efforts. The web-based tool encompasses a vulnerability assessment to understand which infrastructural assets will be exposed to climate change variables and to what degree and a risk assessment to understand the level of economic consequence (County of Santa Clara, 2015).
United States Army	Climate Resilience Handbook	A US Army Climate Resilience Handbook (ACRH) has been developed as a guide for Army planners through the process to systematically assess climate hazard exposure risk and incorporate this knowledge and data into existing installation planning processes such as master plans (Pinson et al., 2020). The planning process consists of four steps, which aim to increase climate resilience for US Army installations (Pinson et al., 2020): 1. Set goals and objectives for the plan to be written and/or revised, 2. Determine what extreme weather events may occur along with eight climate related effects, 3. Determine what facilities, infrastructure, assets, and missions may be vulnerable, then 4. Determine which adaptation measures to use, e.g., non-structural, structural, nature-based.
Federal Highway Administration	Adaptation Decision-Making Assessment Process (ADAP)	The Adaptation Decision-Making Assessment Process (ADAP) is a risk-based tool that helps to determine preferred approaches to project design based on life cycle cost, resilience, regulatory, and political settings, among others. ADAP can be applied to assess existing assets or to new projects (FHWA, 2016).
Department of Homeland Security (DHS)	DHS Critical Infrastructure Risk Management Framework	In support of the National Infrastructure Plan of the Department of Homeland Security, a five step risk management framework for assessing critical infrastructure exists which aims to support owners and operators of public and/or private critical infrastructure as a tool to identify priorities, articulate clear goals, mitigate risk, measure progress, and adapt based on feedback and the changing environment (DHS, 2013). This framework demonstrates utility for maritime environments, operations, and infrastructure as part of a vulnerability assessment.

Agency or Organization	Resource	Description
National Oceanic and Atmospheric Administration (NOAA)	Guidance for Considering the Use of Living Shorelines (2015)	The National Oceanic and Atmospheric Administration (NOAA) Living Shorelines Workgroup has put forward guidance to support the use of living shorelines as innovative adaptation measures to support coastal resilience efforts. Physical and ecological considerations alongside site factors to consider are provided for employing living shorelines as an adaptation measure to encourage shoreline stabilization and combat shoreline erosion (NOAA, 2015).
U.S. Army Engineer Research and Development Center	Risk Quantification for Sustaining Coastal Military Installation Asset and Mission Capabilities	Research focused on quantifying the risks of rising sea levels and coastal hazards for coastal military installation assets and mission capabilities at the Naval Station Norfolk in Virginia. A key outcome of this study was the development of a defensible risk-based approach to communicate the risks associated with sea level rise in the context of military assets and readiness that can be applied elsewhere (Burks-Copes et al., 2014).
Port Authority of New Jersey	Climate Resilience Design Guidelines	Standards which represent a risk-informed approach to building the region's infrastructure for the long term. The design guidelines consider factors like flood elevation, asset service life relative to future sea level rise projections, and asset criticality, and provide links to engineering recommendations and requirements (PANYNJ, 2018).
US Department of Transportation	Assessing Criticality in Transportation Adaptation Planning (ICF International, 2014)	A resource to narrow the range of assets considered in a climate change vulnerability assessment.

5.1.4 United States-Based Adaptation Strategies

Adaptation strategies have emerged through the assessment of climate vulnerability approaches in the United States.

Table 4 details adaptation strategies utilized in the United States specific to the marine environment.

Table 4. Adaptation Strategies from the United States

Organization or Jurisdiction	Climate Hazards Identified	Assets at Risk	Adaptation Measures Considered or Employed
United States Coast Guard (USCG) (GAO, 2019)	Storm events, especially hurricanes, flooding, natural disasters, drought	Buildings, facilities, and infrastructure owned by the United States Coast Guard (USCG) including piers, wharfs, boathouses, small boat lifts, stations, and maintenance buildings	• Placing key systems (heating, ventilation, etc.) on the roof of buildings • Relocating facilities inland • Issuing engineering planning guidance to increase the resiliency of infrastructure as it relates to natural hazards and climate risks
Port of Providence, Rhode Island (Becker et al., 2017)	Implications of a Category 3 hurricane scenario (flooding, inundation)	Port transport infrastructure	• Protect • Relocate • Accommodate
US Army Corps of Engineers (USACE) (USACE, 2013)	Waves, surges associated with sea level change, and coastal storms	Vulnerable coastal areas	• Natural and nature-based features considered consider dunes and beaches, vegetated features, oyster and coral reefs, barrier islands, and maritime forests/shrubs • Non-structural measures considered include floodplain policies and management, floodproofing, flood warning and preparedness efforts, and relocation • Structural measures considered include the use of levees, storm surge barriers, seawalls and revetments, groins, and detached breakwaters
Port of Long Beach (Port of Long Beach, 2016)	Sea level and storm surge	The Port's infrastructure, transportation networks, critical buildings, and utilities	• Addressing climate change impacts through Port policies, plans, and guidelines • Adding sea level rise analysis to the Harbor Development Permit process

Organization or Jurisdiction	Climate Hazards Identified	Assets at Risk	Adaptation Measures Considered or Employed
			• Completing a study focused on the combined impacts of riverine and coastal flooding to inform adaptation measures • Shoreline protection measures
The Cochrane-Africatown USA Bridge Mobile, Alabama (Brinckerhoff and ICF International, 2014)	Sea level rise	Bridge over navigable waterway	• Restrict ship heights • Re-configure seaward ports to handle more vessels • Replace with higher bridge at the end of the life-span • Monitor sea level and act accordingly
I-10 George C. Wallace Tunnel, Mobile, Alabama (Brinckerhoff and ICF International, 2014)	Storm surge	Coastal tunnel	• Raise portal wall • Raise all approach walls • Install "temporary" flood gates
Dock One at the McDuffie Coal Terminal Mobile, Alabama (Brinckerhoff and ICF International, 2014)	Storm surge	Shipping pier	• Adaptations should be considered to preserve critical equipment and ancillary services
County of Santa Clara	Sea level rise, storm surge, riverine flooding, wildfires, and extreme heat	Building and properties, communications, ecosystems, energy, transportation	• Conduct an overtopping analysis of existing shoreline flood protection assets • Increase the design criteria for current and future flood protection projects from 100-year flood events to higher-impact flood events • Identify and consider relocation opportunities for critical facilities • Assess assets for criticality and consider adaptation options by weighing their relative costs and benefits • Secure locations of assets in non-hazard prone areas • Mainstream climate change considerations in all transportation agency planning and decision making processes

Organization or Jurisdiction	Climate Hazards Identified	Assets at Risk	Adaptation Measures Considered or Employed
Cape Lookout National Seashore (NPS, 2018)	Climate hazards considered included flooding potential, extreme event flooding, sea-level rise, inundation, shoreline change	152 structures (buildings and shelters) and 70 transportation assets (roads, road segments, parking lots, boardwalks, waterfront systems/waterways/ marinas, fuel systems, and primary trails)	• Elevate • Relocate • Protect/engineer • Decommission and remove • Storm resistant redesign • Engineering downgrades

5.2 Norway

5.2.1 Frameworks, Strategies, and Policies

In 2007, an inter-ministerial working group was appointed to promote coordination and dialogue in the national climate adaptation work. The working group was led by the Ministry of Climate and Environment and in 2008 the Government presented a five-year platform to enhance society's resilience to climate change, to reduce Norway's climate change vulnerability and while strengthening their climate change resilience. In 2010, an Official Norwegian Report (NOU 2010:10), Adapting to A Changing Climate, was published (Norwegian Ministry of the Environment, 2012). In this report, a committee appointed by the Government assessed Norway's vulnerability to the effects of climate change and the need to adapt. This committee consisted of experts from government agencies, research institutes, and civil society. The NOU incorporates many of the aspects described in the Intergovernmental Panel on Climate Change (IPCC) Technical Guidelines for Assessing Climate Change Impacts and Adaptations and the United Nations Environment Programme (UNEP) Handbook on Methods for Climate Change Impacts Assessment and Adaptation Strategies (Lieberknecht, 2020).

The Norwegian Climate and Environment Ministry is responsible for the overall reporting of the climate change policy in Norway, including reporting on adaptation progress. The national Climate Act commits the government to providing annual reports to the parliament on the status regarding adaptation. A national system for monitoring, reporting and evaluation of climate change adaptation in Norway is yet to be established. However, Norway joined the Sendai Framework for Disaster Risk Reduction 2015 - 2030 and is committed to its implementation. The Sendai Framework sets four specific priorities for action: 1) Understanding disaster risk; 2) Strengthening disaster risk governance to manage disaster risk; 3) Investing in disaster risk reduction for resilience; 4) Enhancing disaster preparedness for effective response, and to "Building Back Better" in recovery, rehabilitation and reconstruction.

Norway relies on numerous agencies to gather the latest climate data to further inform their climate adaptation efforts. Several examples of these agencies are discussed in the following sections. One notable entity in the field of climate research in Norway is the Norwegian Center for Climate Services (NCCS), which serves as a coordinated center where decision makers can access relevant climate information for climate adaptation. The NCCS is a collaboration between the Norwegian Meteorological Institute, the Norwegian Water Resources and Energy Directorate, Uni Research and the Bjerknes Centre for Climate Research (Arctic Council, 2018). In 2017, the NCCS launched the report Climate in Norway 2100 NCCS – A Knowledge Base for Climate Adaptation. The Bjerknes Center for Climate Research (BCCR) is also one of Europe's largest scientific climate research centers and is a major contributor of climate knowledge to decision-makers, businesses, and the general population. Similar to the NCCS, BCCR is a collaboration between four partner institutions in Norway. These research initiatives are crucial in retrieving the necessary climate data to understand past, present and future climate trends that are fundamental to assessing Norwegian municipalities' vulnerability to climate change.

The Institute of Marine Research (IMR) has an extensive monitoring programme on physical and biological oceanographic parameters. The Norwegian Mapping Authority (NMA) provides expertise on tides, sea level extremes (storm surges), reference levels for use in planning, and observed and projected changes in sea level. Norway has a great amount of terrestrial monitoring programmes that include climate parameters or indicators, which also may be used to evaluate the effects of climate change. Long-term monitoring programs of several glaciers on the Norwegian mainland are performed mainly by the Norwegian Water Resources and Energy Directorate (NVE) (Norwegian Ministry of Climate and Environment, 2018). A successful climate monitoring program can support risk and vulnerability assessment through ongoing review of climate hazard changes; and can support the development adaptation and resilience practices on a more regular basis (with the capacity to react more quickly to climate change hazards and related impacts).

5.2.2 Risk and Vulnerability Assessment Examples

It is suspected that Norway's historically low exposure to climate change impacts (University of Notre Dame, 2019) contributed to the challenge of finding limited relevant literature throughout the jurisdictional scan of Norway relating to risk and vulnerability assessments and adaptation planning efforts. Few examples of risk and vulnerability assessments were uncovered. Considerations relevant to risk and vulnerability assessments in Norway are presented below.

The European ROADAPT is a set of guidelines for adapting transportation infrastructure to climate change (Bles et al., 2015). This joint effort between Norway, the Netherlands, Germany, and Denmark, is a multi-step process that takes a risk-based approach to assessing vulnerabilities and identifying adaptation strategies. First, it involves selecting appropriate data to use in decision-making and conducting stakeholder-driven climate risk assessments. Insights gleaned from this process are used in GIS-based vulnerability and socio-economic impact assessments (described below) which ultimately drive the selection of appropriate adaptation strategies (FHWA, 2017b).

The Norwegian Coastal Administration (NCA) conducts risk and vulnerability assessments in order to adjust infrastructure projects to climate change. The NCA has implemented a Climate and Environmental Strategy (2016-2018). In addition to its related Action plan, the strategy outlines how the

NCA must contribute to meet both national goals and international environmental and climate obligations (Norwegian Ministry of Climate and Environment, 2021).

A notable practice that is adopted in Norway is the integration of climate projections into planning and design procedures (FHWA, 2017b). For example, the Norway Public Roads Agency's project planning, design, operations, maintenance, and network management includes considerations of climate change impacts in design and operation. This is exemplified in the maintenance manual which recommends developing and deploying climate adaptation measures as part of scheduled maintenance operations (FHWA, 2017b). Updating technical guidance to include these considerations can only support future adaptation efforts.

Furthermore, Norway has also taken steps to respond to the anticipated increase in the accessibility of Arctic waters to human activities which would also increase the need for search and rescue operations. In light of this, helicopter services have been expanded and new Automatic Identification System (AIS) satellites were launched to strengthen ship tracking efforts (Norwegian Ministry of Climate and Environment, 2021).

5.2.3 Risk and Vulnerability Assessment Tools and Resources

AISyRisk is a module for assessing the risk related to shipping traffic and includes environmental data (including climate) in its approach. It utilises AIS-data, information about the ship, weather data, historic accident statistics, and advanced algorithms to calculate the probability of ship accidents, risk of an oil spill and loss of life (Skinnermoen et al., 2021). Probabilities and risks for collisions (head-on, overtaking and crossing), grounding (powered and drifting), fire, foundering and loss of life due to accidents are calculated (Skinnermoen et al, 2021).

The EnviRisk module utilises data from AISyRisk, environmental data from havmiljo.no, other environmental data sets, and oil drift models to produce near real-time environmental calculations of oil spill risks along the entire coast of Norway (Brude et al., 2021). The system will give users the possibility to drill down from an overview to detailed information about the area, ecosystem, species, vulnerability and estimated recovery time.

In April of 2021, the Norwegian Coastal Administration commissioned the launch of the NorSat-3 maritime tracking microsatellite built by Space Flight Laboratory in Toronto. The payload contained an Automatic Identification System (AIS) receiver which is instrumental in acquiring messages from civilian maritime vessels to provide information on ship locations and marine traffic. The information received can be used for Norway's risk assessment models such as AISyRisk and EnviRisk.

5.2.4 Norway-Based Adaptation Strategies

Adaptation strategies have emerged through the assessment of climate vulnerability approaches in Norway. Table 5 details adaptation strategies utilized in Norway specific to the marine environment.

Table 5. Adaptation Strategies from Norway

Organization or Jurisdiction	Climate Hazards Identified	Assets at Risks	Adaptation Measures Considered or Employed
Norwegian Ministry of Climate and Environment (2012)	Sea level rise, storm surges, ocean acidification	Fairways, lighthouses, buoys, breakwaters, and ports and their associated infrastructure	Designing assets to withstand more rapid corrosion as a result of ocean acidification
	Erosion, melting permafrost, melting sea ice	Cableways	Moving facilities further inland
	Sea level rise	Historical coastal buildings	Raising the foundations of buildings
Norway Public Roads Agency	Coastal hazards (site specific)	Public roads	Integration of climate projections into planning and design procedures (FHWA, 2017b)

5.3 The Netherlands

The Netherlands has a long history of flood protection implementation outside of impacts associated with climate change. The country's geographical position makes it vulnerable to flooding from marine and freshwater sources, and as such the country has had several flood adaptation measures in place for decades (Netherlands Ministry of Infrastructure and the Environment, 2016). The increased vulnerability of infrastructure and assets as a result of climate change has resulted in the vast majority of risk and vulnerability assessments and adaptation strategies focused on flooding.

5.3.1 Frameworks, Strategies, and Policies

5.3.1.1 National Climate Adaptation Strategy (2016)

The Netherlands has several initiatives, policies, and strategies aimed at assessing climate hazards, risks, and impacts in order to identify appropriate adaptation measures. The National Climate Adaptation Strategy (Netherlands Ministry of Infrastructure and the Environment, 2016) identifies necessary climate actions based on effect, risk, and urgency. It organizes climate change impacts according to four effect categories based on observed and anticipated changes in the environment: hotter, wetter, drier, and rising sea level. The significance of these changes is assessed based on their impact on nine sectors: public safety and security; IT and telecommunications; energy, infrastructure (road, rail, water and aviation); recreation and tourism; health and welfare; agriculture, horticulture and fisheries; nature; and water and spatial management. Each of these sectors contain elements that are relevant to the marine and coastal environment, and impacts on one sector may lead to primary or secondary impacts on the operations of maritime service providers.

This strategy, in combination with the Delta Programme (see below) guides the Netherlands' approach to assessing climate change, identifying vulnerabilities, and implementing and monitoring adaptation measures. It identifies key players in vulnerable sectors and outlines how they should contribute to adaptation under the National Strategy. For example, the national agency Rijkswaterstaat plays a critical role in water level monitoring for both marine and freshwater environments with predictive tools that serve as an early warning system for flooding events which is crucial for the protection of infrastructure and assets (Spatial Adaptation Knowledge Portal, 2022).

The City of Rotterdam has a Climate Proof Programme that seeks to make both the city and the port resilient to climate impacts by 2025. For example, the Botlek Water Safety pilot project was undertaken in 2015 and 2016 by the Port of Rotterdam with the aim of examining the consequences of flooding as a result of climate change, in particular sea level rise. The pilot project was a joint initiative among the Port of Rotterdam Authority and other stakeholders, including private sector firms (Port of Rotterdam, n.d.-a; Port of Rotterdam n.d.-b; PIANC, 2020).

5.3.1.2 Bilateral Agreement with the United States Federal Highway Administration

Rijkswaterstaat currently has a bilateral agreement with the United States Federal Highway Administration to collaborate on transportation infrastructure climate resilience strategies (FHWA, 2017c). Utilizing pieces of frameworks from both jurisdictions – the European ROADAPT methodology and the United States Federal Highway Administration Climate Adaptation Framework – to collaborate on joint projects has benefited organizations from both countries. The European ROADAPT is a set of guidelines for adapting transportation infrastructure to climate change (Bles et al., 2015). This bilateral cooperation highlights the dual benefit that comes from collaborating with other jurisdictions on similar issues.

5.3.1.3 Delta Programme (2010)

The Delta Programme, ongoing since 2010, focuses on freshwater resources and water safety in the context of climate change and adaptation (Netherlands Ministry of Economic Affairs and Climate Policy, 2018). The three primary themes of the programme are based around flood risk management, freshwater management, and spatial adaptation. Plans within the policy outline specific actions that will ensure the Netherlands is "climate-proof" by 2050, from mapping out vulnerable areas, to implementing and monitoring adaptation measures.

The Delta Plan for Spatial Adaptation outlines predicted impacts related to flooding and spatial adaptation to flooding (among others that are less relevant to the marine sector). This information is used to conduct vulnerability assessments for prioritizing adaptation. Governing bodies take a risk-based approach (i.e., instead of focusing on only probability of impact) to determine priorities for climate adaptation based on urgency and severity, as well as probability of effect (Netherlands Ministry of Economic Affairs and Climate Policy, 2018). As of the publication date of the NC7 report (February

2018), it was noted that ongoing concrete climate change adaptation projects involved "no regret" (i.e., low risk) options and that the focus primarily remains on policies and agreements between stakeholders.

The Knowledge Programme Sea Level Rise, under the Delta Programme, hones in on aspects of water safety specific to the impacts of sea level rise on several sectors (economy, spatial planning, agriculture, and nature) (Spatial Adaptation Knowledge Portal, 2022).

It is evident that continual research into climate change impacts is a focus for the Netherlands to ensure that appropriate risks and vulnerabilities are captured as advancements are made in scientific and climate policy research. Currently, adaptation measures are in the early stages of implementation and focus has been placed on understanding the breadth of impact and required adaptation measures by consistent communication between involved stakeholders. This involves workshops and collaborative studies to identify knowledge gaps in sectors such as water quality and quantity, urban planning, marine transport, and fisheries.

5.3.2 Risk and Vulnerability Assessments

Several initiatives are currently underway in the Netherlands with respect to risk and vulnerability assessments for prioritizing climate adaptation measures.

5.3.2.1 Stress Tests

Drought, heat, waterlogging and flooding have been identified through the Delta Programme as the main categories of climate change impacts against which vulnerability assessments are conducted. Several online resources have been created to assist in conducting "stress tests", whereby the relevant effects of climate change on specific areas can be assessed. Stress tests constitute the first step in vulnerability assessments for the Netherlands and are considered exploratory and preliminary in nature (Spatial Adaptation Knowledge Portal, 2022). The goal of this exercise is to identify which effects of climate change are relevant to a particular scenario or area which helps focus further analyses. Then, more specific vulnerabilities can be established based on results from the stress test from which concrete goals for adaptation can be set. The utilisation of this two-step process allows governing bodies to identify both challenges and opportunities potentially arising from the impacts of climate change.

5.3.2.2 Port of Rotterdam and the City of Rotterdam

The Port of Rotterdam and the City of Rotterdam have worked collaboratively together to map out the probabilities and consequences of flooding, weighing the risks, and identifying and selecting appropriate adaptation measures in numerous port areas (AIVP, 2021). The methodology and framework used was developed specifically for the Port of Rotterdam and features the following elements:

- A matrix based approach to assess the probabilities and consequences of flooding
- The inclusion of economic damage, environmental damage, risk to life and social disruption as consequence categories in the analysis

- A series of workshops to assess the risk of sea level rise and inundation

Adaptation strategies arising from this approach fall under the categories of preventative measures, spatial adaptation and crisis management and examples are provided in the following section.

5.3.2.3 The Government of the Netherlands

The Dutch government is conducting a study to determine the current status of government buildings and sites, including ports, in the context of climate change vulnerability, and have begun assessing the insurability of these assets with regard to climate change risks. Continual research into climate change hazards, vulnerabilities, and adaptation measures has been raised as a priority for the region and studies are underway to climate-proof government buildings (Netherlands Ministry of Infrastructure and Water Management, 2018).

5.3.3 Risk and Vulnerability Assessments Tools

The Climate Adaptation Knowledge Portal is the online resource for climate adaptation information and also serves as a tool to monitor the efficacy of adaptation policies by sector. It houses the Climate Impact Atlas which is a web map that allows users (citizens, governments, industries, etc.) to assess the vulnerabilities of areas of interest. The Netherlands Implementation Programme indicates that the Climate Adaptation Knowledge Portal will be used as a hub for knowledge-sharing with regard to the monitoring of adaptation measures. Implementation will be assessed for effectiveness of risk reduction and climate change risks will be concurrently monitored (Spatial Adaptation Knowledge Portal, 2022). Similarly, the Climate Damage Atlas is a tool by which stakeholders can gain understanding of the anticipated economic costs resulting from impacts in each effect category based on geographic location throughout the country.

Amsterdam Rainproof is an initiative that aims to raise awareness and create partnerships to encourage citizens, government, industry and other stakeholders to build climate-resilient infrastructure focused on handling heavy rainfall (Amsterdam Rainproof, 2022).

5.3.4 Netherlands-Based Adaptation Strategies

Currently, adaptation measures are in the early stages of implementation and focus has been placed on understanding the breadth of impact and required adaptation measures by consistent communication between involved stakeholders. The Implementation Programme for the National Climate Adaptation Strategy (Netherlands Ministry of Infrastructure and Water Management, 2018) recognizes that climate change adaptation initiatives are relatively new, and as such have adopted a “learn by doing” approach. Most measures currently in place are procedural or administrative in nature, such as identifying climate risks and making responsible parties aware, coordinating dialogue between government, industry, and other stakeholders, and collecting, managing, and analyzing climate data to inform decision making (Netherlands Ministry of Infrastructure and Water Management, 2018).

Adaptation strategies have emerged through the assessment of climate vulnerability approaches in the Netherlands. Table 6 details adaptation strategies utilized in the Netherlands specific to the marine environment.

Table 6. Adaptation Strategies from the Netherlands

Organization or Jurisdiction	Climate Hazards identified	Assets at Risk	Adaptation Measures Considered or Employed
City Council of Rotterdam (UNCTAD, 2020)	Flooding, sea level rise	Physical infrastructure	• Safe terp for the protection of goods at safe collections points • Wet-proof construction due to floodable ground floor and internal moving of goods to higher floors • Small compartment dike • Elevated infrastructure • Ecological structure • Dry-proof construction and flood wall to protect essential functions whose continual operation must be guaranteed
Government of the Netherlands (Netherlands Ministry of Infrastructure and Water Management, 2018)	Flooding, extreme weather events	Government buildings/ infrastructure	• Climate proofing buildings • Assessing the insurability of infrastructure damaged by extreme weather events as a proactive measure for minimizing financial loss • Exploration for creating new building regulations
Government of the Netherlands (Netherlands Ministry of Infrastructure and Water Management, 2018)	Water intrusion	Infrastructure	• The construction of dikes which transforms water intrusions into canals and lakes (Rosenburg, 2020) • Relocating structures and adjusting the location of dikes (FHWA, 2017c)
Government of the Netherlands (Netherlands Ministry of Infrastructure and Water Management, 2018)	Sea level rise, erosion	Coastal zones	• Replenishment of sand in coastal zones - The Sand Engine (FHWA, 2017b) • Broadening dunes • Growing mudflats, meadows, and salt marshes • Wave attenuation devices to encourage ecological habitat (FHWA, 2017c) • Ecodynamic engineering (FHWA, 2017c)

Organization or Jurisdiction	Climate Hazards identified	Assets at Risk	Adaptation Measures Considered or Employed
Government of the Netherlands (Netherlands Ministry of Infrastructure and Water Management, 2018)	Sea level rise, erosion and flooding	Protected infrastructure such as dikes	• Physical alterations to the width and depth of riverbeds • Adjusting the location of dikes (FHWA, 2017c)
Port of Rotterdam and the City of Rotterdam (AIVP, 2021)	Flood risks	Port infrastructure and processes	• Emergency, recovery and crisis management plans and the preparation of emergency facilities (AIVP, 2021) • Raising barriers, sites and bank structures and raising vulnerable systems, and waterproofing assets (AIVP, 2021)

6.0 Adaptation Measures and Strategies for the Maritime Sector

This section describes adaptation strategy themes and provides adaptation measures and strategies gleaned from the literature review, interviews, and other resources that demonstrate utility for sectors of the Canadian maritime environment. Adaptation measures vary depending on which aspects of the maritime sector they apply to. The literature review has demonstrated that there are five general types of adaptation strategies for marine infrastructure and assets: procedural, avoidance, accommodation, protection, and retreat. A definition for these adaptation strategies is described below and followed with examples in Tables 7-11. Swanson et al. (2021) has previously described the five general adaptation strategy types, of which their definitions have been adapted for this report:

Procedural: Strategies which support or inform adaptation planning processes. Examples include: climate change education programs, climate data collection and organization, planning frameworks, and regulations.

Avoidance: Strategies which seek to direct developments and assets away from vulnerable areas and are especially relevant for new infrastructure and projects.

Accommodation: Strategies which seek to reduce or minimize the impact of climate change. These strategies may include engineering measures or nature-based solutions to adapt to climate impacts. Examples include: implementing artificial reefs, perched beaches, living shorelines, wetlands, drainage ditches, and rain gardens into coastal planning to temper the impacts of sea level rise, erosion, extreme weather events, and numerous other hazards (Swanson et al., 2021).

Protection: Strategies which focus on reducing climate impacts on infrastructure and the environment through the implementation of protective barriers or buffers. Examples include: breakwaters, retaining walls, artificial reefs, engineered revetments or gabions, shore armouring, dikes, and constructed wetlands.

Retreat: Strategies which seek to relocate vulnerable assets to prevent further damage or avoid complete failure. These strategies are especially relevant for existing assets and infrastructure.

6.1 Adaptation Strategy Types

This section provides a summary of specific adaptation strategies gleaned during the analysis to relevant to sectors of the Canadian maritime environment. Not all adaptation strategy types are applicable for each relevant sector in the Canadian maritime environment and strategies are expected to vary on a site and location basis. For example, avoidance strategies pertain primarily to ports and coastal infrastructure and are less applicable to the marine fishing industry, though procedural strategies can be implemented in all sectors. Table 7, Table 8, Table 9, Table 10, and Table 11 present adaptation strategies from other jurisdictions (international examples) and also include relevant Canadian strategies and examples for sub-sectors of the Canadian maritime environment, as identified in Canadian specific reports and literature.

6.1.1 Port and Coastal Infrastructure

Table 7. Adaptation Strategies and Measures Relating to Port and Coastal Infrastructure

Canadian Strategies	International examples
• Data collection: monitoring sea levels, tracking extreme weather events, designing predictive tools, assessments of foundation stability in permafrost zones and other coastal infrastructure • Coastal zoning to avoid development of new infrastructure in vulnerable areas • Implementation of regulatory requirements for foundation systems in permafrost zones that will better absorb earth shifting due to freeze/thaw cycles • Use of tools such as thermosyphons in permafrost zones • Raising crests of seawalls and retaining walls • Incorporation of hybrid infrastructure such as nearshore breakwaters and artificial reefs • Building flood protection into coastal infrastructure (e.g., elevated or floating buildings) • Addition of riprap armouring or scour protection to existing infrastructure and assets • Restoration or construction of shoreline habitat including dunes, salt marshes, marine forests, and wetlands • Incorporation of measures to stabilize shoreline vegetation • Replenishment of sand in coastal zones • Strengthening of bankside permafrost areas in coastal zones • Hard-protection measures such as riprap, seawalls, groynes (Lemmen et al., 2016) *Interview Insights (D. Bolduc, Green Marine)* • When analyzing climate resilience, incorporate ongoing maintenance of assets as well as initial building	*United States* • Relocation of facilities inland • The use of water resistant materials and elevated telecommunication systems for rebuilding/repairing USCG infrastructure • The implementation of design evaluation criteria for existing and new infrastructure projects • Active engagement with stakeholders and determine resilience strategies • Exploring infrastructural shoreline protection measures for port terminals • Engineering assessments to evaluate the vulnerabilities of facilities, including those relevant to ports • Considering the use of living shorelines as an adaptation measure *Netherlands* • The assessment of the insurability of infrastructure damaged by extreme weather events as a proactive measure for minimizing financial loss • Amsterdam Rainproof: creating partnerships to encourage citizens, government, industry and other stakeholders to build climate resilient infrastructure • Broadening of dunes • Insurance coverage of vulnerable buildings, and potentially new building regulations that are adaptation-focused • Reclamation of excess water from heavy rainfall events • Building climate-resilient infrastructure focused on handling heavy rainfall • Replenishment of sand in coastal zones (The Sand Engine) • Growing mudflats/meadows/salt marshes to accommodate sea level rise • Onshore adaptation measures aimed at rapid drainage of excessive water from flooding (Netherlands Ministry of Infrastructure and the Environment, 2016; Netherlands Ministry of

Canadian Strategies	International examples
• Include climate change strategies in long term planning (building docks, investing in terminal expansion)	Economic Affairs and Climate Policy, 2018; Netherlands Ministry of Infrastructure and Water Management, 2018; Rosenberg, 2020)

6.1.2 Commercial Marine Shipping

Table 8. Adaptation Strategies and Measures Relating to Commercial Marine Shipping

Canadian Strategies	International examples
• Data collection: migratory patterns of marine megafauna, extreme weather event tracking, monitoring of ice calving in Arctic • Improvement of emergency preparedness measures: incident reporting, safety systems and maritime search and rescue delivery and preparing and responding to marine pollution • Collaboration with the Canadian Armed Forces to develop procedures to improve emergency preparedness and emergency response (e.g., strategic stationing of CCG or CAF assets) (Smith, 2020) • Planning for shorter road seasons in northern regions (start supplies contracts early, modify cargo transport to accommodate more per trip) (Lemmen et al., 2016) • Increases in forecasting, planning, and permitting for vessel activities in the Arctic (Swanson et al., 2021) • Avoiding areas in the Arctic that have become more hazardous due to ice calving • The inclusion of greater endurance of vessels into future planning efforts due to the potential for greater access to the Arctic due to sea ice coverage changes, changes to multi-year ice conditions and yearly shoulder season conditions Survey Insights • Greater endurance of CCG vessels to take into consideration the potential of access to the Arctic due to reductions in ice coverage due climate change • Future fleet icebreaker hull forms resulting in a full capability spectrum (CCG) • Emergency management planning efforts	*United States* • Mainstream climate change considerations in all transportation agency planning and decision making processes *Netherlands* • Crisis management efforts, including emergency, recovery and crisis management plans and the preparation of emergency facilities *Norway* • Increased search and rescue capacity in preparation for more hazardous marine navigation conditions (Norwegian Ministry of Climate and Environment, 2021) • The use of online modules (AISyRisk) to assess the risks related to shipping traffic, including ship accidents, risk of an oil spill and loss of life • The use of a maritime tracking microsatellite to understand ship locations and marine traffic for risk assessment models • Integration of climate projections into planning and design procedures

6.1.3 Marine Fishing

Table 9. Adaptation Strategies and Measures Relating to Marine Fishing

Canadian Strategies	International examples
• Data collection: behaviour, spawning, migration and feeding patterns, catch volumes, by-catch, monitoring of invasive species occurrences • Reassessment of fishing seasons and locations based on most recent available species data • Improvement of emergency preparedness measures • Collaboration with the Canadian Armed Forces to develop procedures to improve emergency preparedness and emergency response (e.g., strategic stationing of CCG or CAF assets) (Smith, 2020) • Increases in forecasting, planning, and permitting for vessel activities in the Arctic (Swanson et al., 2021) • Modifications to vessels and fleets to accommodate larger surf • Addition of riprap armouring or scour protection to existing infrastructure and assets Survey Insights • Gear modifications to access harvest of new commercial species • Considerations relating to aquaculture siting, early warning (technological), and culture diversification • Emphasis on regional and international (transboundary management) • Inclusion of climate change data in fisheries models • Strategies to increase resiliency of current fish stocks • Collaboratively setting fisheries targets with other jurisdictions to facilitate fisheries resources being available for a longer period of time	*United States (Johnson, 2012; Gregg et al., 2012)* • Establishing marine reserves and other schemes for improving fish stock resilience and rebuilding • Utilizing adaptive fishery management • Spreading risk through insurance, cooperatives, and alternative forms of financing • Developing programs to encourage and assist in diversifying livelihoods • Improving climate research, monitoring, and forecasting • Forming national and regional strategies to prevent habitat destruction • Protecting critical coastal infrastructure used in the fishing industry • Conducting research and assessments for fishery species *Netherlands* • Adjust fishing quota • Adaptation of target species and fishing techniques • Introduction of ecosystem management • Eco-labelling and certification of fish • Reallocation of mussel nursery plots • Aquaculture on former grassland - happening for sole and turbot (Nillesen and van Ierland, 2006)

6.1.4 Marine and Coastal Tourism

Table 10. Adaptation Strategies and Measures Relating to Marine and Coastal Tourism

Canadian Strategies	International examples
• Data collection: behavioural, spawning, feeding, and migratory patterns of marine megafauna; environmental spill monitoring • Regulation of development for new tourism activities in vulnerable areas • Increases in forecasting, planning, and permitting for cruise ship and other tourism-based vessel activities in the Arctic (Swanson et al., 2021) • Development of policies to restrict use and access to sensitive tourism sites (Dawson et al., 2017)	*United States* • Natural and nature-based features considered by USACE can mitigate the impacts of climate hazards in the coastal zone while supporting marine and coastal tourism and serving as coastal attractions (i.e., dunes and beaches, oyster reefs) • Living shorelines as a nature-based adaptation measures *Please note that marine and coastal tourism is closely linked to shipping and port and coastal infrastructure sectors. Please see above for specific examples relating to these elements of the sector for additional insights.*

6.1.5 Inland Waterway Transport

Table 11. Adaptation Strategies and Measures Relating to Inland Water Transport

Canadian Strategies	International examples
• Data collection: riverine water levels, extreme weather tracking, river bathymetry • Building and broadening dunes • Increases in dredging of channels • Restoration or construction of wetlands, floodplains, and riparian buffer zones in riverine ecosystems • Establishment of flood bypass zones or relief channels Interview Insights (D. Bolduc, Green Marine) • Water studies on water levels in the Great Lakes and the St. Lawrence • Assessing erosion and sources of erosion from transportation activities, including pleasure craft and commercial vessels	*United States* • Restriction of ship heights to accommodate sea level rise where bridges occur over navigable waterways (Brinckerhoff and ICF International, 2014) *Netherlands* • Excessive water from high water levels in rivers has been accommodated with the construction of dikes transforming these water intrusions into canals and lakes • Predictive tools that serve as an early warning system for flooding events • Physical alterations to width and depth of riverbeds • Reinforcement of existing protective infrastructure such as dikes • Implementation of retreat measures in areas prone to riverine flooding by relocating structures and adjusting the location of dikes (United States Department of Transportation Federal Highway Administration, 2017b)

6.1.6 Indigenous Perspectives and Climate Change Adaptation

The National Inuit Climate Change Strategy (Inuit Tapiriit Kanatami, 2019) aims to address climate change impacts with adaptation strategies specific to five identified priorities: knowledge and capacity; health, well-being, and the environment; food systems; infrastructure; and energy. Procedural strategies to achieve set objectives include Inuit-driven climate change research and monitoring that will be used to inform future policy development. A primary focus is placed on conducting vulnerability assessments to identify adaptation priorities, one of which is to improve marine safety for Inuit food harvesters who rely on sea ice for travel. This includes the adoption of harvester safety support and better capacity and infrastructure for search and rescue services.

6.1.7 Survey Findings: Adaptation Measure Priorities

Survey respondents were asked to identify their research and operational planning priority level for a series of climate hazards and impacts, including increased storm intensity, increased wave action and intensity, sea level rise, species migration, sea ice melt, erosion/sedimentation, changes in ocean chemistry, melting permafrost, and coastal flooding. Each climate hazard was selected (to varying degrees) as a priority for adaptation planning and research efforts. The climate hazard selected most frequently as an adaptation measure priority is sea ice melt.

7.0 Key Themes and Findings

This section discusses over-arching themes and findings arising from the analysis relating to adaptation and resilience planning, including risk and vulnerability assessments.

7.1 Climate Change Adaptation: A Recent Practice

In the past, global climate efforts have focused more on limiting and reducing the growth of greenhouse gas (GHG) emissions. Climate change mitigation has historically been in the foreground of climate efforts while climate change adaptation has not been given much attention due to numerous uncertainties related to the timing and levels of impact (Timilsina, 2021). This is exemplified by a 2019 report from a group of multilateral development banks that noted that over 80% of global climate finance committed to date has gone towards climate change mitigation activities and less than 20% has been allocated towards adaptation and resilience (Timilsina, 2021). As such, most strategies observed in the analysis focused on early, more procedural adaptation measures rather than, for example, updates to physical infrastructure. However, there is now a consensus among most policymakers around the world that both climate change mitigation and adaptation should go hand in hand.

7.2 The Importance of Cross-Sector Collaboration

Throughout the frameworks and policies described in each jurisdiction, stakeholder (e.g., industry, government, neighbouring parties, and coastal communities) and rightsholder (e.g. Indigenous communities) collaboration taking place early in the process is highlighted as being critical to the successful design and implementation of climate adaptation and resilience strategies. The stakeholder and rightsholder collaboration process is expected to be context and location specific. Explicit support across multiple levels of government and industry for climate-based initiatives is critical in achieving desired outcomes for climate resiliency and sets the backdrop against which regulatory and legislative decisions can be made. This level of support has been observed by other countries looking to the Netherlands and Norway for climate adaptation guidance and is identified as a necessary step in building climate resilience (i.e., U.S Department of Transportation Federal Highway Administration, 2017a).

7.3 Accessibility of Climate Data

The implementation of vulnerability assessments and adaptation strategies and monitoring of progress is supported by continuous research into changing climate conditions and can benefit from a comprehensive data management strategy. This requires forming partnerships with stakeholders from government, industry, and academia to ensure decision-making is based on the most recent available data. In having an understanding of climate projections, decision makers are equipped with the information needed to develop the appropriate responses to adapt to anticipated climate change impacts. Norway has committed to conduct climate research through several research initiatives, and the Netherlands has committed to this through their Knowledge Portal for Climate Adaptation. Having accessible climate data is important; so, however, is climate data that is comprehensible by decision-makers. Climate data that is targeted, contextual, and understandable can be the difference between actionable measures and further confusion, inaction, or a lack of awareness of unidentified risks. In all jurisdictions, continuous research was identified as a priority to ensure decisions are based on the most relevant and recent climate information.

The development of effective adaptation strategies is dependent on the quality and quantity of climate data utilized to inform the risk and vulnerability assessments. As more and more governments are grappling with the impacts of a changing climate, and with ever evolving climate science, climate data databases are expected to continue expanding. This could set the stage for opportunities for collaboration between various entities across sectors and industries. The key measures highlighted in the literature also emphasize the significance of collaboration between public and private entities at the local, regional, and national levels, as it can support the streamlining of risk and vulnerability assessment and adaptation planning processes – especially for critical infrastructure.

7.4 Inherent Uncertainties in Climate Data

There are inherent uncertainties in climate science and climate change data projections. These include:

1. Natural climate variability – Climate data projections are based on climate normals (usually a 30 year period) - averaged climate data over a period of time. This may lessen the impact of extremes; which may not be captured in projections. Additionally, climate projections are generated at large geographic scales (using global and regional climate models), and then a statistical downscaling or other similar process is used to generate more granular projections. Uncertainty is introduced when downscaling or producing projections that are at a more granular scale than the climate models. Contributing to that uncertainty are the land-based features and microclimate-induced variability of weather patterns and climate events. Furthermore, there are other contributors to climate variability that are external to the climate system, e.g., volcanic activity and changes to solar output. Due to the unpredictability of these events, they are not accounted for in climate data projections (Climate Data Canada, 2022).
2. Model uncertainty – Climate models continue to be updated as technology and climate science advance. These models have extensive applications, but maintain uncertainties related to effects like feedback mechanisms, uncertainty of atmospheric GHG concentrations in the future, and general nuances of natural systems that may not be captured. Each model will generate slightly different results as they are calibrated differently (Climate Data Canada, 2022). Best practice is to use ensembles, or sets of climate models to identify common trends and the whole range of possible futures (Climate Data Canada, 2022).

Understanding the uncertainties in climate data projections is important for effective planning to mitigate risks related to climate change. In the Netherlands, researchers advocate choosing flexible strategies with timeframes that allow for pivoting when and as needed. As the climate changes, the effectiveness of planned adaptation strategies can also shift. A lesson learned resulting from the vulnerability assessment conducted by the Port Authority of New York and New Jersey (PANYNJ) further reiterated the importance of access to data and information, especially institutional knowledge, for conducting their respective vulnerability and risk analysis (PANYNJ, 2011).

7.5 The Flexibility and Variety of Risk and Vulnerability Assessment Frameworks

As evidenced in the jurisdictional scan, a variety of approaches and methodologies exist within risk and vulnerability assessment frameworks. Approaches vary in their inclusion of qualitative or quantitative approaches, stakeholder engagement, professional judgment, decision support systems, among other elements. Approaches used rely on the objectives of the assessment and site specific goals.

This reality is also evidenced In the Canadian context, as Lemmen et al. (2016) identifies differences between community-based, engineering-based, and sectoral-based vulnerability assessments. Community-based assessments incorporate traditional knowledge with western science and are often governance-focused. Engineering-based assessments are often conducted in northern regions where impacts from climate change are strongly linked to permafrost thaw and reduction in sea ice cover. For example, analyses of ground profiles and available coastal erosion data would assist in vulnerability assessments for coastal infrastructure in the Arctic. Sectoral-based assessments are primarily focused on how impacts from climate change will affect the vulnerability of an entire industry or sector, such as maritime transportation.

7.6 Core Principles and Utility of the Risk and Vulnerability Assessment Processes

Despite differences in risk and vulnerability frameworks and approaches, they tend to follow the same risk management process principles (ex., ISO31000 Risk Management), and are informed, in part, by climate data analytics specific to the region or area in question. Frameworks such as the Vulnerability Assessment and Adaptation Framework used by the US Federal Highway Administration, the Critical Infrastructure Risk Management Framework of the US Department of Homeland Security, Climate Change Adaptation Planning for Ports and Inland Waterways Guidance by PIANC, and the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol developed in Canada outline the necessary steps to complete vulnerability assessments and analyze risk. These frameworks tend to follow similar key steps which are:

3. Gathering and integrating data and information on asset location, characteristics, and climate sensitivities;
4. Collecting data on historical weather events and climate change projections;
5. Assessing asset and climate information to identify vulnerabilities; and
6. Using a systematic process to assign the level of risk posed by climate change hazards (as a function of one or more of: exposure, sensitivity, likelihood, consequence, severity, probability).

7.7 The Utility of Risk and Vulnerability Frameworks as Decision Support Tools

Risk and vulnerability frameworks like the PIEVC developed by Engineers Canada, the Defense Climate Assessment Tool used by the US Department of Defense, and the Vulnerability Assessment Scoring Tool (VAST) used by the US Department of Transportation, can support development of climate risk assessments that support long-term planning and informed decision making. They lay out stepwise processes to develop hazard thresholds and indicators, assess risks and vulnerabilities and prioritize impacted assets, with recommendations to develop adaptation measures for the assets at highest risk/vulnerability. For example, in the Netherlands, the Climate Damage Atlas provides estimates of climate change induced damage for each municipality, mainly from heat, drought, urban flooding, and coastal/river flooding.

Additionally, predictive tools and frameworks, as evidenced by the predictive early warning system for flooding in the Netherlands, or the Federal Highway Administration Adaptation Decision-Making Assessment Process (ADAP), represent examples of tools which support adaptation measure selection and implementation efforts.

7.8 The Variability of Climate Change Adaptation Efforts

Although climate change impacts can be felt across different jurisdictions, their contexts can vary greatly. For this reason, climate change adaptation measures are not 'one size fits all' solutions and are instead specific to the unique context of each region which includes geographical, topographical, meteorological, and even socio-cultural factors. For example, the main concern in the Netherlands is related to flooding due to the country's unique position relative to sea level. On the other hand, while being the world's least vulnerable country to climate change, Norway's primary concern has been documented to be the anticipated rise in precipitation levels which will in turn increase the risks of events such as landslides and avalanches (Norwegian Ministry of Climate and Environment, 2013). In the United States, concerns tend to focus on sea level rise, extreme weather events, and temperature changes and have prompted a variety of adaptation efforts which vary widely depending on assets, operations, and facilities of concern. In Canada, adaptation efforts vary geographically across the country and are variable across marine and freshwater environments depending on climate hazards of greatest concern and priorities among jurisdictions and organizations.

7.9 Maladaptation

Maladaptation has been flagged as an unintentional consequence of failing to adapt properly (and flexibly) to climate change (PIANC, 2020). Although observed trends and patterns are crucial to inform decision making under an adaptation framework, it must be recognized that projections carry uncertainties – they are not predictions, but rather scientifically-supported estimations of future climate hazard frequency. Flexibility should be incorporated into adaptation strategies to support a healthy use of resources. Additionally, failure to consider the implications of intervention in one area on other infrastructure, assets, or sectors may lead to maladaptation by way of increasing vulnerabilities elsewhere (PIANC, 2020). The risk of maladaptation can be mitigated by conducting appropriate risk and vulnerability assessments, understanding uncertainties and including their consideration in planning, and by fostering collaboration among relevant stakeholders.

8.0 Best Practices and Strategies

This section describes best practices and strategies gleaned from the analysis specific to managing the climate change adaptation process to inform future strategic program decisions, investments, and climate change mitigation plans in the Canadian marine environment. Strategies presented herein are broad in nature to capture the entirety of the climate assessment and adaptation planning process. Please note that adaptation strategies for addressing climate hazards specific to Canadian marine sectors are detailed in Section 6.0. Strategies and best practices are detailed below specific to aspects of the climate assessment process and adaptation planning.

8.1 Strategy

- Strategies should be system, asset, operation, or facility-specific and based on risk and vulnerability assessment frameworks (Perrs. Comm., Jan Brooke, PIANC)
- Planning should account for both the short and long term and account for the lifespan of physical assets (Centre for Climate and Security, 2016)
- Continuously identify and build capacity to address infrastructural, operational and strategic risks (Centre for Climate and Security, 2016)
- Integrate climate impact scenarios and projections into regular planning cycles (Centre for Climate and Security, 2016)
- Integrate collaboration and engagement with public and private entities into the risk and vulnerability assessment and adaptation planning process (Becker et al., 2018)

8.2 Climate Data

- Establish partnerships with organizations or agencies that develop or use climate projections (FWHA, 2017a)
- Collaborate with research, government departments, industry, and other stakeholders to support the inclusion of data and the development of a climate database in the assessment processes
- Continue to invest in improvements in climate data (Centre for Climate and Security, 2016)
- Establish and utilize a climate database to compile climate data and information over time
- Utilize long term historical data sources to inform baseline climate information (PIANC, 2020)
- Include historic extreme events data to inform baseline climate information (PIANC, 2020)
- Utilize climate scenarios representing possible future climates if the adaptation strategy extends beyond 10 years from the present (PIANC, 2020).

8.3 Asset Data

- Develop an inventory of infrastructure assets, operations, and systems (an annex is provided in PIANC (2020) report which can help guide assets, operations, and systems to consider in the adaptation planning process)
- Engage stakeholders to help identify assets as part of an asset inventory (PIANC, 2020)
- Where possible, include vulnerability specific data into asset management reporting processes (FWHA, 2017a)
- Georeference asset data during the data collection process and inventory development (FWHA, 2017a)

8.4 Risk and Vulnerability Assessment

- Subject matter experts, staff, and local stakeholders can support the risk assessment process and ensure alignment with the local context, especially when using indicator-based approaches (FWHA, 2017a)
- Numerous risk management frameworks exist and have been applied globally. When selecting a risk assessment framework, ensure alignment with the ISO 31000 Risk Management – Principles and Guidelines, First Edition, November 15, 2009 (Government of Canada, 2019)
- Employ tools and risk approaches to assess the vulnerabilities of assets based on site and location characteristics and priorities
- Use a business as usual option in the risk analyses as a measure of risks if no actions occur (PIANC, 2020)

8.5 Adaptation Options

- Include operation and institutional measures alongside structural and physical measures (Perrs. Comm., Jan Brooke, PIANC)
- Avoid using a 'one size fits all' approach as this can result in maladaptation (Perrs. Comm., Jan Brooke, PIANC)
- Adaptation strategies for ports and waterways with a planning horizon beyond thirty years should assess a range of future climate scenarios (PIANC, 2020)
- Utilize a participatory process to engage stakeholders to support the analysis of adaptation strategies (FWHA, 2017a; Becker et al., 2018)

8.6 Decision Making Processes

- Ensure decision making processes account for the lifespan of physical infrastructure (PIANC, 2020)

- Economic analysis methods and tools can support the evaluation of adaptation options (PIANC, 2020)
- Consider highest risk level projections when making climate related decisions (Centre for Climate and Security, 2016)

8.7 Monitoring and Evaluation

- An adaptation strategy should be a living document that is reviewed and updated frequently (PIANC, 2020)
- Establish monitoring and evaluation processes to assess the success of adaptation strategies and initiatives arising from vulnerability assessments (FWHA 2017a)
- Reassess vulnerabilities as new climate science and data becomes available (FHWA 2017a)

8.8 Communication

- Cimate data, risk assessments, adaptation options and reports should be easily understood and readable by decision makers and civil society
- Climate data needs to be available and accessible to all levels of governments, NGOs, industry etc.

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