Client: Natural Resources Canada (NRCAN)

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Project Title: Metocean Assessment for Offshore Wind in Atlantic Canada

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Metocean Assessment for Offshore Wind in Atlantic Canada

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GAVIN & DOHERTY GEOSOLUTIONS

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REVISION

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DISCLAIMER

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EXECUTIVE SUMMARY

Gavin & Doherty Geosolutions (GDG) and ASL Environmental Services (ASL) were contracted by Natural Resources Canada (NRCan) (hereafter the "Client) to consult on metocean parameters and phenomena required to support the development of Offshore Wind Farms (OWF) in the Atlantic Canada region.

The Client is engaged in preliminary metocean investigations and planning exercises aimed at defining Offshore Wind Farm lease areas in the waters surrounding Newfoundland and Labrador, Nova Scotia and Quebec. This report, prepared by GDG and ASL, presents three work packages.

- Work Package 1 (WP1): Develop a comprehensive list of metocean data required for offshore wind in Atlantic Canada.
- Work Package 2 (WP2): Identify key data sources for parameters in WP1 and conduct a gap analysis against existing data holdings.
- Work Package 3 (WP3): Provide recommendations for efficient data collection within priority areas in Atlantic Canada, and identify priority data collection activities before bidding, based on potential risk to offshore wind developers.

These include the identification of key atmospheric, oceanic, and ice-related variables and phenomena, as well as the identification of appropriate data sources for these variables. Additionally, the report encompasses a regional gap analysis and provides recommendations for data collection campaigns. These campaigns aim to address existing data deficiencies and facilitate future offshore wind development in Canada's Atlantic region.

To support the Client in identifying the key metocean variables that are required for offshore wind, a comprehensive list of atmospheric, wave, ocean currents, water levels and tides, temperature, sea ice and ice accretion, extreme environmental parameters, bathymetry, and other parameters were provided. In accordance with the relevant standards and best practices guidelines, the requirements for each have been documented. Furthermore, the report includes information on the developmental stage of each parameter and provides illustrative examples of their utilization in various analyses.

Several key parameters have been identified as primary variables. At this point, GDG suggests that the Client prioritize attention on these specific variables in order to advance with the zonation of the Offshore Wind Farm. These parameters include wind speed and direction, ocean current speed and direction, significant wave height, peak wave period, mean wave direction, water levels, water depth (bathymetry), sea ice concentration, ice thickness, freezing spray and ice accretion, and iceberg data.

The second work package involved conducting research to identify appropriate resources that fulfill the criteria for all parameters outlined in Work Package 1. The investigations were aimed at identifying in-situ measurements, numerically modelled datasets, and data from academic literature. Furthermore, a regional gap analysis revealed that for each of the primary non-ice-related variables, there are adequate numerically modelled datasets covering the entire study area. However, there is a lack of physical measurements for all variables except wind and wave in the more offshore regions.

For historical wind and wave data, GDG suggests that the Client consider using the Meteorological Service Canada's (MSC) hindcast model (MSC50). For ocean currents and water levels, the Hybrid Coordinate Ocean Model (HYCOM) is recommended. The latter may be supplemented by physical measurements provided by the Canadian Hydrographic Service (CHS) Department of Fisheries and Oceans (DFO) at various coastal measurement stations. The Generic Bathymetric Chart of the Oceans (GEBCO) provides a low-resolution (500 m) but comprehensive bathymetric dataset throughout the area of interest. Other notable sources of bathymetric data include the CHS Non-Navigational 10 m

(NONNA10) and 100 m (NONNA100), and the multi-beam echosounder (MBES) datasets in the National Centers for Environmental Information (NCEI) catalogue.

Regarding sea ice concentration and developmental stage datasets, the Canadian Ice Service offers comprehensive coverage. Nonetheless, there exists a notable gap concerning regional ice thicknesses and the formation of dynamic ice features. To address this gap additional times series would be required for ice draft measurements. Analysis with higher-density observation networks would be necessary in areas that may see offshore wind development and where turbines are likely to be subject to ice impact loading.

Existing iceberg datasets relevant to offshore wind activities are spare in many sub-regions, especially in the Gulf of St. Lawrence and adjacent waters. Further direct observations should be conducted in site-specific areas whenever possible and practical.

Furthermore, in-situ observations of freezing spray and ice accretion represent a significant data gap. It is recommended that ice accretion be conducted as part of baseline metocean data collection activities.

Terms of reference (TOR) were provided as a basis for recommendations for data collection activities. The recommendations include survey objectives, indicative equipment, and quantity of instruments, deployment and retrieval methodologies, quality control, data management, and reporting requirements. At this stage, the TORs do not specify instrument placement locations. Once the Offshore Wind Farm lease areas are defined, these locations should be determined in collaboration with survey contractors.

The findings from this report regarding important metocean variables include:

- Wave and Wind: Good numerical data availability exists within acceptable areas for offshore wind turbine installation, facilitated by datasets like MSC50 and ERA5. Limited physical measurements are available in specific regions.
- Ocean Currents: There is good temporal and spatial coverage of ocean current variables, primarily through numerical models like HYCOM. However, there's a lack of physical measurements for more offshore regions.
- Water Levels and Tides: Data sources provide good coverage, with the HYCOM model being particularly useful. However, local topological effects may influence measurements in some areas and therefore this needs to be addressed carefully for some specific locations.
- Bathymetric Data: Available datasets, including GEBCO and CHS NONNA, enable preliminary zonation, but detailed surveys will be necessary once lease areas are defined.
- Ice related variables:
    - Sea Ice Concentration and Stage of Development: Canadian Ice Service datasets are well-developed, but there's a significant gap in regional ice thickness and dynamic ice feature data.
    - Freezing Spray and Ice Accretion: Modelling is possible, but in-situ observations are lacking, indicating a significant data gap.
    - Iceberg Data: Sparse datasets exist, especially in the Gulf of St. Lawrence, highlighting the need for additional direct observations and historical database improvements.

Some key recommendations also include:

- Preliminary Offshore Wind Farm Lease Area Zonation: The first step should be to proceed with zoning preliminary lease areas, aligning survey instruments with regional wind potential assessments.
- Integration of Weather Analysis: It is necessary to integrate weather window and downtime analysis into metocean data analysis to assess region suitability for wind farms.
- Additional Data Needs from Regional Assessments: It is necessary to extract additional data needs from ongoing regional assessments to meet comprehensive data requirements.
- Coordination of Metocean Data Collection Efforts: Coordination efforts should be made for data collection with relevant organizations to address environmental, social, and economic considerations holistically.
- Extension of C-Core Pipeline Ice Risk Assessment Program: Extend the existing ice risk assessment program to include offshore wind projects, ensuring comprehensive risk management.

LIST OF ACRONYMS

ADCP	Acoustic Doppler Current Profiler
ALS	Accidental Limit State
BIO	Bedford Institute of Oceanography
CAD	Computer Aided Drawing
CFD	Computational Fluid Dynamics
CFSR	Climate Forecast System Reanalysis
CHS	Canadian Hydrographic Service
CIS	Canadian Ice Service
CTD	Conductivity Temperature Depth
DFO	Department of Fisheries and Oceans
DOF	Degrees of Freedom
DPR	Daily Progress Reports
DTM	Digital Terrain Model
E.GSL	East Gulf St. Lawrence
E.NF-Off	East Newfoundland Shelf (Offshore)
ECCC-ASITS	Environment and Climate Change Canada Automated Sea Ice Tracking System
ECMWF	European Centre for Medium-Range Weather Forecasts
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
ESRI	Economic and Social Research Institute
EWLR	Extreme Water Level Range
FEED	Front End Engineering Design
FLS	Fatigue Limit State
FOWT	Floating Offshore Wind Turbines
GEBCO	General Bathymetric Chart of the Ocean

GIS	Graphical Information System
GOCDP	Global Ocean Currents Data Portal
GOFS	Global Ocean Forecasting System
HAT	Highest Astronomical Tide
HYCOM	Hybrid Coordinate Ocean Model
ICDC	Integrated Climate Data Center
IHO	International Hydrographic Organization
IPS	Ice Profiler Sonar
LAT	Lowest Astronomical Tide
LCOE	Levelized Cost of Energy
LED	Light Emitting Diode
LiDAR	Light Imaging Detection, and Ranging
M.LAB-In	Mid Labrador Shelf (Inshore)
M.LAB-Off	Mid Labrador shelf (Offshore)
MBES	Multibeam echosounder
MCS	Monte-Carlo-Simulations
MEDIN	Marine Environmental Data Information Network
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLWN	Mean Low Water Neap
MLWS	Mean Low Water Spring
MNR	Mean Neap Range
MSC	Meteorological Service Canada
MSL	Mean Sea Level
MSR	Mean Spring Range
NARR	North American Regional Reanalysis

NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NE.GSL	Northeast Gulf St. Lawrence
NE.NF-In	Northeast Newfoundland Shelf (Inshore)
NESS	Nalcor Energy Exploration Strategy System
NIC	National Ice Center
NOAA	National Oceanic and Atmospheric Administration
NOAA GFS	National Oceanic and Atmospheric Administration – Global Forecasting System
NONNA	Non-Navigational
NWLR	Normal Water Level Range
O&M	Operations and Maintenance
OSS	Offshore Substation
OWF	Offshore Wind Farm
PIRAM	Pipeline Ice Risk Assessment and Mitigation
PSU	Practical Salinity Unit
QA	Quality Assurance
QC	Quality Control
QHSE	Quality, Health and Safety, Environment
RCM	RADARSAT Constellation Mission
S.LAB-In	South Labrador Shelf (Inshore)
S.LAB-Off	South Labrador Shelf (Offshore)
SAR	Synthetic Aperture Radar
SBES	Single beam echosounder
SIM	Sea Ice Motion
SONAR	Sound Navigation and Ranging
SSS	Sub Scan Sonar

T&I	Transportation and Installation
THU	Total Horizontal Uncertainty
TOR	Term of Reference
TVU	Total Vertical Uncertainty
ULS	Ultimate Limit State
W.GSL	West Gulf St. Lawrence
WMO	World Meteorological Organization
WOD	World Ocean Database
WRF	Weather Research and Forecast Model
WTG	Wind Turbine Generator
WW3	WAVEWATCH III

1. Introduction

GDG and ASL have been commissioned by the Client to conduct a metocean study in Canada, with a specific emphasis on the metocean attributes of Atlantic Canada. The study aims to identify the key metocean variables that are required to aid offshore wind development in the region. It focuses specifically on the conditions that are unique to Atlantic Canada, including factors such as freezing spray, sea ice, interactions between wind, waves, and ice, and extreme weather events. The proposed area of interest is located along the coasts of Newfoundland, Labrador, and Nova Scotia, as shown in Figure 1-1.

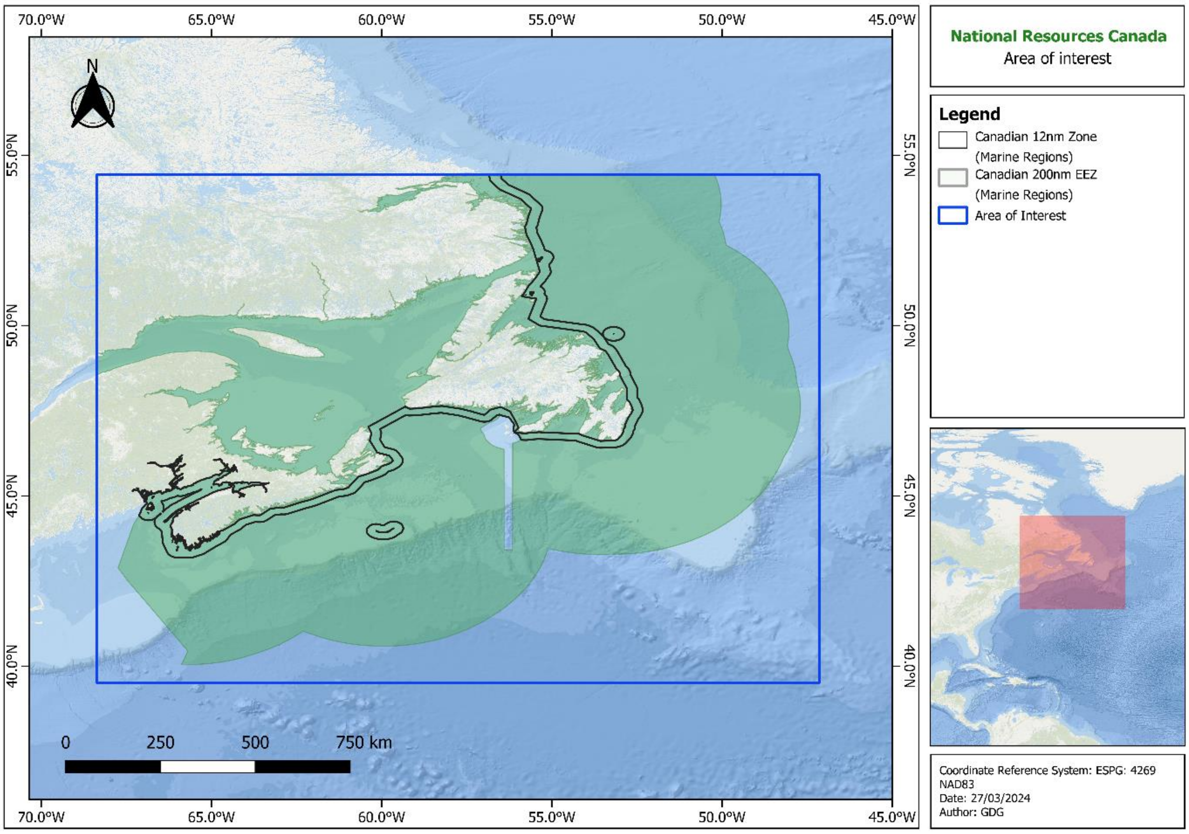

Figure 1-1 - Atlantic Canada Region and Area of Interest

1.1 Description of the Project

The area of interest covers an approximate area of 2654890 km² (including land), the boundary coordinates are provided in Table 1-1.

Table 1-1 - Area of Interest Coordinates

Location	Latitude	Longitude
Northwest	54.4315° N	68.3687° W
Northeast	54.4315° N	47.1438° W
Southwest	39.5023° N	68.3687° W
Southeast	39.5023° N	47.1438° W

Offshore wind in the Atlantic Canada region is currently at an early stage of development.

Canada, Nova Scotia and Newfoundland and Labrador see offshore wind energy as providing an important pathway to support the decarbonization of their electricity systems and to produce hydrogen. Considerable work is underway to establish a strong foundation for Canada's future offshore wind energy industry, including:

- Amending the Accord Acts to expand the existing joint management regimes for offshore petroleum to include offshore renewable energy
- The development of offshore renewable energy regulations
- Regional Assessments of offshore wind development in Nova Scotia and Newfoundland and Labrador, which will examine potential effects of projects, propose mitigation measures and suggest suitable areas for offshore wind development; and
- Investments in science-based activities to better understand and de-risk optimal areas for future development.

This initiative aims to facilitate the responsible deployment of offshore wind technologies in Canada, considering economic, environmental, and social factors. Understanding the crucial meteorological and oceanic (metocean) conditions for both existing and emerging offshore wind technologies is essential. As a result, GDG has been tasked with compiling the necessary documentation for this purpose.

1.2 SCOPE OF REPORT

The scope of work involved the identification of metocean phenomena and variables relevant to developing Offshore Wind Farms through all stages of their life cycle. The following environmental categories were investigated:

- Atmospheric conditions
- Marine conditions
- Extreme weather conditions
- Bathymetry
- Sea ice, icebergs, and freezing spray

The following work packages (WP) have been conducted in accordance with the procedures and guidelines set out in the relevant standards and recommended practices:

Work Packages:

1) Work package 1 (WP1) is to develop a comprehensive list of metocean data required to support offshore wind in Atlantic Canada.
2) Work package 2 (WP2) is split into two tasks:
   a) Identify key data sources, both modelled and measured, which can provide the parameters listed in Work Package 1.
   b) Perform a gap analysis by comparing existing data holdings with the necessary data for the successful implementation of offshore wind projects.
3) Work package 3 (WP3) is split into two tasks:
   a) Provide recommendations for collecting new metocean data as efficiently and accurately as possible within priority areas in Atlantic Canada identified by NRCan, including instrumentation, collection techniques, QA/QC techniques, and timelines.
   b) Identify data collection activities that should ideally be conducted before issuing a call for bids in a specific area, prioritizing them based on the potential risks to offshore wind developers.

Under each work package, we acknowledge the metocean parameters required for the full lifecycle of the Offshore Wind Farm, including:

a) Planning
b) Design
c) Transport and Installation
d) Operation and Maintenance
e) Decommissioning

2. WP1: METOCEAN PHENOMENA

The following work package documents a list of the various measured and derived metocean variables required to support the development of Offshore Wind Farms in the Atlantic Canada region. In accordance with the scope of this study, and recommendations provided by DNV GL (DNV, 2018), metocean site conditions affecting the design of offshore wind turbine structures and related components have been identified.

Figure 2-1 shows an overview of the process of producing metocean parameters according to ISO (2015b).

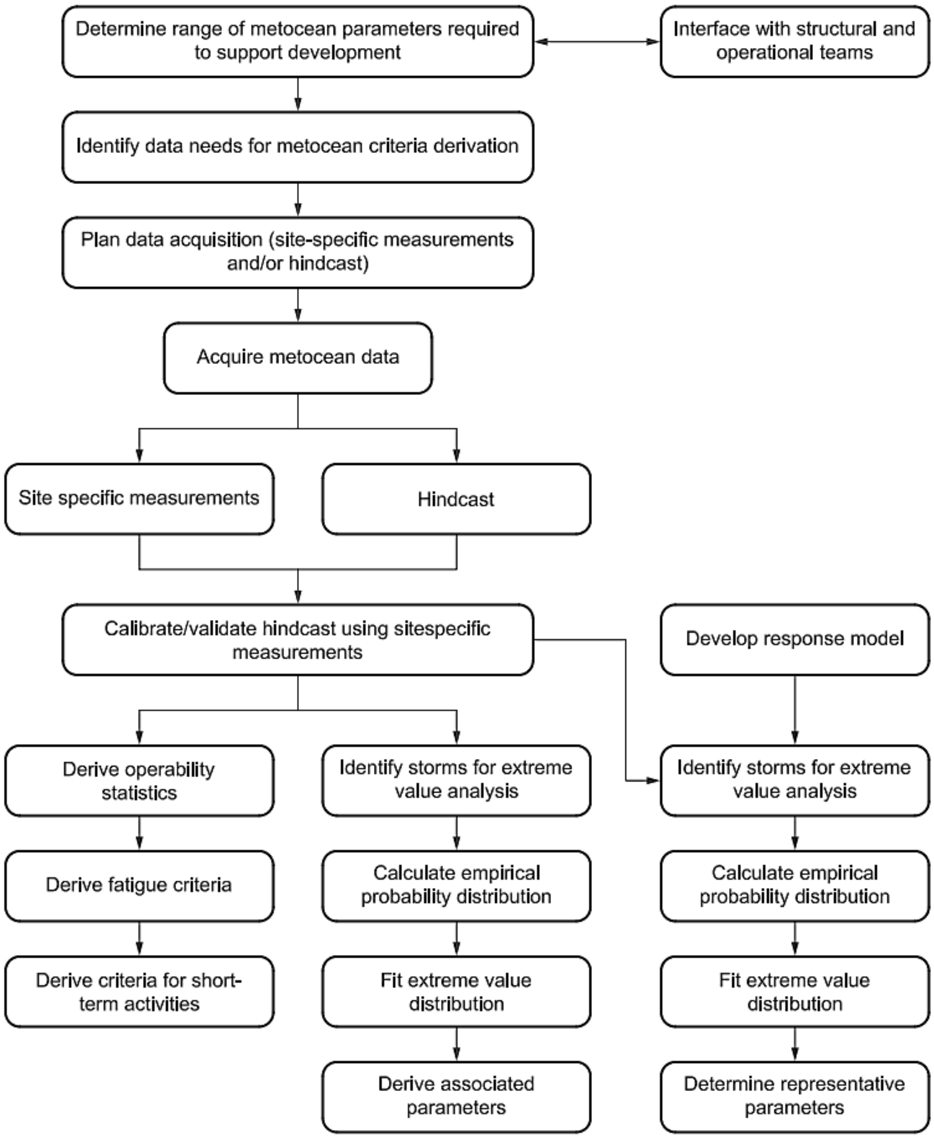

Figure 2-1 – Overview of the process of producing metocean parameters (ISO, 2015b)

In Table 2-1 a list of the identified metocean parameters is shown. The table provides the variable name, category, description, unit, notation, an indication of the type of organization that is recommended to collect the data (developer or regulator), relevant standards and best practice guidelines, and project stages and analyses in which they will be utilized.

Table 2-1 - Metocean variables and phenomena (Work Package 1)

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Atmospheric	Wind Speed (1-min, 10-min and 1-hour average)	(m/s)	(U_1, U_{10}, U_{1hr})	Regulator / Developer	DNV-RP-C205 (DNV, 2021a), DNV-ST-0437 (DNV, 2016c), IEC 61400-1 (IEC, 2019a) IEC 61400-3 (IEC, 2019b), IEC 61400-12 (IEC, 2022a), ISO 19901-1 (ISO, 2015b), ISO 9001 (ISO, 2015c), ISO 14001 (ISO, 2015a)	The wind speeds that are typically required are the 1-minute, 10-minutes and 1-hour mean wind speeds (U_1, $U_{10,}$ U_{1hr}) at height 10 m and standard deviation (σ_U) at height 10 m. Scaling is typically conducted to extrapolate wind speeds to hub height. Wind speeds here are not intended to cover wind conditions experienced in tropical storms. Moreover, wind data collection campaigns should employ Lidar equipment at various reference heights to ensure accurate recordings, particularly at hub height. This approach eliminates the necessity for scaling or extrapolation and facilitates precise measurement of both wind shear profile and hub height wind speeds.	All	Resource assessment, Wind loading, WTG selection, Structural engineering, AEP calculation, O&M / T&I weather limitation
Atmospheric	Wind speed vertical profile	(m/s m)	U(z)	Developer	IEC 61400-3 (IEC, 2019b)	The wind speed vertical profile represents the variation of the mean wind speed with height above the ground or above the still water level, whichever is applicable. Initially, various theoretical models are commonly employed, contingent upon the terrain and surface roughness below. However, at later development stages, greater precision is essential. Ideally, this is achieved through direct measurement using Lidar or met-mast instrumentation.	All	Resource assessment, Wind loading, WTG Selection, Structural Engineering, AEP calculation. O&M / T&I weather limitation
Atmospheric	Wind Shear	(m/s/km)	(S)	Developer	IEC 61400-3 (IEC, 2019b)	Wind shear describes the changes in wind speed and direction either vertically with altitude or horizontally over distances in the atmosphere. In essence, it signifies how wind varies when moving upward or across the atmosphere. It also represents the dynamic fluctuations of wind in the atmosphere. Understanding wind shear is crucial for forecasting and addressing various weather and aviation challenges.	Planning, Design	Resource assessment, Power curve determination WTG selection, Structural Design; wind loading - ULS/ALS/FLS, AEP calculation

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Atmospheric	Ambient turbulence intensity	(%)	(TI)	Developer	IEC 61400-3 (IEC, 2019b) IEC 61400-1 (IEC, 2019a)	Turbulence intensity represents the degree of turbulence or turbulence strength that is naturally present in the atmosphere without any specific or localized sources of turbulence.	Design	Resource assessment, wind loading, WTG Selection, Structural Engineering, AEP calculation
Atmospheric	Turbulence	NA	(T)	Developer	IEC 61400-3 (IEC, 2019b)	Turbulence represents the irregular and chaotic motion of air. It is characterized by sudden changes in wind speed and direction, resulting in an unstable or turbulent flow.	Planning, Design	Resource assessment, Wind loading, WTG Selection, AEP calculation
Atmospheric	Air density	(kg /m³)	(ρ), $\rho_{(\theta mean,year)}$	Developer	IEC 61400-3 (IEC, 2019b)	Air density represents how much mass is present in a given volume of air and is influenced by temperature and pressure. It plays a significant role in various scientific and practical contexts, particularly in areas where the behaviour of air is a critical factor.	Planning, Design	Resource assessment, wind loading, WTG Selection, structural engineering, AEP calculation
Atmospheric	Air humidity	(%)	(RH)	Developer	IEC 61400-3 (IEC, 2019b)	Relative humidity represents the amount of water vapor in the air relative to its maximum capacity at a given temperature. Although it's a secondary factor, higher relative humidity can reduce air density, potentially impacting wind farm output.	Planning, Design	Resource assessment, wind loading, WTG Selection, Structural Engineering, AEP calculation
Atmospheric	Wind Direction	(degrees)	(N,E,W,S)	Regulator / Developer	IEC 61400-3 (IEC, 2019b)	Wind direction represents the compass direction from which the wind is blowing. Wind direction has a significant impact on the operation and efficiency of a Wind Farm. The orientation of wind turbines and the prevailing wind direction are crucial factors in the design, layout, and performance of wind farms.	All	Resource assessment, wind loading, WTG Selection, Structural Engineering, AEP calculation. O&M / T&I weather limitation

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Wave	Significant wave height	(m)	Hs, Hm0	Regulator / Developer	DNV-RP-C205 (DNV, 2021a), DNV-ST-0437 (DNV, 2016c),	It is a statistical measure of the height of waves in a sea state. It is defined as either the average height of the highest one third of the zero up-crossing waves or as 4 times the standard deviation of the sea surface elevation. It is one of the parameters used to describe a wave climate and is typically represented over a short-term period, i.e., over a 3-hour or 6-hour period. During these times, stationary wave conditions with a constant Hs and constant Tp are assumed to prevail.	Preliminary design, detailed design, T&I, O&M, Decommissioning	Structural design; ULS/FLS/ALS Transportation and installation of equipment, turbines, piles, cables and secondary structures (O&M / T&I weather limitation) Operations and maintenance Ground investigation campaign planning
Wave	Significant wave height of wind generated waves and swell	(m)	$Hs = Hs_{wind} + Hs_{swell}$	Regulator/ Developer	DNV-RP-C205 (DNV, 2021a), DNV-ST-0437 (DNV, 2016c),	Significant wave height including the contributions from wind generated waves and swell is one of the parameters used to describe a wave climate and is typically represented over a short-term period, i.e., over a 3-hour or 6-hour period. During these times, stationary wave conditions with a constant Hs and Tp are assumed to prevail. Wind seas are generated by local wind, while swell have no relationship to the local wind.	Preliminary design, detailed design, T&I , O&M, Decommissioning	Structural design; ULS/FLS/ALS Transportation and installation of equipment, turbines, piles, cables and secondary structures (O&M / T&I weather limitation) Operations and maintenance Ground investigation campaign planning
Wave	Wave direction	(deg)	β	Regulator /Developer	DNV-RP-C205 (DNV, 2021a), DNV-ST-0437 (DNV, 2016c),	The wave direction variable describes the direction in which the wave is propagating.	Preliminary design, detailed design, T&I, O&M	Structural design; ULS/FLS/ALS Ground investigation campaign planning
Wave	Maximum individual wave height	(m)	Hmax	Developer	DNV-RP-C205 (DNV, 2021a), DNV-ST-0437 (DNV, 2016c),	The maximum individual wave height refers to the vertical distance between the peak and trough of a single zero up-crossing wave over a specified period. This measurement is often derived from historical wave data.	Preliminary design, detailed design, T&I , O&M, Decommissioning	Structural design; ULS/FLS/ALS

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Wave	Peak wave period	(s)	T_p	Regulator / Developer	DNV-RP-C205 (DNV, 2021a), DNV-ST-0437 (DNV, 2016c), ISO 19901-1 (ISO, 2015b)	The peak wave period, also known as the spectral peak period, refers to the duration associated with the highest energy in the wave spectrum. It's a key parameter in describing wave conditions. Typically, it's represented over short durations, such as 3-hour or 6-hour periods. During these times, stationary wave conditions with a constant significant wave height (Hs) and peak period (Tp) are assumed.	Preliminary design, detailed design, T&I , O&M, Decommissioning	Structural design; ULS/FLS/ALS Transportation and installation of equipment, turbines, piles, cables, and secondary structures (O&M / T&I weather limitation) Operations and maintenance Ground investigation campaign planning.
Wave	Combined significant wave height and peak wave period exceedance charts.	% (m, s)	(H_s, T_p)	Developer	DNV-ST-0437 (DNV, 2016c),	Exceedance charts that combine Hs (significant wave height) and Tp (peak wave period) graphically display the likelihood of particular Hs and Tp combinations happening at a specific location within a defined time frame.	Preliminary design, detailed design, T&I , O&M, Decommissioning	Structural design; ULS/FLS/ALS Transportation and installation of equipment, turbines, piles, cables, and secondary structures (O&M / T&I weather limitation) Operations and maintenance activities.
Wave	Wave breaking conditions	N/A	H_b	Developer	DNV-RP-C205 (DNV, 2021a)	Various factors determine whether a wave will reach its breaking point. The process that results in depth induced wave breaking is called shoaling. Typically, wavelength and water depth are utilized to ascertain the breaking wave height (Hb).	Preliminary design, detailed design	Wave breaking is mainly considered in the structural design of a fixed or floating offshore wind turbines. Wave breaking can lead to excessive impact/pressure forces on the turbine.
Wave	Wind and wave joint distribution	(m,s,m/s)	(Hs, Tp, U)	Developer	DNV-RP-C205 (DNV, 2021a)	Joint wind and wave distributions are a statistical representation of the joint probability of occurrence of various sets of waves (Hs and Tp) and wind speeds (U) at a certain location, and over a certain period of time. They are typically derived from historical wave data.	Preliminary design, detailed design, T&I , O&M, Decommissioning	Structural design; ULS/FLS/ALS Transportation and installation of equipment, turbines, piles, cables, and secondary structures

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
								(O&M / T&I weather limitation) Operations and maintenance activities
Wave	Wave spectra (Energy Spectra / Amplitude Spectra)	(m^2/Hz) and (m/Hz)	S(f), S(ω)	Developer	DNV-RP-C205 (DNV, 2021a), IEC 61400-3 (IEC, 2019b)	Wave spectra are tools used to pinpoint the energy densities of waves at a specific location. These spectra depict how energy is distributed across different frequencies, often derived from historical wave data or theoretical models. Wave spectra can be presented in tabular format, as directly measured data, or through a parameterized analytical formula based on theoretical models.	Preliminary design, detailed design, T&I , O&M, Decommissioning	Structural design: ULS/FLS/ALS Transportation and installation of equipment, turbines, piles, cables, and secondary structures (O&M / T&I weather limitation) Operations and maintenance activities
Water Level and Tides	Highest Astronomical Tide	(mMSL)	HAT	Regulator / Developer	IEC 61400-3 (IEC, 2019b)	HAT, or Highest Astronomical Tide, represents the highest water level anticipated to occur due to any combination of astronomical factors. It's typically measured in relation to the mean sea level (MSL) tidal benchmark. The values for both HAT and LAT (Lowest Astronomical Tide) are usually established by examining data over several years.	Preliminary design, detailed design	Structural design: ULS/FLS/ALS O&M / T&I weather limitation Substructure scour assessments and sediment transport
Water Level and Tides	Lowest Astronomical Tide	(mMSL)	LAT	Regulator / Developer	IEC 61400-3 (IEC, 2019b)	LAT, or Lowest Astronomical Tide, represents the lowest water level anticipated to occur due to any combination of astronomical factors. It's typically measured in relation to MSL. The values for both HAT and LAT are usually established by analysing data over several years.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Water Level and Tides	Mean high water springs	(mMSL)	MHWS	Developer	DNV-RP-C205 (DNV, 2021a)	MHWS refers to the average height of the high water level during spring tides. This variable is typically defined relative to MSL.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport
Water Level and Tides	Mean high water neaps	(mMSL)	MHWN	Developer	DNV-RP-C205 (DNV, 2021a)	MHWN refers to the average height of the high water level during neap tides. This variable is typically defined relative to MSL.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport
Water Level and Tides	Mean low water springs	(mMSL)	MLWS	Developer	DNV-RP-C205 (DNV, 2021a)	MLWS refers to the average height of the low water level during spring tides. This variable is typically defined relative to MSL.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport
Water Level and Tides	Mean low water neaps	(mMSL)	MLWN	Developer	DNV-RP-C205 (DNV, 2021a)	MLWN refers to the average height of the low water level during neap tides. This variable is typically defined relative to MSL.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport
Water Level and Tides	Mean spring range	+- (mMSL)	MNR	Developer	DNV-RP-C205 (DNV, 2021a)	The mean spring range represents the average difference in height between high water and low water observed during spring tides. This variable is typically defined relative to MSL.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport
Water Level and Tides	Mean neap range	+- (mMSL)	MNR	Developer	DNV-RP-C205 (DNV, 2021a)	The mean neap range represents the average difference in height between high water and low water observed during neap tides. This variable is typically defined relative to MSL.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Water Level and Tides	Mean Sea Level (MSL)	(m)	MSL	Regulator / Developer	IEC 61400-3 (IEC, 2019b)	MSL is described as the average level of the sea over a period of time long enough to remove variations due to waves, tides and storm surges. It is often defined as the average of HAT and LAT. It is a commonly used tidal datum.	All	Structural design; ULS/FLS/ALS Inter array and export cable engineering Geotechnical/Geophysical Analysis Installation operations and transportation
Currents	Depth-average current speeds	(m/s)	Vc_{Davg}	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	Current velocity varies with water depth. The depth-averaged current speed is a measure of the average velocity across the entire water column. The current velocity is taken as the sum of each current component, Vc(z) = Vc,wind(z) + Vc,tide(z) + Vc,circ(z)	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter-array and export cable crossing scour assessments Crew transfer planning ROV inspection
Currents	Depth-average current directions	(deg)	N/A	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	The direction in which the depth-averaged currents are moving.	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter array and export cable engineering ROV inspection
Currents	Bottom current speeds	(m/s)	Vc_{bot}	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	Current velocity varies with water depth. The bottom current speed is a measure of the velocity at the bottom of the water column. The current velocity is taken as the sum of each current component, Vc(z) = Vc,wind(z) + Vc,tide(z) + Vc,circ(z)	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter array and export cable engineering ROV inspection

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Currents	Bottom current directions	(deg)	N/A	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	The direction in which the bottom currents are moving.	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter array and export cable engineering ROV inspection
Currents	Surface current speeds	(m/s)	Vc_{surf}	Regulator / Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	Current velocity varies with water depth. The surface current speed is a measure of the velocity at the surface of the water column. The current velocity is taken as the sum of each current component, Vc(z) = Vc,wind(z) + Vc,tide(z) + Vc,circ(z)	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter array and export cable engineering ROV inspection
Currents	Surface current directions	(deg)	N/A	Regulator / Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	The direction in which the surface currents are moving.	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter array and export cable engineering ROV inspection
Currents	Mid current speeds	(m/s)	Vc_{mid}	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	Current velocity varies with water depth. The mid current speed is a measure of the velocity at the midpoint in water column. The current velocity is taken as the sum of each current component, Vc(z) = Vc,wind(z) + Vc,tide(z) + Vc,circ(z)	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter array and export cable engineering ROV inspection
Currents	Mid current directions	(deg)	N/A	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	The direction in which the mid currents are moving.	Preliminary design, detailed design, T&I and O&M	Structural design; ULS/FLS/ALS Substructure scour assessments and sediment transport Inter array and export cable engineering ROV inspection

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Temperature	Air Temperature	(°C) or (°F)	$\theta_{mean,year}$	Developer	IEC 61400-3 (IEC, 2019b), DNV-RP-C205 (DNV, 2021a) DNV-RP-0363 (DNV, 2021c)	Air temperature is a critical meteorological parameter that affects the air density, energy generation, and operational efficiency of wind farms. It also plays a role in the creation of wind patterns and influences the long-term durability of wind turbine components. Understanding temperature variations is essential for optimizing wind farm design and operation.	Preliminary design, detailed design, T&I , O&M	Resource assessment, WTG selection, Material selection, Maintenance planning. O&M / T&I weather limitation Brake system design
Temperature	Sea surface temperature	(°C) or (°F)	N/A	Developer	DNV-RP-C205 (DNV, 2021a) ISO 19901-1 (ISO, 2015b)	Sea surface temperature refers to the temperature of the water in the uppermost layer of the sea.	Preliminary design, detailed design, T&I , O&M	Structural design Material selection, Material selection and corrosion protection design Operations and maintenance planning ROV inspection
Temperature	Subsurface water temperature	(°C) or (°F)	N/A	Developer	DNV-RP-C205 (DNV, 2021a) ISO 19901-1 (ISO, 2015b)	Subsurface water temperature is the measure of the temperature of the sea water below the sea surface.	Preliminary design, detailed design, T&I , O&M	Structural design Material selection, Material selection and corrosion protection design Operations and maintenance planning ROV inspection
Salinity	Sea water salinity	(g/m³)	N/A	Developer	DNV-ST-0437 (DNV, 2016c) IEC 61300-1 (IEC, 2019a) IEC 61400-3 (IEC, 2019b) ISO 19901-1 (ISO, 2015b)	Sea water salinity is a measure of the salt content (g) dissolved in a kilogram (kg) of water.	Preliminary design and detailed design	Material selection and corrosion protection design Cable design; electrical conductivity, heat dissipation and cable insulation requirements. Design of cooling systems

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Solar Irradiance	Solar Irradiance	(W/m²)	I	Developer	IEC 61400-3 (IEC, 2019b)	Solar irradiance represents the amount of solar energy received at a specific location. While it doesn't directly affect the operation of wind farms, it plays a role in the broader energy landscape by influencing atmospheric conditions, temperature gradients, and wind patterns. Understanding solar irradiance can help optimize the integration of wind and solar energy resources, particularly in regions where both are viable sources of renewable energy.	Planning, Design,	Resource assessment, Material selection, Maintenance planning
Precipitation	Rainfall	(mm)	N/A	Developer	IEC 61400-3 (IEC, 2019b)	The amount of rain which has fallen in an area over a specific period of time.	Design, T&I, O&M	Material selection, Consideration of freezing rain, drizzle or wet snow Installation; visibility concerns Ice accretion considerations
Precipitation	Sleet	N/A	N/A	Developer	IEC 61400-3 (IEC, 2019b)	Sleet is described as a mixture of rain and snow.	Design, T&I, O&M	Material selection Ice accretion calculations
Precipitation	Snowfall	(mm/m)	N/A	Developer	IEC 61400-3 (IEC, 2019b)	The amount of snowfall in an area over a specific period of time.	Preliminary design and detailed design	Structural design; ULS/ALS Material selection, Resource assessment Power curve assessment Ice accretion considerations
Extreme Weather Events	Extreme wind speeds (10-minute and 3-second (gust) averages) for specified recurrence periods	(m/s)	V	Developer	IEC 61400-3 (IEC, 2019b)	The extreme wind speeds (10-minute and 3-second (gust) averages) describe the maximum respective wind speeds in a particular location within a specified return period. It is typically derived from historical wind data and hindcasting. Gusts are sudden brief increases in wind speed, characterised by a duration of less than 20 seconds, and follow by a lull or slackening in the wind speed.	Preliminary design and detailed design	Structural design: ULS/ALS

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Extreme Weather Events	Extreme joint probability of wind, wave and currents	(m/s, m, s, m/s)	U, Hs, Tp, V	Developer	IEC 61400-3 (IEC, 2019b)	The extreme joint probability of wind, wave and currents is statistical representation of the joint probability of specific sets of these environmental conditions occurring at once at a certain location for a specified recurrence period. They are typically derived from historical wave, wind and current data and numerical hindcasting. In various design load cases the wind speeds at hub height (U_{hub}) are required for analysis.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme wind shear and wind profile	(m/s/m) and (m/s)	EWS and U(z)	Developer	IEC 61400-3 (IEC, 2019b) IEC 61400-1 (IEC, 2019a) DNV-ST-0437 (DNV, 2016c)	Extreme wind shear and wind profiles represent rapid and significant changes in wind speed and direction. In the context of wind farms, they can affect turbine performance, turbine life, and the overall efficiency of the wind farm. Proper planning, design, and operational adjustments are necessary to address the challenges posed by extreme wind shear.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme turbulence intensity and standard deviation	(%)	σ_{ETM}	Developer	IEC 61400-3 (IEC, 2019b) IEC 61400-1 (IEC, 2019a) DNV-ST-0437 (DNV, 2016c)	The extreme turbulence intensity is a measure of the maximum variability in the wind speed and direction in a particular location within a specified return period. It represents the standard deviation of the wind speed divided by the mean wind speed, multiplied by 100. The standard deviation is a measure of the variability of the wind speed about the mean.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme deterministic wind or wave events, such as extreme gust events and extreme direction change events	(m/s) (deg)	EOC and EDC	Developer	IEC 61400-3 (IEC, 2019b)	Extreme deterministic wind/wave events are unique sets of wind and/or wave conditions representing a particular design scenario set out in Extreme Sea State (ESS) design load cases (See IEC 61400-3-1).	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Tidal variations and/or storm surge for specified recurrence periods (1-,10-, 50-year)	(mMSL)	N/A	Developer	DNV-RP-C205 (DNV, 2021a), ISO 19901-1 (ISO, 2015b) IEC 61400-3 (IEC, 2019b)	Extreme tidal variations and/or storm surge represents the extreme variations in water level due to storm surge. It is typically derived from long term historical tidal data and hindcasting. Storm surge includes wind- and pressure-induced effects. Generation of surge contributions is unrelated to tides and should be modelled as separate random processes to be imposed on tidal variations.	Preliminary design and detailed design	Structural design: ULS/ALS

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Extreme Weather Events	HSWL for specified recurrence periods (1-,10-, 50-, 100-year)	(mMSL)	$HSWL_1$, $HSWL_{10}$, $HSWL_{50}$, $HSWL_{100}$	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c), DNV-RP-C205 (DNV, 2021a)	The extreme highest still water level is described as the combination of the highest astronomical tide (HAT) and the 50-year positive storm surge. According to DNV-RP-C205, alternatively the extreme water level may be based on joint probability of occurrence of tide, storm surge, and wave crest.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	LSWL for specified recurrence periods (1-,10-, 50-, 100-year)	(mMSL)	$LSWL_1$, $LSWL_{10}$, $LSWL_{50}$, $LSWL_{100}$	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c), DNV-RP-C205 (DNV, 2021a)	The extreme lowest still water level is described as the combination of the lowest astronomical tide (LAT) and the 50-year negative storm surge. According to DNV-RP-C205, alternatively the extreme water level may be based on joint probability of occurrence of tide, storm surge, and wave crest.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Significant wave height for specified recurrence periods (1-,10-, 50-, 100-year)	(m)	H_{s1}, H_{s10}, H_{s50}, H_{s100}	Developer	DNV-RP-C205 (DNV, 2021a) DNV-ST-0437 (DNV, 2016c)	The extreme significant wave height is used to describe the maximum significant wave height that can be expected in a particular location within a specified return period. It is typically derived from hindcast wave data and statistical forecasting.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Peak wave periods for specified recurrence periods (1-,10-, 50-, 100-year)	(s)	T_{p1}, T_{p10}, T_{p50}, T_{p100}	Developer	DNV-RP-C205 (DNV, 2021a) DNV-ST-0437 (DNV, 2016c)	The extreme peak wave period is used to describe the range of peak wave periods that can be expected in a particular location within a specified return period. It is typically derived from hindcast wave data and statistical forecasting.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme individual wave height for specified recurrence periods (1-,10-, 50-, 100-year)	(m)	H_1, H_{10}, H_{50}, H_{100}	Developer	IEC 61400-3 (IEC, 2019b) DNV-RP-C205 (DNV, 2021a) DNV-ST-0437 (DNV, 2016c)	The extreme individual wave height is used to describe the maximum individual wave height that can be expected in a particular location within a specified return period. It is typically derived from hindcast wave data and statistical forecasting.	Preliminary design and detailed design	Structural design: ULS/ALS

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Extreme Weather Events	Range of associated wave periods for specified recurrence periods (1-,10-, 50-, 100-year)	(s)	Thmax	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c)	The extreme range of wave periods is used to describe the range of most probable wave period associated with the extreme individual wave height that can be expected in a particular location within a specified return period. It is typically derived from historical wave data and hindcasting.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme crest height for specified recurrence periods (1-,10-, 50-, 100-year)	(m)	H_C	Developer	DNV-RP-C205 (DNV, 2021a) DNV-ST-0437 (DNV, 2016c)	The extreme wave crest height is used to describe the maximum wave crest height that can be expected in a particular location within a specified return period. It is typically derived from historical wave data and hindcasting. It may also be derived empirically from extreme individual wave height for a specified recurrence period.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme sea surface current for specified recurrence periods (1-,10-, 50-, 100-year)	(m/s)	V_1, V_{10}, V_{50}, V_{100}	Developer	IEC 61400-3 (IEC, 2019b)	The extreme sea surface currents describe the maximum surface current speeds to be expected in a particular location within a specified return period. It is typically derived from historical current data and hindcasting.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Joint wind and wave distributions	(m, s)	(Hs,Tp, U)	Developer	DNV-RP-C205 (DNV, 2021a)	The extreme joint wind and wave distributions are a statistical representation of the joint probability of extreme occurrence of various sets of waves (Hs and Tp) and wind speeds (U) at a certain location for a specified recurrence period. It is typically derived from historical wave and wind data and hindcasting. In various design load cases the wind speeds at hub height (U_{hub}) are required for analysis. Input data to design would typically come in the form of scatter diagrams.	Preliminary and detailed design	Structural design: ULS/ALS

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Extreme Weather Events	Wind-wave misalignment	(deg)	COD/UNI/MUL/MIS	Developer	DNV-ST-0437 (DNV, 2016c) DNV-RP-C205 (DNV, 2021a)	Wind-wave misalignment is a phenomenon that occurs when the wind and wave directions are not aligned. DNV-ST-0437 lists several abbreviations used to describe the misalignment conditions used in the design load cases for offshore wind turbines, they are: COD = Co-directional, UNI = Unidirectional, MUL = Multi-directional, MIS = Misaligned. Extreme wind-wave misalignment is typically obtained from historical wind and wave data, and hindcasting.	Preliminary and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme Wave spectra (Energy Spectra / Amplitude Spectra)	(m^2/Hz) and (m/Hz)	S(f), S(ω)	Developer	DNV-RP-C205 (DNV, 2021a)	Wave spectra are used to identify the energy densities of waves in a particular location. It describes the wave energy distributions in the frequency domain and are typically derived from historical data, hindcasting and/or theoretical models. Wave spectra may be given in table form, as measured spectra, or by a parameterised analytic formula (theoretical model). The extreme wave energy spectra are associated with extreme significant wave heights and peak wave periods.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Potential for breaking waves, type and parameters	(m)	Hb	Developer	DNV-RP-C205 (DNV, 2021a)	Numerous variables are used to describe whether a wave will exceed its breaking limit. The phenomenon leading to wave breaking is known as shoaling, and commonly the wavelength and water depth are used to determine the breaking wave height (Hb). In extreme weather events, a developer would typically need to consider the potential for breaking waves under extreme wave and water level conditions in order to study the impact that breaking waves can have on the structures.	Preliminary design and detailed design	Structural design: ULS/ALS
Extreme Weather Events	Extreme air and sea temperatures including minimum and maximum ambient temperature to be expected in hourly average (recurrence period 1 year)	Degrees Celcius (°C) or Farenheit (°F)	θ1year,min θ1year,max	Developer	DNV-RP-0363 (DNV, 2021c)	Extreme air and sea temperatures are the average air and sea temperatures expected in a certain area within a specific return period. Extreme temperatures can affect turbine performance, material fatigue, risk of ice formation, thermal expansion, and cooling systems.	Preliminary design and detailed design	Structural design: FLS/ULS/ALS, Load calculations - consideration of air density variations. Material selection Cooling system design,

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Extreme Weather Events	Extreme air density associated with extreme minimum ambient air temperature to be expected in hourly average (recurrence period of 1-year)	(kg/m³)	ρ(θ1year, min)	Developer	DNV-RP-0363 (DNV, 2021c)	The extreme air density is the density of the air whose temperature is equal to the extreme minimum ambient temperature. The minimum temperature is only considered, as the air density decreases in higher ambient air temperatures, where the loads are not expected to increase.	Preliminary design and detailed design	Structural design: FLS/ULS/ALS, load calculations
Tropical Cyclones	**Generic tropical cyclone parameters:** 1) No of tropical cyclones per year within a given area 2) Central pressure (Pc) 3) translation speed (C) 4) translation angle (q) 5) minimum distance (d_min) 6) Radius of maximum wind speed (R_m)	(Pa, m/s, deg, m, m)	Pc, C, q, $d_{min, Rm}$	Developer	IEC 61400-1 (IEC, 2019a), IEC 61400-3 (IEC, 2019b)	A tropical cyclone is described as a rapidly rotation storm system characterised by a low-pressure centre, a closed low-level atmospheric circulation, strong winds, and a spiral arrangement of thunderstorms that produce heavy rain and/or squalls, deriving its energy through the condensation of water vapor from the ocean surface; depending on its location and strength, it is referred to by different names, including hurricane, typhoon, tropical storm, cyclonic storm, tropical depression, cyclone. It's important to note that the specific impact of a cyclone on an Offshore Wind Farm will depend on factors like the storm's intensity, path, the design of the wind turbines, and the geographic location of the wind farm. Proper planning and risk management are essential to mitigate the potential effects of cyclones on offshore wind operations.	Preliminary design and detailed design	Structural design: ULS/ALS Material selection

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Tropical Cyclones	Extreme wave heights during tropical cyclones (50- and 100-year)	(m)	N/A	Developer	IEC 61400-3 (IEC, 2019b)	Annex H of the IEC 61400-3-1 standard states that in tropical or subtropical regions, where tropical cyclones play significant effect on extreme wave height these effects should be considered appropriately. The extreme wave height can be derived from either historical wave measurements or hindcasting techniques using third generation wave models such as WAVEWATCH III (WW3) or SWAN. According to TAP 672, synthetic hurricane modelling is needed to accurately estimate extreme event return period statistic at the upper most tail end of the statistical distributions.	Preliminary design and detailed design	Structural design: ULS/ALS Material selection
Tropical Cyclones	Extreme wind fields during tropical cyclones	N/A	N/A	Developer	IEC 61400-1 (IEC, 2019a) IEC 61400-3 (IEC, 2019b) TAP 672 (U.S. Bureau of Environmental Safety and Enforcement, 2014)	Parameters required to estimate wind fields in tropical cyclones according to IEC 61400-3: 1) r - Distance from the centre of the tropical cyclone (m), 2) P_c - Central pressure (Pa) 3) P_∞ Pressure outside the tropical cyclone (Pa) 4) R_m - Radius at the maximum wind speed (m/s) Furthermore, historical cyclone track data is required for wind field estimation using simulated cyclone tracks. Synthetic cyclone track methods are alternatives. The estimation of extreme wave and wind parameters for extratropical cyclones is similar to that of the tropical cyclones. According to TAP 672, synthetic hurricane modelling is needed to accurately estimate extreme event return period statistic at the upper most tail end of the statistical distributions.	Preliminary design and detailed design	Structural design: ULS/ALS Material selection

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Extratropical Cyclones	Extreme wind speeds (10-minute) for specified recurrence periods (50- and 100-years)	(m/s)	U_{50}, U_{100}	Developer	IEC 61400-1 (IEC, 2019a) IEC 61400-3 (IEC, 2019b) TAP 672 (U.S. Bureau of Environmental Safety and Enforcement, 2014)	The extreme wind speeds in extratropical cyclones require careful consideration of historical data and numerical hindcasting. The historical wind data should contain past extratropical storm events and be long enough to provide a good statistical representation of the phenomenon. Numerical hindcasting and extreme value analysis appear to the be the advised methodologies for predicting the extreme wind speeds in extratropical storms.	Preliminary design and detailed design	Structural design: ULS/ALS Material selection
Extratropical Cyclones	Extreme wave parameters (Hs, Tp) for specified recurrence periods (50- and 100-years)	(m,s)	Hs, Tp	Developer	IEC 61400-1 (IEC, 2019a) IEC 61400-3 (IEC, 2019b) TAP 672 (U.S. Bureau of Environmental Safety and Enforcement, 2014)	The estimation of extreme wave parameters for extratropical cyclones is similar to that of the tropical cyclones. Using historical wave data, estimations can be made using numerical hindcast models.	Preliminary design and detailed design	Structural design: ULS/ALS Material selection
Water Depth / Bathymetry	Water depth	(mMSL, mLAT)	N/A	D/R	IEC 61400-3 (IEC, 2019b) DNV-RP-C205 (DNV, 2021a) DNV-ST-0437 (DNV, 2016c) ISO 19901-1 (ISO, 2015b)	The water depth is defined as the distance between the sea surface and the seabed at a given location. The distance is typically measured from the mean sea level or lowest astronomical tide. The seabed slope or gradient is typically derived from bathymetry datasets.	All	Geotechnical/Geophysical analysis Inter array and export cable engineering Structural design: ULS/FLS/ALS Transportation and installation activities Substructure scour assessments and sediment transport

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Marine Growth	Growth thickness	(mm)	N/A	Developer	IEC 61400-3 (IEC, 2019b) DNV-ST-0437 (DNV, 2016c) ISO 19901-1 (ISO, 2015b)	Marine growth is described as the surface coating on structural components caused by plants, animals and bacteria. Marine growth can have several implications and effects on wind farms such as reduced efficiency, maintenance and repair costs, biofouling, additional mass and load issues. The thickness shall be assessed based on applicable recommendations, local experience and existing measurements. Site specific measurements may be necessary to determine the nature, likely thickness and depth dependencies of the marine growth.	Preliminary design and detailed design	Inter array and export cable engineering Structural design: ULS/FLS/ALS Material selection and biofouling protection
Marine Growth	Marine growth density	(kg/m³)	ρ_{mg}	Developer	DNV-ST-0437 (DNV, 2016c) ISO 19901-1 (ISO, 2015b)	The density of the marine growth can have an impact on the structural mass of the turbine.	Preliminary design and detailed design	Structural design; structural mass calculations, ULS/ALS/FLS
Marine Growth	Type	N/A	N/A	Developer	IEC 61400-3 (IEC, 2019b) ISO 19901-1 (ISO, 2015b)	Marine growth type represents the type of accumulation, such as marine organisms, such as algae, barnacles, mussels, and other marine life, on the submerged structures of offshore wind turbines and associated infrastructure. These structures can include the turbine foundations, support structures, and underwater cables. The type can have an effect on the structural mass, drag coefficients, coating requirements and maintenance schedules.	Preliminary design and detailed design	Inter array and export cable engineering Structural design: ULS/FLS/ALS Material selection and biofouling protection

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Water Density	Water density	(kg/m³)	ρ_w	Developer	IEC 61400-3 (IEC, 2019b)	Water density is a critical factor in the design, operation, and environmental impact of Offshore Wind Farms. Wind farm engineers and operators must consider variations in water density to ensure the stability and efficiency of their installations while minimizing environmental consequences.	Preliminary design and detailed design	Geotechnical/Geophysical analysis Inter array and export cable engineering Structural design: ULS/FLS/ALS Substructure scour assessments and sediment transport
Sea Ice	Ice flow thicknesses with a 50-year return period, extreme ice feature dimensions, ice strength coefficient, ice density, current speed 1m below ice keel, 10m surface winds, ice concentration frequencies, wind drag coefficient, current drag coefficient, horizontal ice loading, vertical ice forces, limit stress, limit force, limit energy	%, m, m/s, T, Pa, N/m2	C, t, v, D, V, $(u,v)10_m$, C_w, C_c, P	Developer	DNV-RP-0175 (DNV, 2021b); IEC 61400-3 (IEC, 2019b); WMO No. 259 (WMO, 2014) ISO 19906 (ISO, 2019)	Sea ice concentration (fraction of surface covered by ice), ice thickness and ice velocity data are the key parameters required to address the impacts of sea ice on the design of offshore wind platforms, including subsea cables, and as operational constraints for servicing the platforms. Specific ice thickness parameters include: sheet ice thickness (50 year return period) and dimensions of thick ice features (ridges; 50 year return period). These parameters will be required for computation of ice loads, according to the derived limit stress/force/energy values.	Preliminary design, detailed design, T&I	Structural design; ULS/FLS/ALS Inter array and export cable engineering

Category	Variable	Unit	Notation	Developer and / or Regulator	Reference Standard	Description	Development Stage	Analysis
Icebergs	Iceberg mass and volume, dimensions, velocity, groundings	kg, m^3, m, m/s	M, (x,y,z), v	Developer	. DNV-RP-0175 (DNV, 2021b) IEC 61400-3 (IEC, 2019b) WMO No. 259 (WMO, 2014) ISO 19906 (ISO, 2019)	Iceberg mass, dimensions, velocities and groundings data are the key parameters required to address the impacts of icebergs on the design of offshore wind platforms and subsea cables used for the platforms.	Preliminary design, detailed design	Structural design; ULS/FLS/ALS Inter array and export cable engineering
Freezing Spray and Ice Accretion	Freezing degree days, computed from: Wind Speed, Below-Freezing Temperature and Wind Generated Water Spray Concentrations, ice accretion rates	C° m/s, °C cm/hr	FDD, U, (0-Tair)	Developer	DNV-RP-0175 (DNV, 2021b) IEC 61400-3 (IEC, 2019b) WMO No. 259 (WMO, 2014) ISO 19906 (ISO, 2019)	Freezing Spray computations from marine meteorological data sets, as well as empirical methods for freezing spray will be considered for assessing the impacts of freezing spray on Structural Design and Support Operations. (Overland, J. E., 1990; Makkonen, L, Laasko, T, Marjaniemi, M and Finstad, K J, 2001)	Preliminary design, detailed design, T&I, O&M	Structural design; ULS/FLS/ALS Inter array and export cable engineering

3. WP2: METOCEAN DATA SOURCES

The primary need for a metocean site conditions assessment is to acquire reliable long-term datasets for calculating necessary parameters. This work package focuses on obtaining both measured and modelled datasets available within the study area.

At every stage of offshore wind farm (OWF) development, distinct metocean data needs arise, varying from general historical data for initial evaluations to site-specific real-time data essential for Transport and Installation (T&I) and Operations and Maintenance (O&M) tasks. The accuracy and resolution of the data typically increases as the project progresses from the conceptual phase to actual operations and maintenance. The duration of the required data typically varies depending on the development stage. In general, having access to longer-duration datasets and in-situ measurements is preferable over shorter-duration and nearby measurements. Overall, the period covered by the data should be long enough to represent the different meteorological phenomena and their temporal variability (DNV, 2018).

Taking into account the various stages of offshore wind farm development, below is an overview delineating the necessities for each phase:

(a) Planning:

- Early-stage data requirements include basic wind, wave, currents, and bathymetry data to assess the potential of the site or region.
- Data sources may include historical data, regional climate models, and satellite data.
- Data durations are typically 20+ years.
- The purpose is to conduct an initial assessment of an area's suitability for wind energy generation, and to understand long-term trends, seasonal variations, and extreme weather patterns.

(b) Preliminary and detailed design:

- Basic and site-specific data, high-resolution data for wind, waves, currents, and seabed conditions.
- Data sources may include historical data, regional and advanced models, satellite data, in-situ, or nearby measurements, using survey data and instrumentation.
- Data durations are typically 1-2 years of site-specific data collection. These datasets are typically used to calibrate and enhance regional numerical models that are then used to produce long-term datasets.
- The purpose is to provide a detailed understanding for engineering design, environmental impact assessments (EIA).

(c) Transportation and installation:

- Short-term, real-time data and historical data of wind, wave, currents, and weather forecasts.
- Data sources may include historical data, onsite monitoring systems, and short-term forecasting models.
- Data durations for real-time and short-term forecasts are generally daily and hourly data. Historical datasets for weather windows are typically 5-10 years, as they cover multiple seasonal cycles.
- The purpose is to provide safe and efficient scheduling of transport and construction activities and risk management.

(d) Operations and maintenance:

- Continuous analysis of wind and marine weather data for performance monitoring and maintenance planning.
- Data sources may include on-site instruments, and regional and short-term forecasts.
- Ongoing data collection activities may span the entire lifetime of the OWF.
- The purpose is to optimise power production, predict maintenance windows and ensure safety.

(e) Decommissioning stage:

- The requirements are similar to the T&I stage, focusing on the conditions required for safe removal.
- Data sources may include historical data, on-site monitoring systems, and short-term forecasting models.
- The purpose is to provide safe and efficient dismantling and removal of the infrastructure.

For the study area, numerous data sources have been identified for each of the respective variables identified in Work Package 1, a comprehensive list of these may be found in Appendix A. Several data sources have been pinpointed as particularly valuable for preliminary site condition and resource assessment studies. The objective was to identify sources offering sufficient temporal and spatial resolution and extent, meeting the requirements specified in Work Package 1. This section will delineate the key data sources identified, along with the findings of the gap analysis.

At this stage, essential environmental factors include wind, waves, currents, water levels and tides, bathymetry, and parameters related to ice. Additionally, extreme wave parameters play a crucial role in floating wind concept selection and could impact the viability of specific regions for Offshore Wind Farm installation. These parameters are not directly considered here as they can be derived from historical wave data. Overall, these metocean environmental factors are critical in assessing the feasibility, safety, and economic viability of offshore wind projects. The analysis of the metocean parameters guide decision making processes from the early stages and will inform on wind resources and weather window and downtime analysis, two important factors which help identify feasible regions for installing wind farms. It should be noted, however, that other factors such as seabed slope, seabed lithology, wind resource, distance to nearest grid infrastructure, areas of conservation, existing offshore infrastructure (oil, gas and renewable) and military exclusion zones should be considered during the zonation of Offshore Wind Farms. This list is non-exhaustive, and such considerations are beyond the scope of this report.

The aim of the gap analysis was to compare existing data holdings against required data for successful deployment of offshore wind.
After discussions with the Client, it was mutually agreed that the current water depths in part of the offshore area do not support the installation of offshore wind turbines using existing technologies. Therefore, the scope of the gap analysis will be limited by water depth to regions deemed feasible given the current technological and economical limitations.

It's important to note that for deeper areas (greater than -500 mLAT), the installation of floating offshore wind turbines poses significant technical challenges, such as increased engineering complexity and higher maintenance costs. These challenges can substantially escalate the overall project expenses, rendering installations in such depths economically unfeasible.

The area considered in the gap analysis will be limited to the sea area contained within the 200 nm exclusive economic zone and depths below -500 mLAT (Figure 3-1). This depth is considered with the possibility that floating wind turbine technologies may become economically competitive up to these depths in the future.

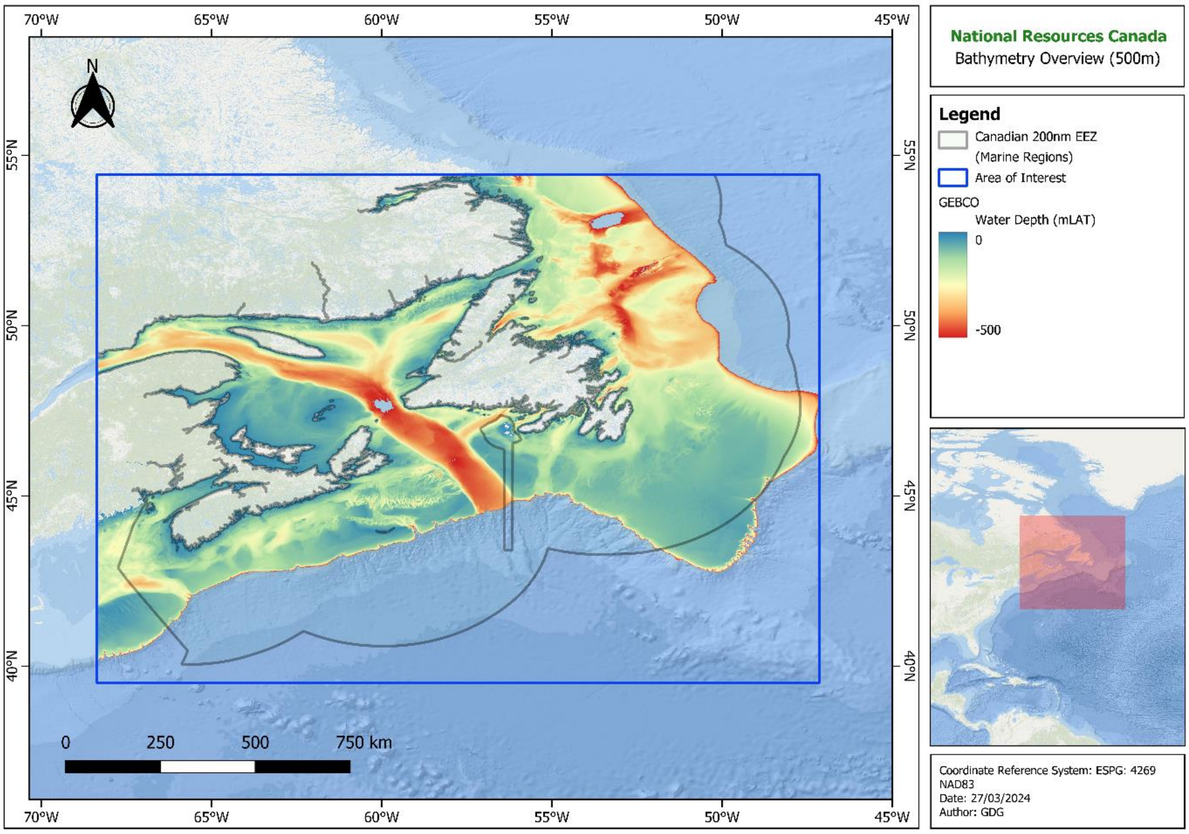

Figure 3-1 – GEBCO Bathymetry (<= -500 mLAT) (The General Bathymetric Chart of the Oceans (GEBCO), 2023)

3.1 WIND AND WAVE SOURCES

In the early stages of Offshore Wind Farm development, specifically during the pre-feasibility and feasibility stage, wind and wave data are of key importance for resource assessment and identifying areas suitable for WTG installation.

The main focus should be on key wind and wave variables, including wind speed and direction, significant wave height, wave direction, maximum wave height and peak wave period. These parameters may be used for pre-feasibility and feasibility studies by the Client, and for preliminary site conditions assessment and other studies thereafter by a developer. Most other wind and wave parameters may be derived from these primary variables.

At this stage of development, the following wind and wave sources were identified as most useful for the Client:

(a) Meteorological Service Canada (MSC) (Department of Fisheries and Oceans Canada, 2024), or Oceanweather Incorporated's GrowFab model. The MSC50 model provides both wind and wave variables across a 0.5 x 0.5-degree grid within the area of interest. The averaging period is 1-hour and has adequate temporal extent.

(b) The ERA5 model is a fifth-generation atmospheric reanalysis model produced by Copernicus Climate Change Service at ECMWF (European Centre for Medium-Range Weather Forecasts) (C3S, 2018). It provides a 0.5 x 0.5-degree wave grid and a 0.25 x 0.25-degree wind grid throughout the area of interest. The service provides 1-hour averaged data spanning several decades.

(c) The Department of Fisheries and Oceans (DFO) Canada offers wave and wind data collected from buoys stationed at different points across the area of interest (Department of Fisheries and Oceans Canada, 2024). The duration of these measurements varies, with some spanning multiple decades, although they may not be recent measurements. Depending on the location and the specific analysis to be conducted, these datasets could be utilized directly for site conditions assessment or for calibrating regional numerical models.

The MSC50 and DFO wave buoy datasets are illustrated in Figure 3-2, the colour of the DFO wave buoys represents the duration of the measurements at each buoy. In Figure 3-3, the ERA5 wind and wave datasets can be observed. Figure 3-2 displays a buffer zone with a radius of 0.5-degrees around the existing DFO datasets, which is roughly 55 kilometres, aiming to identity any gaps in the available physical measurements. It should be noted that in shallower coastal areas, the applicability of physical measurements is limited because coastal topological features affect wave hydrodynamics effects such as shoaling, reflections, diffraction and refraction are more influential in shallower coastal regions.

In a metocean climate study for the offshore Newfoundland & Labrador areas (C-CORE, 2017), C-CORE performed an investigation into the wind and wave conditions along the Newfoundland and Labrador offshore areas. C-CORE utilised the MSC50 datasets as their primary data source for these variables and discretised the region into a grid consisting of 1 x 1 degrees. The grid may be seen in Figure 3-4. Furthermore, the C-CORE study performed and extreme value analysis into the extreme wind and wave conditions across the grid.

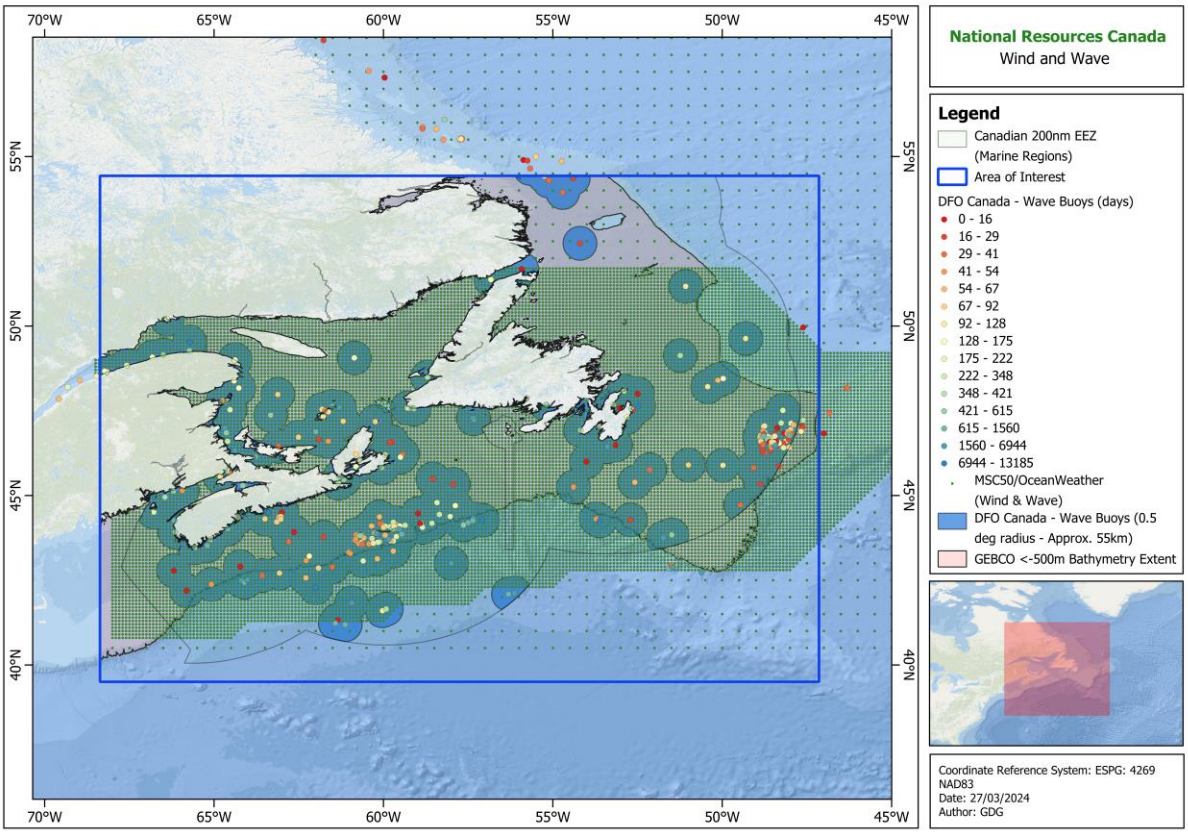

Figure 3-2 – Wind and Wave Overview

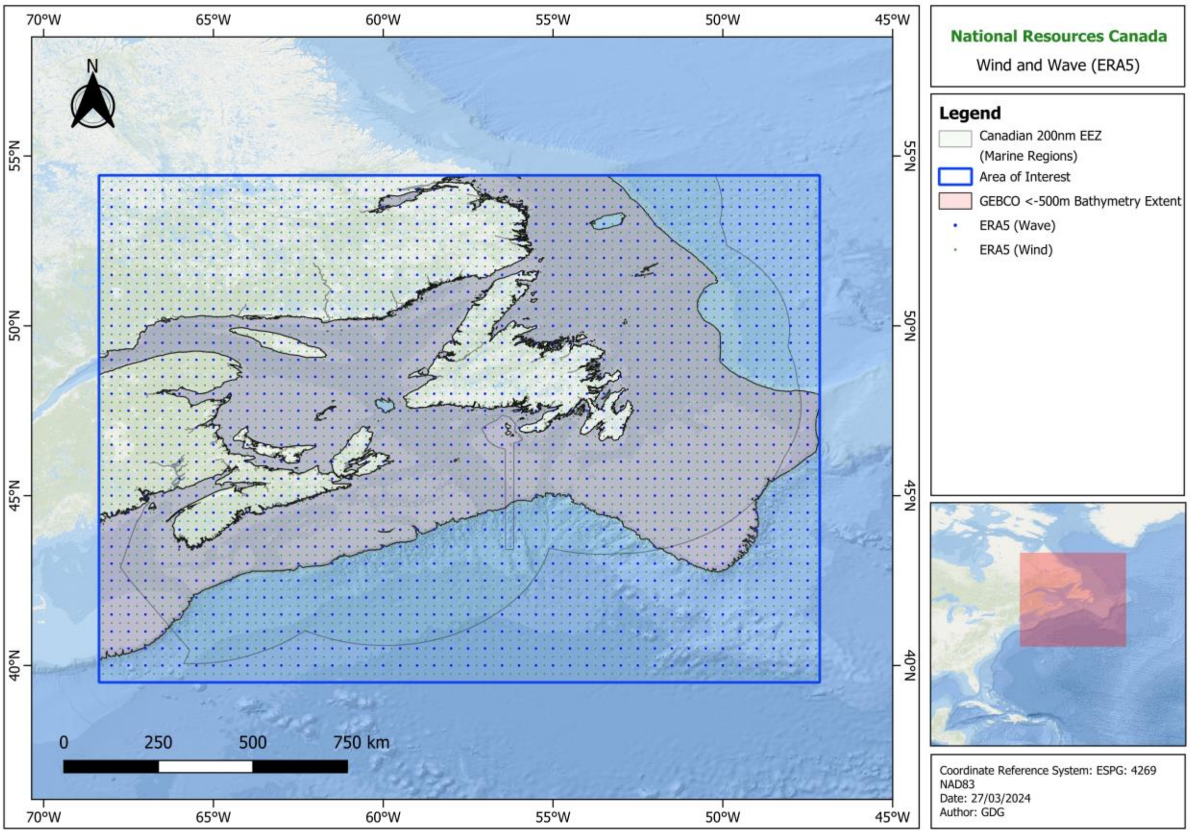

Figure 3-3 – Copernicus ERA5 wind and wave grid overview

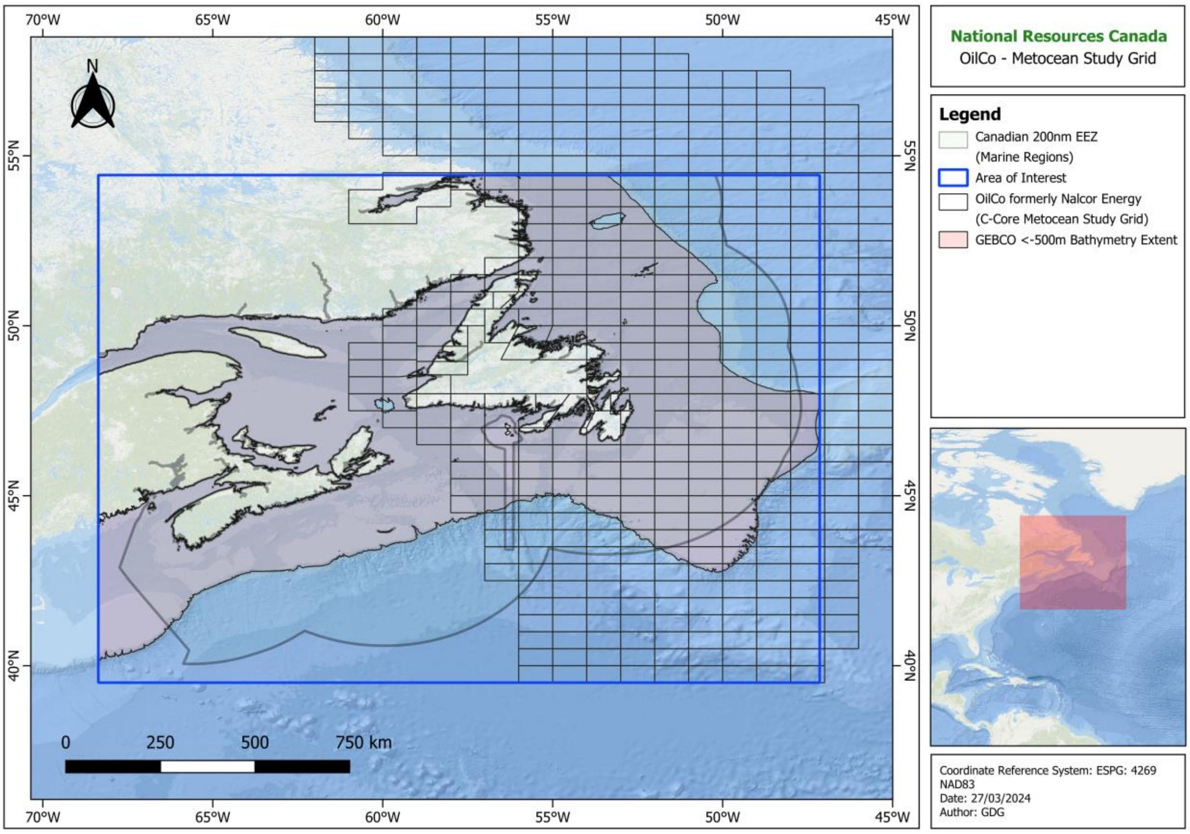

Figure 3-4 – OilCo Metocean Climate Study Grid (C-CORE) (C-CORE, 2017)

It can be seen from Figure 3-2 that the MSC50 datasets provide good spatial coverage in the central nearshore areas such as the Gulf of St. Lawrence, Newfoundland, Bay of Fundy and further offshore along the Grand Banks of Newfoundland. In addition, the ERA5 (Figure 3-3) dataset provides a lower spatial coverage outside of the high-resolution area covered by MSC50.

The DFO wave buoys provide some wind and wave datasets in specific locations throughout the area of interest. However, many of these buoys have data acquisitions of limited durations, as highlighted in Figure 3-2, which may not meet the requirements necessary for conducting metocean site assessments and other preliminary activities, depending on the development phase of the OWF.

Other notable wind data resources include the NCEP Climate Forecast System Reanalysis (CFSR) model (NCEI, 2024), Global Wind Atlas (Global Wind Atlas, 2024), and the NCEP North American Regional Reanalysis (NARR) model (NCEP, 2024)(Figure 3-5), all of which provide good spatial and temporal resolution in the area of interest. Although, the NARR model provides 3-hourly opposed to the 1-hour averaged data from ERA5 and MSC50.

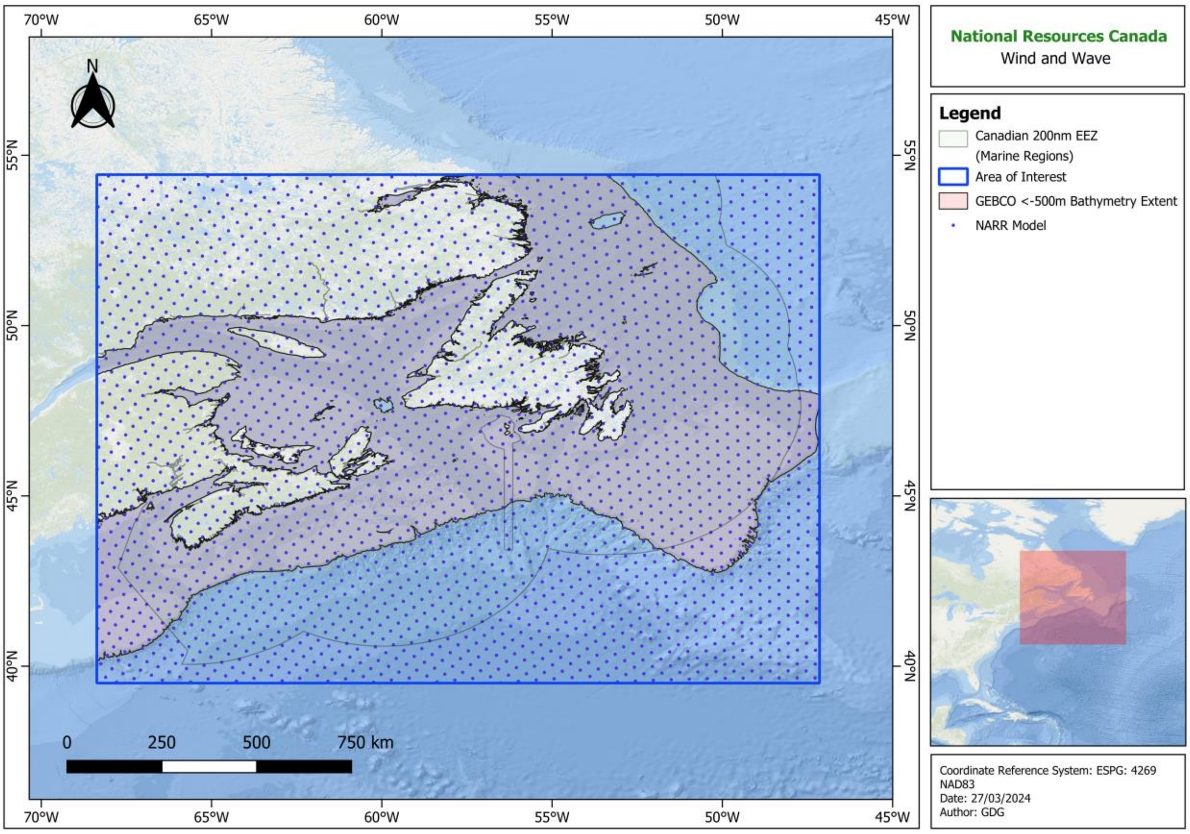

Figure 3-5 – North American Regional Reanalysis (NARR) Grid

In the wind and wave gap analysis, there is a notable level of good numerical data coverage, particularly in the nearshore areas and along most parts of the continental shelf, including the Grand Banks of Newfoundland. However, it is important to mention that within the continental shelf, specifically along the Labrador coastline, the data resolution is lower. This reduced resolution could affect the accuracy of metocean assessments in this region. Beyond the continental shelf, the waters are extremely deep, with depths reaching around 5.5 km, these levels of water depth pose significant technical and economic challenges for offshore wind development. Additionally, within the shelf, especially in areas with suitable depths along the Labrador coast, there is significant presence of ice-related phenomena throughout the year. These conditions make such areas less suitable for offshore wind developments due to increased risk and engineering challenges associated with ice.

3.2 OCEAN CURRENTS

The primary current variables that should be considered by the Client include the surface current speeds and directions. These variables may be utilised in feasibility studies to assess site conditions and accessibility, and weather window analyses for transportation and installation activities.

Figure 3-6 illustrates the mean surface currents in the Atlantic Canada region (ECCC, 2024).

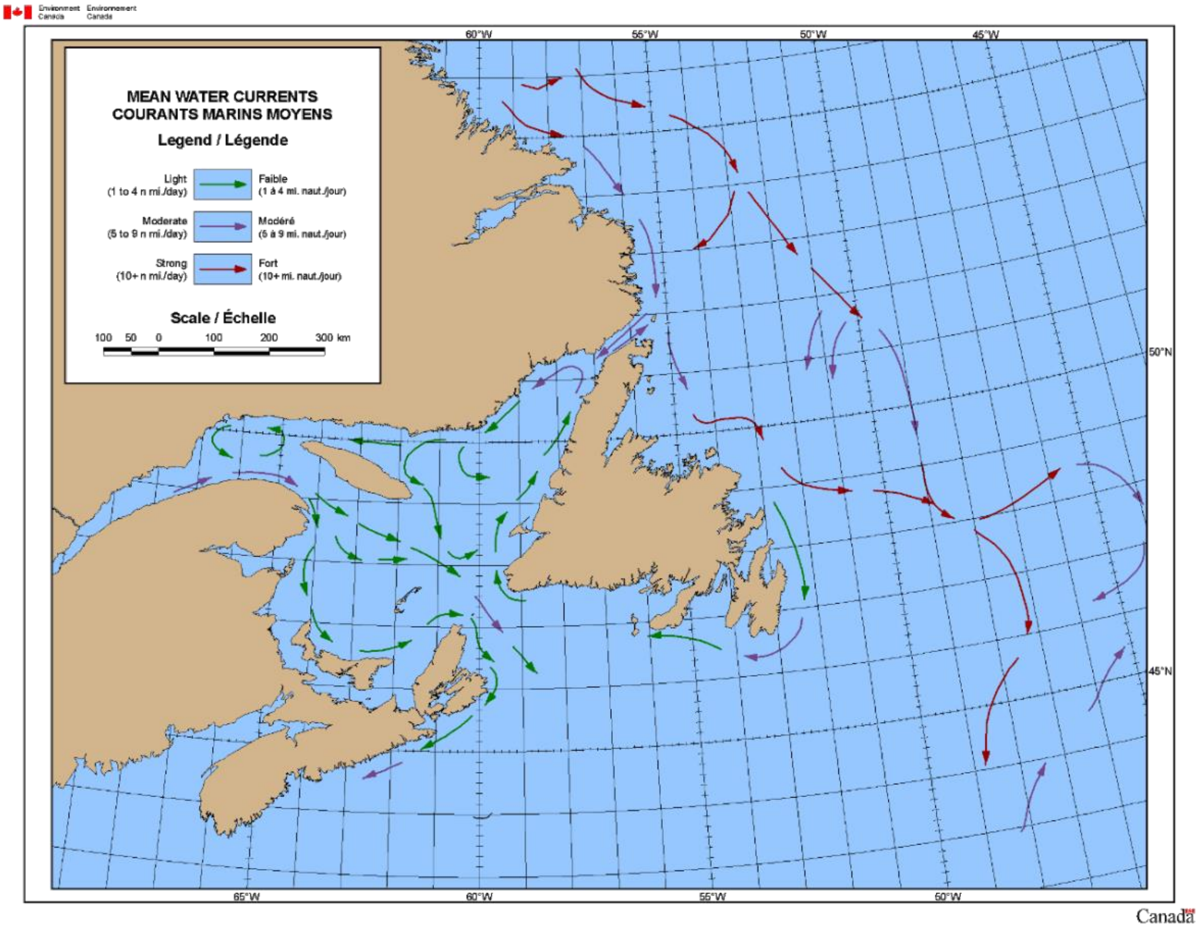

Figure 3-6 – Mean surface currents in the Atlantic Canada region (ECCC, 2024)

One of the notable data sources for currents speeds and directions is the Hybrid Coordinate Ocean Model (HYCOM) - Global Ocean Forecasting System (GOFS) 3.1 Reanalysis model (HYCOM, 2015), providing a high-resolution 3-dimensional grid (0.08 degrees – 9 km resolution approximately) within the area of interest of hourly averaged ocean currents dating between 1994 and 2015. However, it should be noted that the accuracy of the model in shallow coastal regions should be carefully analysed. Typically, in these shallow coastal regions, detailed Offshore Wind Farm design and analysis should be underpinned by site specific measurements.

In our review of existing studies in the region, it is noteworthy to mention that the C-CORE metocean study (C-CORE, 2017) utilised the HYCOM model to provide ocean current data. Its adoption in prior research provides an indication of the model's reliability.

Other important data sources that are worth noting include the National Centers for Environmental Information – Global Ocean Currents Data Portal (GOCDP) moored current buoys and ADCP (Figure 3-7) (NOAA, 2024). A number of measurement systems in the SmartAtlantic's catalogue (SmartAtlantic, 2024) were identified as being potentially useful, particularly in the nearshore regions of Newfoundland, Labrador and Nova Scotia. These data sets are understood to have shorter measurement durations (ranging from 1 hour to a few minutes) and are publicly available through data request services. The short duration of measurements may be useful in calibrating regional numerical models. In Figure 3-8, an illustration of the active and historical measurement systems in the SmartAtlantic's catalogue may be seen, the number refers to the amount of measurement systems in the area and the colour represents whether the datasets consist of active systems only (green) or historical and active measurements (orange).

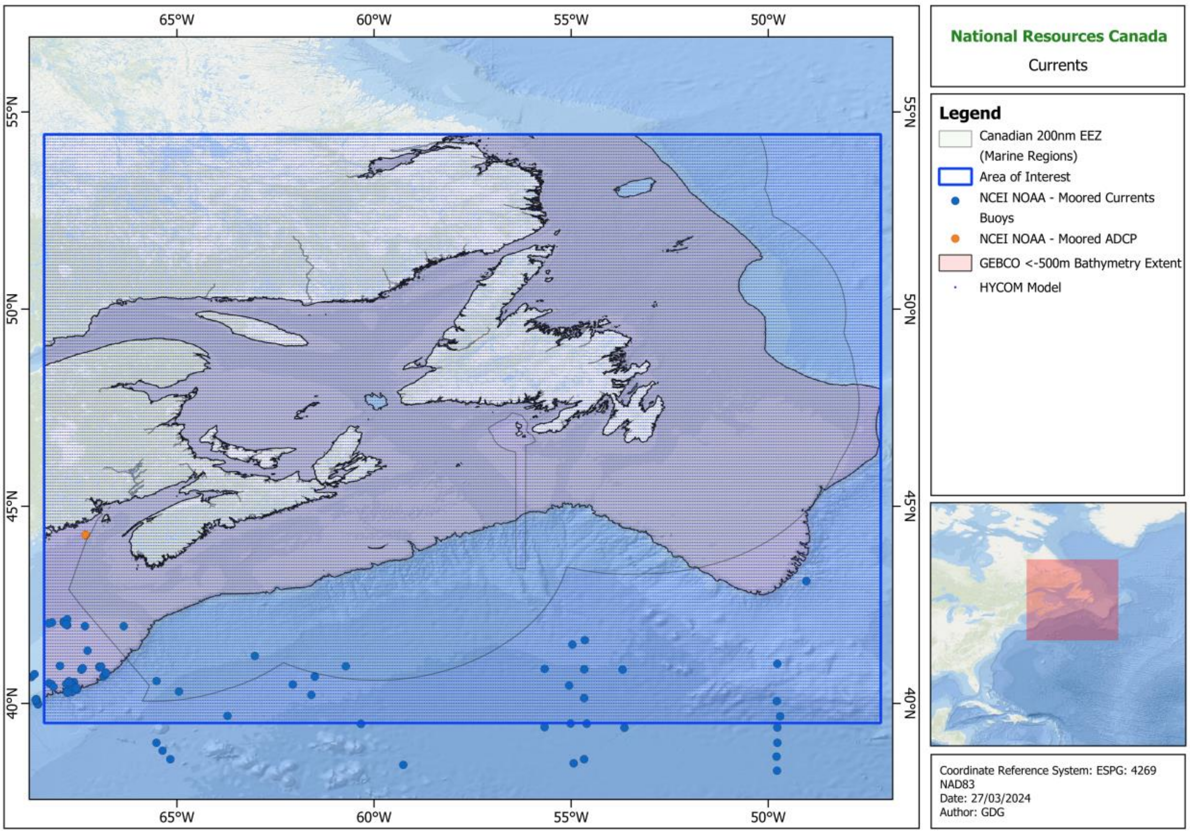

Figure 3-7 – Overview of key current data sources and spatial coverage

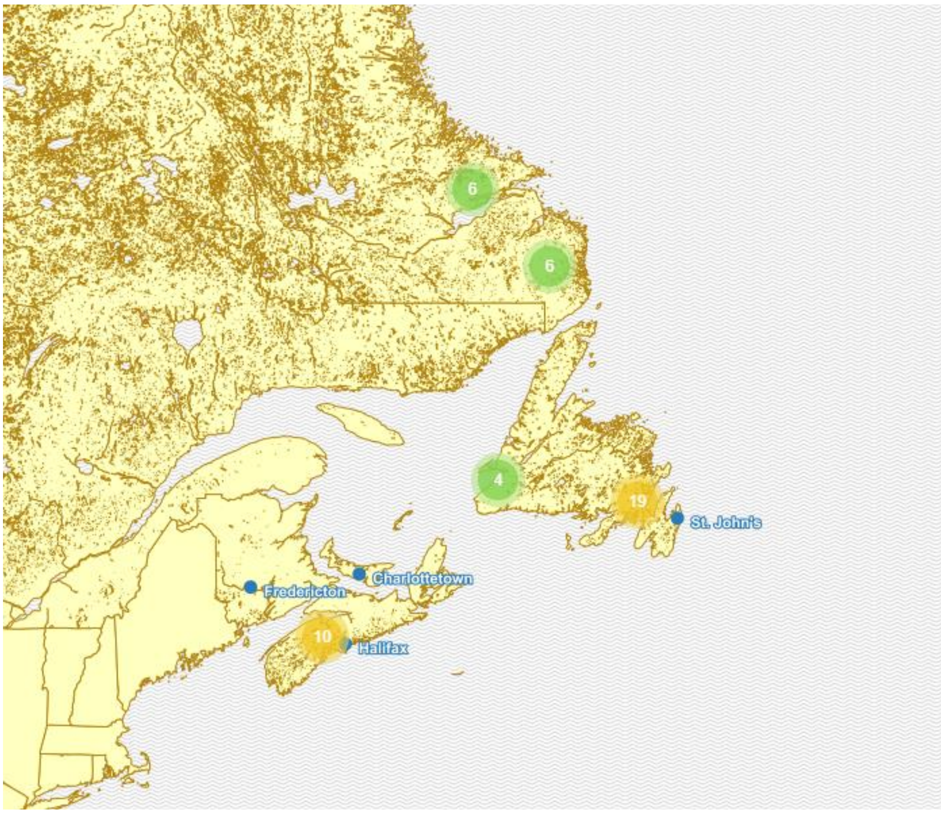

Figure 3-8 – SmartAtlantic's catalogue of active and historical measurement systems. (SmartAtlantic, 2024). Green = Active, Orange = Historical and Active

3.3 WATER LEVELS AND TIDES

According to applicable standards and best practices, historical datasets of tidal height or sea surface height are necessary to derive different water levels and tidal parameters crucial for Offshore Wind Farm development.

From the data sources offering either sea surface level time series or pertinent values for assessing tidal parameters, the following have proven useful for offshore wind developments at this stage:

(a) Hybrid Coordinate Ocean Model (HYCOM) - Global Ocean Forecasting System (GOFS) 3.0 and 3.1 Reanalysis models (HYCOM, 2015).

(b) Integrated Climate Data Center (ICDC) – HAMTIDE Model (Taguchi, et al., 2014).

(c) Canadian Hydrographic Service – Fisheries and Oceans Canada (CHS-DFO): Tidal stations (CHS, 2024).

Each of these sources provide unique data that may be used directly or to calculate the tidal parameters listed in Work Package 1.

The Global Ocean Forecasting System (GOFS) 3.0 and 3.1 - HYCOM models provides sea surface height which factors in astronomical and atmospheric contributions. The data range varies depending on the model used, between 1992 and present day. Providing the sufficient length of data to derive the water levels and tide parameters, this dataset is identified as being useful for NRCan and subsequent OWF developers.

The HAMTIDE model provides a low-resolution spatial grid (7.5° x 7.5° degrees) of the amplitude and phase of the astronomical tidal components but does not offer a continuous time series with specified temporal intervals. Therefore, the HAMTIDE data is useful for determining the astronomical tidal parameters at a number of locations in the area of interest (Figure 3-9) and for validating other datasets.

CHS–DFO provide historical water level measurements from stations located throughout the area of interest. There are many stations that may be useful for determining the water level and tidal parameters at various locations along the continental shelf, although some may be subject to regional bathymetry and topological features that could influence the measured values.

Figure 3-9 illustrates the coverage of each dataset listed above.

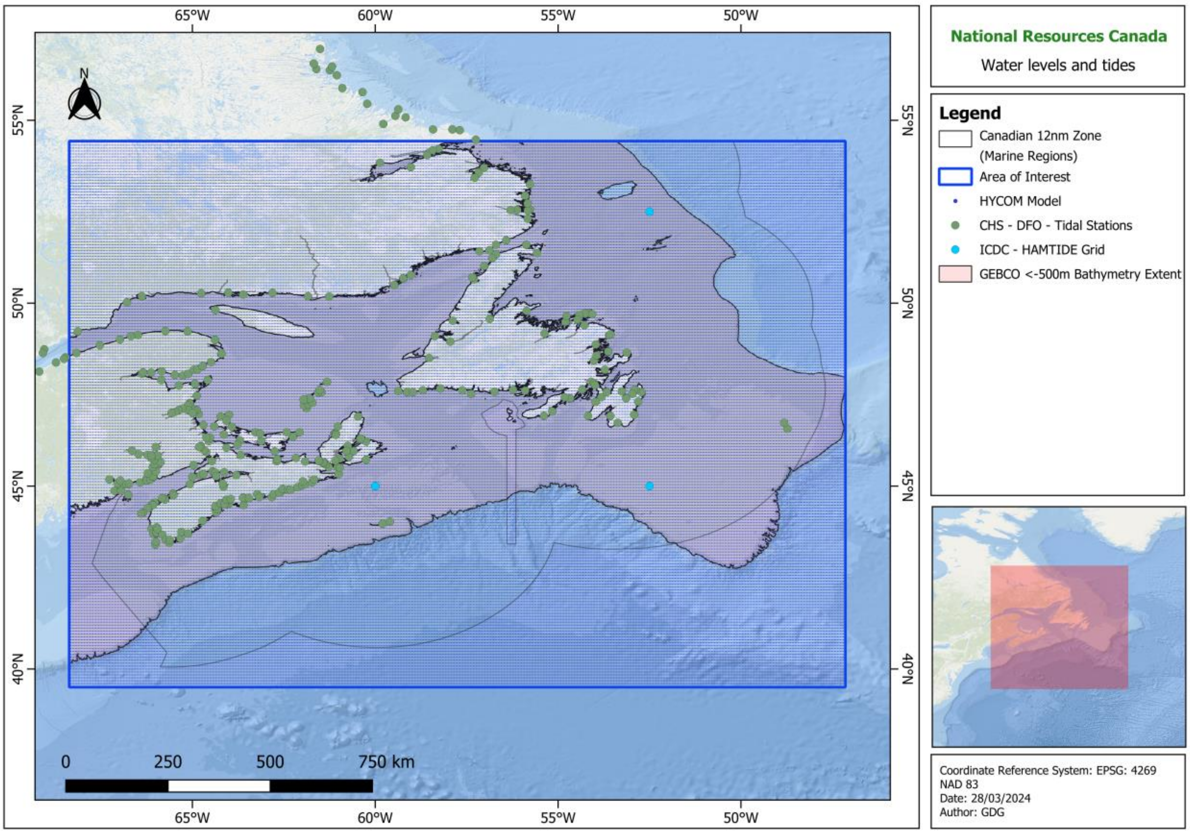

Figure 3-9 – Water levels and tide data sources

3.4 BATHYMETRY

Accurate bathymetric data is important throughout every stage of an Offshore Wind Farm development. In the early stages, it is used to inform decisions regarding site feasibility and technology selection by revealing underwater terrain, such as slopes and seabed features, and the water depths. Water depth is among the critical variables determining the suitability of either floating or fixed foundation concepts for Offshore Wind Farms. The decision between these two types of concepts hinges largely on the depth of the water in a proposed site. Generally, in shallower waters, fixed foundations are more feasible (< 60 m). However, as depth increases, fixed foundations become less viable due to the engineering complexity and costs associated with bigger sub-structures and piles.

Bathymetry data is primarily gathered using echo-sounding techniques, where ships with sonar systems measure water depth by timing sound pulses reflected off the ocean floor. Methods which can provide high-resolution bathymetry datasets include multi-beam echosounder (MBES) and side-scan sonar (SSS). Less detailed bathymetry data may be obtained from single beam echosounder (SBES) surveys.

Within the area of interest, several bathymetric datasets have been identified, each offering unique insights:

1. The General Bathymetric Chart of the Oceans (GEBCO) (The General Bathymetric Chart of the Oceans (GEBCO), 2023): This dataset covers the entire area of interest, offering a

broad and comprehensive overview of the seabed. With a resolution of 500 m, the GEBCO dataset will be useful for initial large-scale planning and site screening. It provides a low-resolution view of the underwater landscape, helping to identify potential regions for OWF development.

2. Canadian Hydrographic Service (CHS) - Non-Navigational 100 m and 10 m (NONNA 100 and NONNA 10) (Secretariat, 2023): Complementing the GEBCO dataset, CHS provides the NONNA 100 and 10 datasets, which offer higher resolution bathymetric data. Although these datasets cover limited areas within the region of interest, these finer resolution (100 m and 10 m) datasets are beneficial for preliminary and detailed site-specific analysis.
3. NOAA – NCEI provide MBES data holdings which primarily cover the offshore areas beyond the continental shelf. The datasets encompass extensive portions of the Atlantic Ocean adjacent to Canadian territories but fall short in providing comprehensive coverage of the continental shelf.
4. NOAA – NCEI (National Centers for Environmental Information - NOAA, 2023) provides SBES data covering both offshore and nearshore (shelf) areas. It’s important to note that while SBES data offers valuable information, its resolution is generally lower compared to MBES measurements. However, SBES data is still crucial for verifying and sense-checking water depths in other datasets, particularly in the context of the continental shelf areas, which are more extensively covered by SBES data in the Atlantic Canada region.

Other notable datasets include:

- CHS’s 500 m dataset, while somewhat less valuable due to the coverage provided by GEBCO’s 500 m dataset, still serves as an alternative in certain areas for validating existing data holdings.
- The International Hydrographic Organization (IHO) provides a comprehensive catalogue of existing bathymetric data holdings across the globe. Their data centre includes some of NRCan and Geological Survey of Canada MBES bathymetric holdings. Figure 3-10 illustrates the coverage of various measurement methods in the area of interest. This shows the presence of extensive direct measurement systems along the continental shelf. Data from direct measurements likely originated from simpler measurement systems, such as depth-finding sonar installed on regular ships, and single-beam echosounder surveys. The figure also shows the coverage of various higher-resolution MBES datasets within the area of interest, alongside data predicted based on satellite-derived gravity data. Data from direct measurements is available for areas above -500mLAT, while satellite-derived gravity data predicts bathymetries for all water depths in the study area.
- The Olex depth database (Olex, 2024) provides fishermen and seafairers alike with water depth data. Access to the database is provided on a contributor basis, whereby anyone who actively contributes to the database is given access to the database. The collective database is gathered by Olex from echosounders attached to contributors vessels. While less useful for NRCan considering the accessibility constraint, if a licensing agreement could be reached then it may prove to be useful dataset.

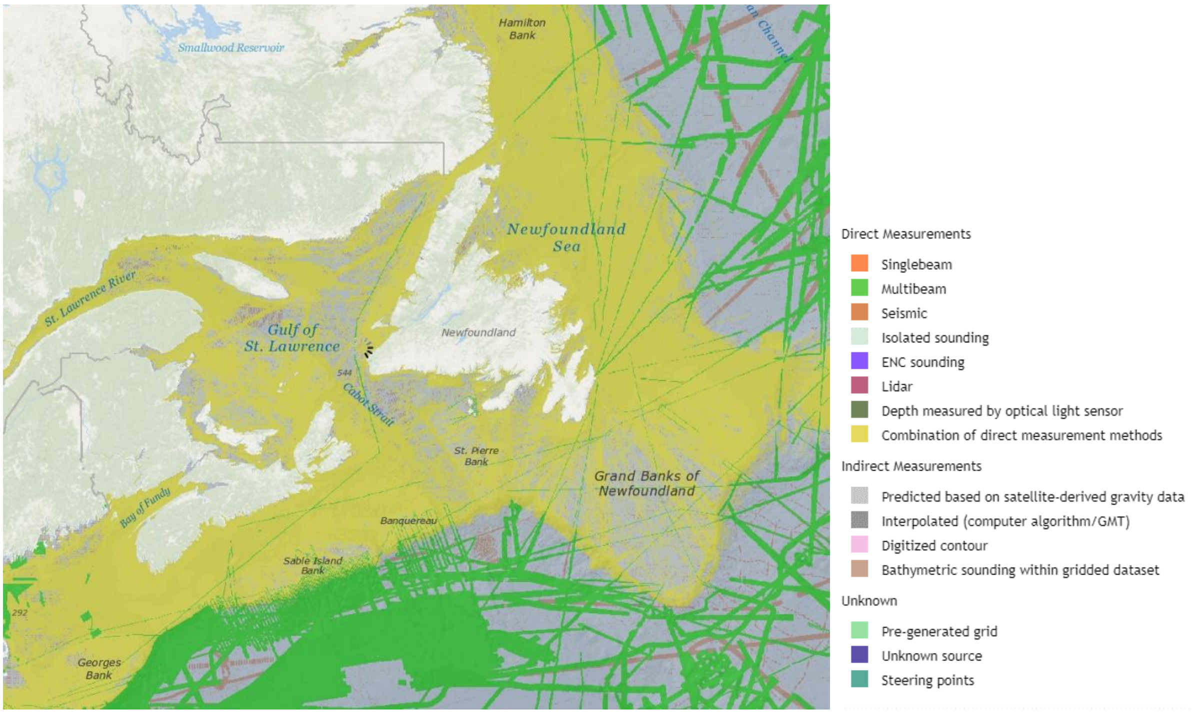

Figure 3-10 – International Hydrographic Organization – Bathymetric Data Overview (IHO, 2023)

Figure 3-11 presents the low-resolution (500 m x 500 m) GEBCO bathymetric dataset. The figure highlights the comprehensive coverage of the dataset.

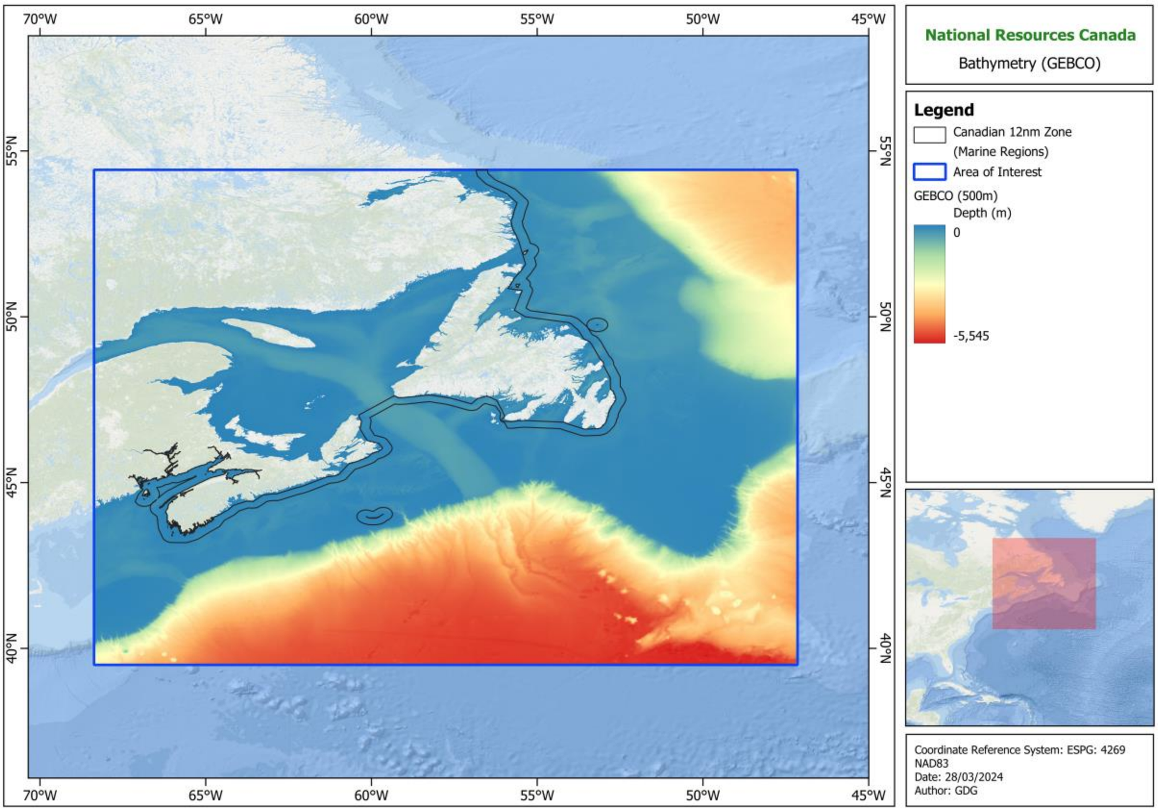

Figure 3-11 – GEBCO 500 m bathymetric dataset (The General Bathymetric Chart of the Oceans (GEBCO), 2023)

Figure 3-12 illustrates the Canadian Hydrographic Service's NONNA 10 and 100 datasets. The data coverage provided by these CHS datasets is limited in the more offshore regions. A sizeable area covered by these datasets is located south of the Sable Island Banks. While the dataset provides some offshore data, it mostly provides data within the 12 nm zone along the coasts of the study area.

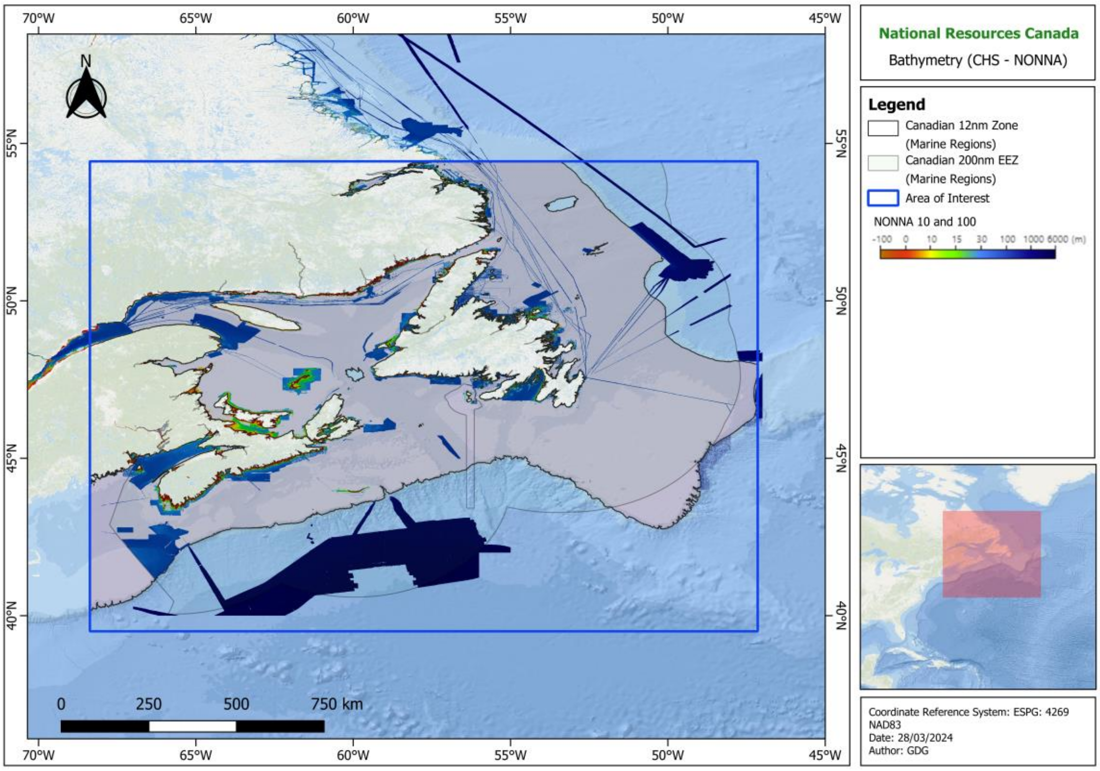

Figure 3-12 – Canadian Hydrographic Service – NONNA 10 and 100 datasets (Secretariat, 2023)

Figure 3-13 shows an illustration of the gridded MBES bathymetry data catalogued in both the NOAA and IHO catalogue. These datasets provide high resolution (500 m x 500 m) bathymetric data mostly along the edges of continental shelf and further. In Figure 3-14, the track lines from single beam echosounder surveys provided in NOAA's catalogue may be seen. The coverage of these datasets coincides with the MBES track lines highlighted in Figure 3-10.

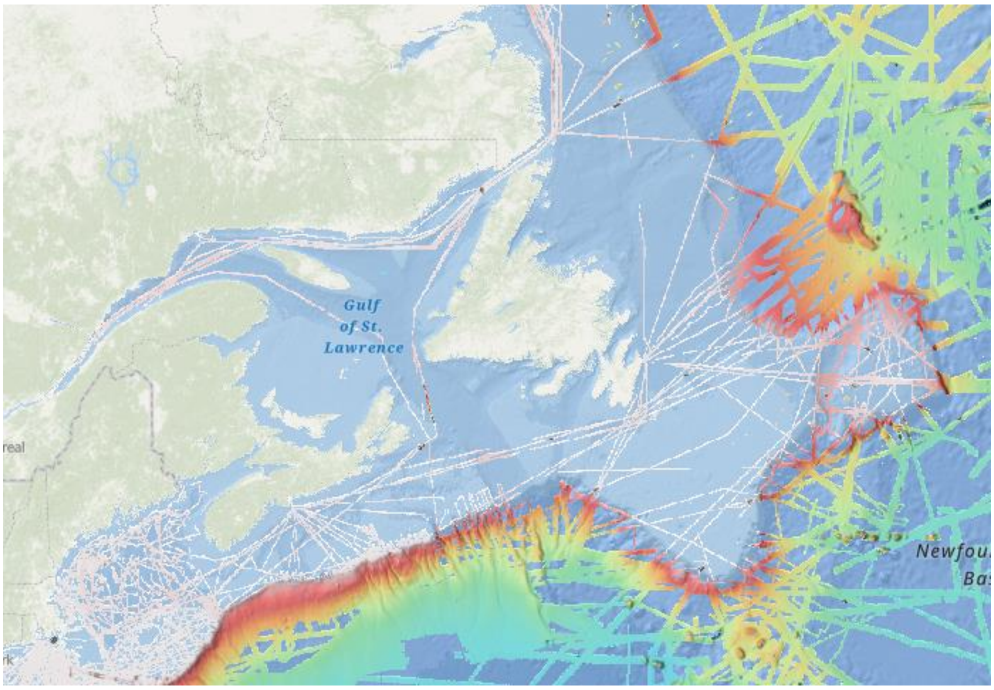

Figure 3-13 – NOAA NCEI / IHO DHCB – Gridded multi-beam bathymetry data from surveys (NOAA NCEI, 2024)

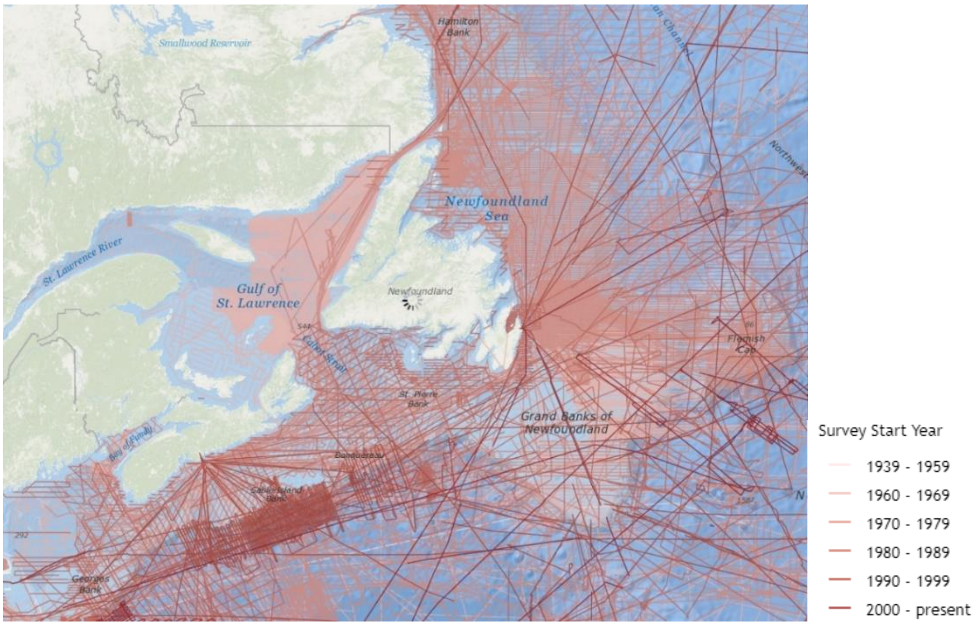

Figure 3-14 – NOAA NCEI – Single-beam echo sounder geophysical track line overview (1939 – 2023) (National Centers for Environmental Information - NOAA, 2023)

3.5 OTHER METOCEAN VARIABLES

Several other metocean variables are classified as less critical for offshore wind development. Despite their potential significance for offshore design requirements, installation activities, and operation and maintenance (O&M) activities, these variables are viewed of lesser importance in this context. However, conducting data analysis on these variables remains necessary for a proper project development that is accordance with standards and security frameworks.

The referred other metocean variables are:

- Water density

- Air Pressure – Extreme Storm Events
- Air Temperature
- Water temperature (Sea Surface and Sub Surface)
- Salinity
- Solar Irradiance
- Precipitation (Rainfall and Snow)

Table 3-1 shows the main data sources available for each of these variables outlined above. Other data sources for these variables are listed in Appendix A.

Table 3-1 – Main data sources for other metocean variables

Variable	Main Data Source
Water Density	Copernicus database - https://data.marine.copernicus.eu/product/MULTIOBS_GLO_PHY_S_SURFACE_MYNRT_015_013/description?view=-&task=results&product_id=-&option=- Provides in-situ observations and satellite observations with a spatial resolution of 0.25 x 0.25 deg. Data available from 1993.
Air Pressure – Extreme Storm Events	NOAA – International Best Track Archive for Climate Stewardship (IBTrACS) – NOAA – information may be found at: https://www.ncei.noaa.gov/products/international-best-track-archive. Provides in-situ and satellite data on extreme storm events and Air Pressure with a spatial resolution of 0.1 x 0.1 deg. Data available from 1980.
Air Temperature	The ERA5 model is a fifth-generation atmospheric reanalysis model produced by Copernicus Climate Change Service at ECMWF (European Centre for Medium-Range Weather Forecasts). Provides hindcast data with spatial resolution of 0.25 x 0.25 deg. Data available from 1979.
Water Temperature	HYCOM - https://www.hycom.org/. Hidcast data with spatial resolution of 0.08 x 0.08 deg (Long x Lat) - between 40°S to 40°N and 0.08 x 0.04 deg poleward of 40°S/40°N. Data available from 2014.
Salinity	HYCOM - https://www.hycom.org/. Hidcast data with spatial resolution of 0.08 x 0.08 deg (Long x Lat) - between 40°S to 40°N and 0.08 x 0.04 deg poleward of 40°S/40°N. Data available from 2014.
Solar Irradiance	The ERA5 model is a fifth-generation atmospheric reanalysis model produced by Copernicus Climate Change Service at ECMWF (European Centre for Medium-Range Weather Forecasts). Provides hindcast data with spatial resolution of 0.25 x 0.25 deg. Data available from 1940.
Precipitation	The ERA5 model is a fifth-generation atmospheric reanalysis model produced by Copernicus Climate Change Service at ECMWF (European Centre for Medium-Range Weather Forecasts). Provides hindcast data with spatial resolution of 0.25 x 0.25 deg. Data available from 1940.

3.6 MARINE GROWTH

Information regarding the extent of marine growth in the Atlantic Canada region is currently limited. Standards and guidelines, including IEC 61400-3 (IEC, 2019b), DNV-RP-C205 (DNV, 2021a), and ISO19901-1:2015 (ISO, 2015b), emphasize the necessity of site-specific studies when data are lacking to determine the characteristics of marine growth, such as thickness, density, and depth dependence. These studies are crucial for understanding the dynamics of marine growth in the region, which can vary significantly based on local environmental conditions and nutrient availability. The absence of comprehensive datasets underscores the importance of conducting thorough marine growth surveys in each area to gather essential information for offshore operations and infrastructure planning.

To address the scarcity of marine growth data in the Atlantic Canada offshore regions, numerical estimation techniques utilizing geographical information systems and environmental datasets are employed. These methods involve the integration of available data on factors such as water temperature, nutrient concentrations, and substrate type to estimate the likely distribution, thickness, and density of marine growth. While these numerical estimations provide valuable insights, they are highly dependent on the accuracy and coverage of the input data. Therefore, continued efforts to collect comprehensive marine growth data through surveys and monitoring programs are essential for improving the reliability of these estimations and enhancing our understanding of marine growth dynamics in the Atlantic Canada offshore regions.

In section 4.3.4 of Work Package 3 (WP3), we explore indicative surveying and data collection specifications. Such surveying methods are deemed essential for the advancement of Offshore Wind projects in Atlantic Canada, primarily due to the scarcity of available data specific to each region.

3.7 SEA ICE

Ice characteristics reviewed consider 50-year assessments typical for PRE-FEED criteria, following ISO 19901:2015 (ISO, 2015b) standards. An assessment of metocean data sources covering available thickness distribution and density, ice floe speeds, ice types and stages of development, and degree of deformation (e.g., ice sheets, hummock ice, rafted ice, ice ridges etc.), and related datasets are compiled.

The Ice Archive from Canadian Ice Service, Environment and Climate Change Canada (Canadian Ice Service, 2024) provides Ice concentration and Ice thickness modelled results. More data from other sources (such as C-CORE) can be found in Appendix A.

3.8 FREEZING SPRAY AND ICE ACCRETION

Freezing spray and ice accretion information, and metocean parameters related to these processes such as air temperature, and frost index (freezing-degree days) have been reviewed along with variables concerning atmospheric conditions conducive to ice accretion on turbine blades and nacelle to support calculations of ice build-up potentially using the Makkonen Equation (Makkonen, 1981) and its specific application to modelling ice accretion on wind turbines (Makkonen, et al., 2001). Additional methods and data sources may be gleaned from aviation meteorology as needed by developers. Data for this variable can be calculated using projections of sea surface temperatures, air temperatures, winds and from the CMIP-6 database (Canadian Government - Environment and Natural Resources, 2023).

3.9 ICEBERGS

Ice load theory was used to derive a list of variables related to icebergs including ice compression and flexural strength, ice crushing, strength, ice crushing coefficient, temperature, porosity, strain rate, Poisson's ratio, Young's modulus, iceberg dimensions, ice driving mechanisms (e.g., current and wind), risk of forces induced by fluctuating water levels, and presence of ice concentrations > 15 % coverage. This assessment has followed guidelines for ice loading as outlined in the ice loading annex of IEC 61400-3-1:2019 (IEC, 2019b). Data from long-term observation programs in the North Atlantic using ships, aircraft and satellites are provided in International Ice Patrol (IIP) (US Coast Guard, 2024) and Canadian Ice Service (Canadian Ice Service, 2024). C-CORE also provides data from daily iceberg and ice island aerial concentrations derived from Envisat and Sentinel-1 satellite sensors. C-Core, ASL, CIS and Carleton University also provide Iceberg velocities computed from time series from satellite-tracked beacons.

3.10 GAP ANALYSIS (NON-ICE RELATED PHENOMENA)

Wave and Wind:

In summary, our analysis concludes that there is good numerical data availability within the areas deemed acceptable for installing offshore wind turbines at this stage. The MSC50 and ERA5 datasets will enable the Client to conduct a wind resource assessment to estimate the power production potential in these regions. These datasets can also be used as input into weather window and weather downtime analysis, whose outputs can provide insights into whether transportation and installation works are feasible in the region. Additionally, the existing OilCo metocean reports may be useful for comparison and validation purposes. In terms of physical measurements, there is limited data availability in the following regions, as indicated from Figure 3-2 to Figure 3-5:

- The Scotian Shelf, Northwest of Sable Island and Southwest of Nova Scotia
- The Southern coast of Labrador in the Gulf of St. Lawrence and around the Anticosti Island
- The Labrador Shelf
- The Northeast Newfoundland Shelf
- The Grand banks of Newfoundland

Ocean Currents:

Overall, our study concludes that there is good temporal and spatial coverage of ocean current variables across the area of interest. GDG recommends that should the Client require ocean current datasets, both in-situ measurements and modelled hindcast data. The HYCOM model is likely going to meet the requirements at this stage of development. Subsequent site condition assessments and regional hydrodynamic model developments may utilise the SmartAtlantic's catalogue and potentially NOAA's datasets. However, these datasets are limited in what they can provide considering that they are primarily coastal measurement systems. There is a notable absence of offshore physical measurements throughout the entire area of interest, once the Client has defined OWF lease areas GDG suggests that a metocean data collection campaign should be conducted to collect measurements of ocean currents speeds and directions in those areas specifically.

Water Levels and Tides:

In summary, the aforementioned data sources provide good temporal and spatial coverage for the Client at this stage. The HYCOM model is considered as one of the more useful datasets considering the dataset covers the duration required to capture the different tidal phenomena and their temporal variability, and it has good spatial coverage throughout the area of interest. There are numerous tidal stations along the coast within the area of interest, providing extensive coverage. However, the duration of measurements vary, which could result in some stations not being suitable for capturing long-term variations effectively. Furthermore, the tidal heights measured at some of these stations may be subject to local topological effects, such as those observed in the Bay of Fundy, which reduces the dataset's suitability for determining water level and tidal parameters in other parts of the area of interest. To minimize uncertainties and ensure accurate analysis of water levels and hydrodynamic flow, it is advised to collect tidal data in conjunction with current and wave data.

Bathymetric Data:

In summary, the combination of outlined datasets i.e., the broad-scale, lower resolution GEBCO datasets, and the more detailed but limited CHS NONNA and NOAA NCEI datasets, provides a good toolset for initial zonation. In an ideal scenario, NRCan and OWF developers would benefit from a high-resolution bathymetric dataset that covers the entire area of interest, however obtaining such a dataset is not recommended as it would not be economically viable. Once the Offshore Wind Farm lease areas have been defined, MBES and geophysical surveys will need to be conducted to provide detailed bathymetry and sub-bottom geophysical and geotechnical data. Until the Client progresses to this stage of development, recommendations on specific survey locations are limited due to the vast extent of the area of interest and areas with water depths less than -500 m.

Other Metocean variables:

The datasets presented in Table 3-1 include various metocean variables for Offshore Wind project development. These variables encompass water density, air pressure during extreme storm events, air temperature, sea surface and subsurface water temperature, salinity, solar irradiance, and precipitation (rainfall and snow). This compilation serves as a valuable data source across all project development phases. The listed data sources offer enough comprehensive information on the specified metocean variables for an Offshore Wind Projects for all stages of development.

3.11 Gap Analysis of Sea Ice, Icebergs, and Freezing Spray and Ice Accretion

Given the very large area of Atlantic Canada offshore waters and the highly inhomogeneous distribution of sea ice and icebergs and ice accretion, a spatial framework is needed for identifying subareas to assess important data gaps. This spatial framework is addressed separately for sea ice and icebergs because the potential hazards for offshore wind development are different for these ice parameters which have a very large variability in their regime characteristics by comparison to most meteorological parameters (see wind speed in Figure 3-15), where the spatial variability is limited to a factor of two.

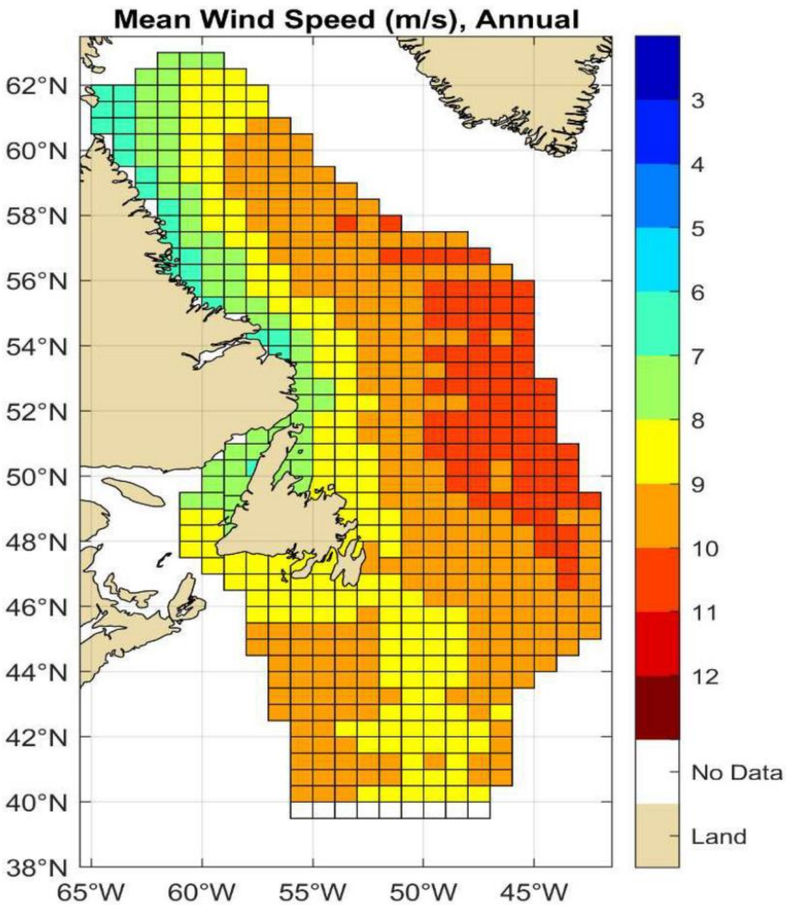

Figure 3-15 - The annual mean wind speed over the waters of Labrador and Newfoundland (Turnbull et al., 2022)

3.11.1 SEA ICE

A revealing indicator of the spatial differences in the sea ice regime within Atlantic Canada offshore waters can be seen in the duration of the sea ice occurrences within the full area. The duration of sea ice cover can be derived from the average date of break-up of the sea ice less the average date of freeze-up (Figure 3-16).

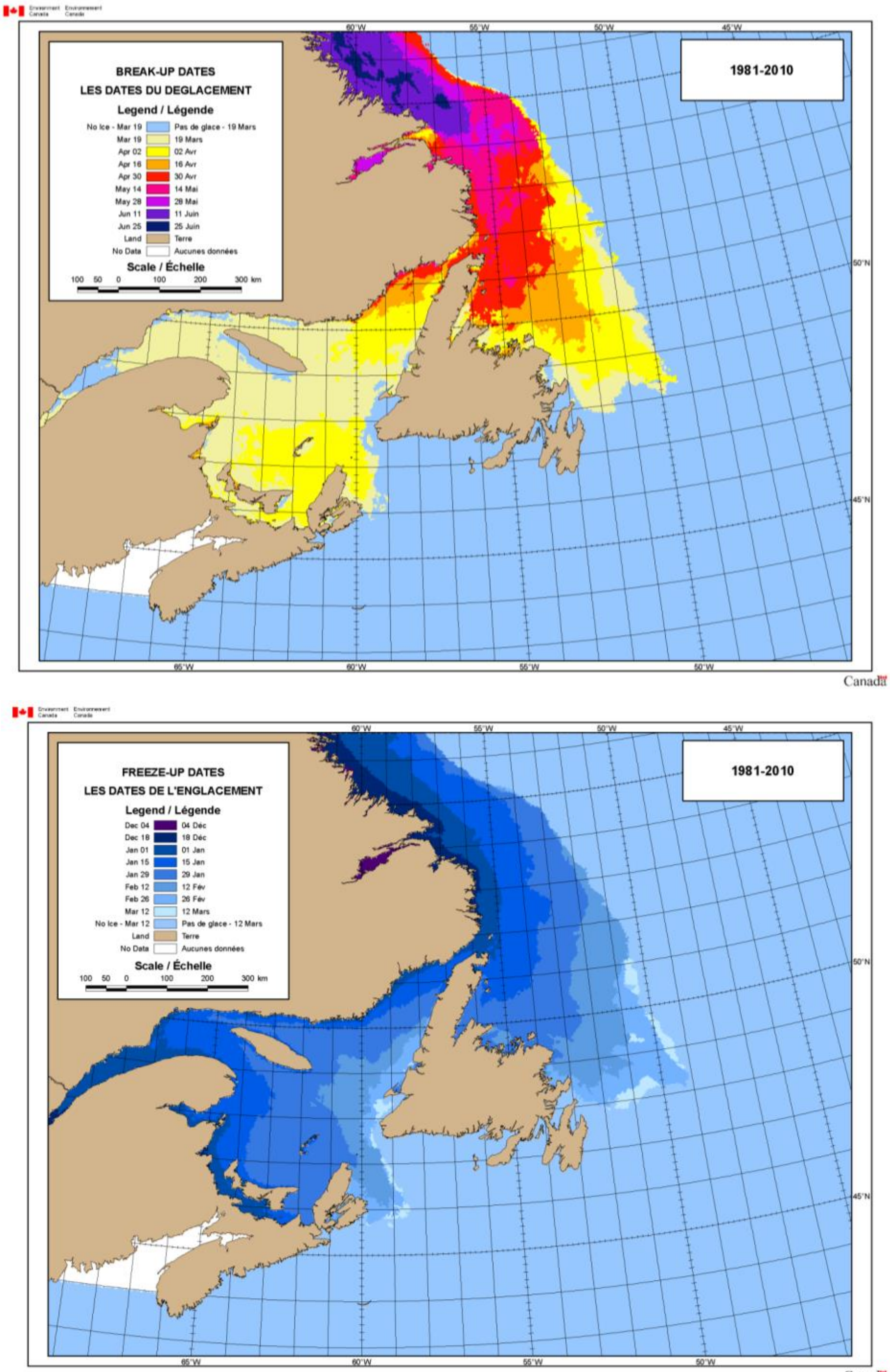

Figure 3-16 - The median dates of break-up and freeze-up derived from East Coast Ice Charts, 1991-2020 (ECCC, 2024).

The duration of the sea-ice season varies significantly across the entire area of Atlantic Canada, ranging from over 5 months on the inner shelf off mid-Labrador to less than one month in the Eastern half of the Gulf of St. Lawrence. In some regions including off the south coast of Newfoundland and off the south coast of Nova Scotia, sea-ice occurrences are scarce. The longest durations of sea-ice occur on the inshore portion of the Labrador Shelf and on the inshore portion of the NE Newfoundland Shelf, with lower durations in the Gulf of St. Lawrence and the offshore portion of the Eastern Newfoundland Shelf.

A total of nine sub-areas or regions for sea-ice occurrences are identified according to sea-ice duration data, as shown in Figure 3-17. The duration of sea ice is described using median break-up and freeze-up dates (Table 3-2).

Table 3-2 - The duration of sea-ice for specific areas in Atlantic Canada, as derived from East Coast Ice Chart data for median break-up dates and freeze-up dates.

Area / Region	Freeze-up dates	Break-up dates	Approximate Sea-ice duration (months)
W. Gulf St. Lawrence (W.GSL)	First half Jan.	Last half. Mar.	2.5
E. Gulf St. Lawrence (E.GSL)	Last half Feb.	Mid-Mar.	<1.0
NE. Gulf St. Lawrence (NE.GSL)	End Jan.	First half Apr.	2.2
NE NF. Shelf (inshore) (NE.NF-In)	Last half Jan.	Early May	3.5
E NF. Shelf (offshore) (E.NF-Off)	First half Feb.	Mid. Apr.	2.1
S. Lab. Shelf (inshore) (S.LAB-In)	End. Dec.	First half Jun.	5.3
S. Lab. Shelf (offshore) (S.LAB-Off)	Late Jan.	End Apr.	3.0
Mid. Lab Shelf (inshore) (M.LAB-In)	Mid. Dec.	Mid. Jun.	6.0
Mid. Lab Shelf (offshore) (M.LAB-Off)	First half Jan.	Last half May	4.5

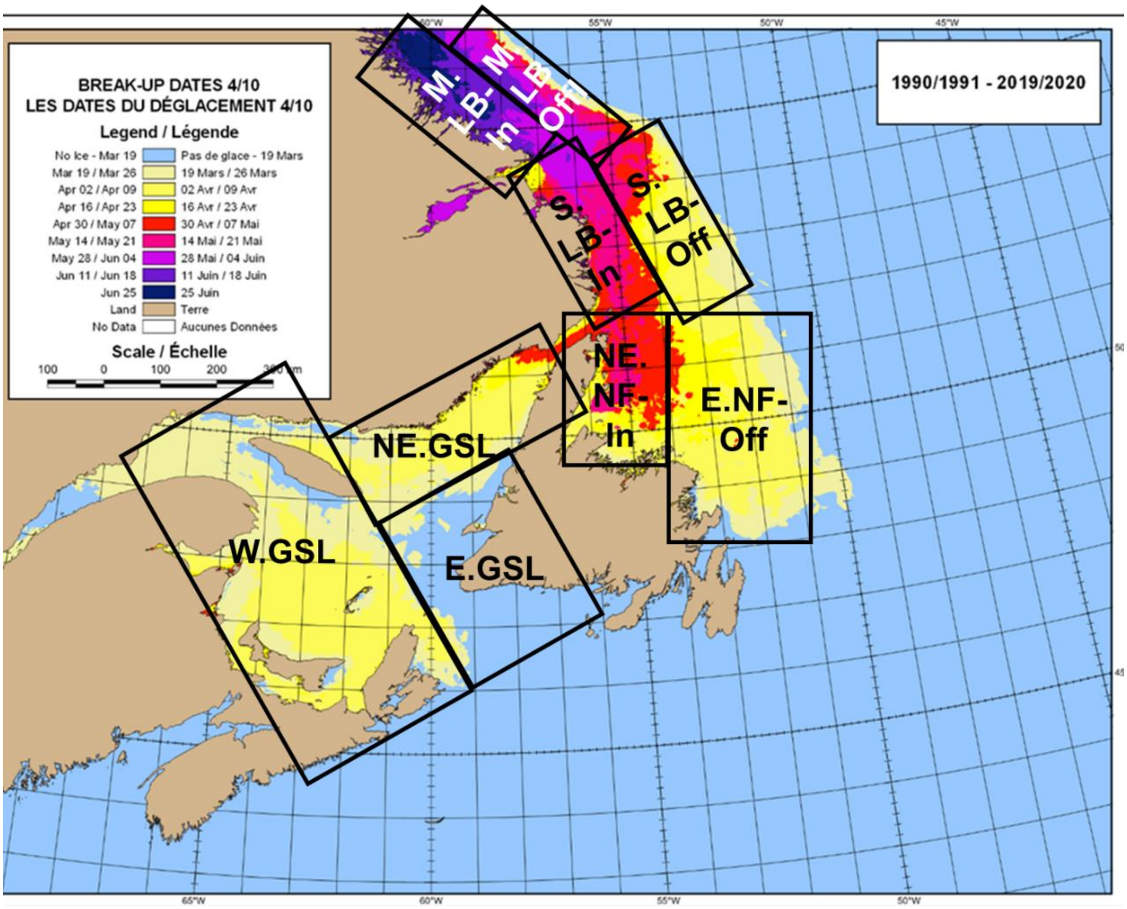

Figure 3-17 - Nine regions in Atlantic Canada having distinctly different occurrences of sea ice (ECCC, 2024).

The nine regions presented in Figure 3-17 are as derived from the data of Figure 3-16. The names of each region are given in Table 3-2.

Sea ice concentration and stage of development maps developed by the Canadian Ice Service (CIS) provide excellent spatial coverage of the sea ice regime (ice concentrations) spanning many decades of observations. However, the CIS ice charts do not provide adequate information on the thickness of the sea ice, which is required for engineering PRE-FEED activities, computing ice loads, and planning Offshore Wind Farm zones. This lack of detail is exacerbated by differences in sea ice dynamics and thermodynamic regimes between the different regions and contrasted between fast ice and mobile ice cover.

Data gaps specific to IEC 61400-3-1:2019 (IEC, 2019b) guidelines are as follows:

Horizontal load due to temperature fluctuation in a face ice cover (thermal ice pressure): information on fast ice temperature profile fluctuations is not regularly collected at any locations within the regions. There are some limited academic and Indigenous-led programs taking place in coastal Labrador (e.g., SmartIce).

Horizontal load from fast ice cover is subject to water level fluctuations in terms of the arch effect: this is an ice-engineering specific parameter that requires observational instrumentation of fast ice zones and is calculated using specific parameters from field datasets for a given location.

We note that land fast ice coverage is limited throughout most of Atlantic Canada (Figure 3-18) where offshore wind developments are likely to be installed, but may be of concern for points where offshore transmission lines may need to cross the shoreline throughout much of the Gulf of St. Lawrence and the northern coast of the Island of Newfoundland where the frequency of presence of fast ice is > 0%. This is also true for all coastal Prince Edward Island, and New Brunswick. Fast ice does not typically extend great distances seaward in these areas, with the exception of southern Chaleur Bay, along the north shore islands at Mingan, from Cape Whittle to Blanc-Sablon and in the Bay of Islands.

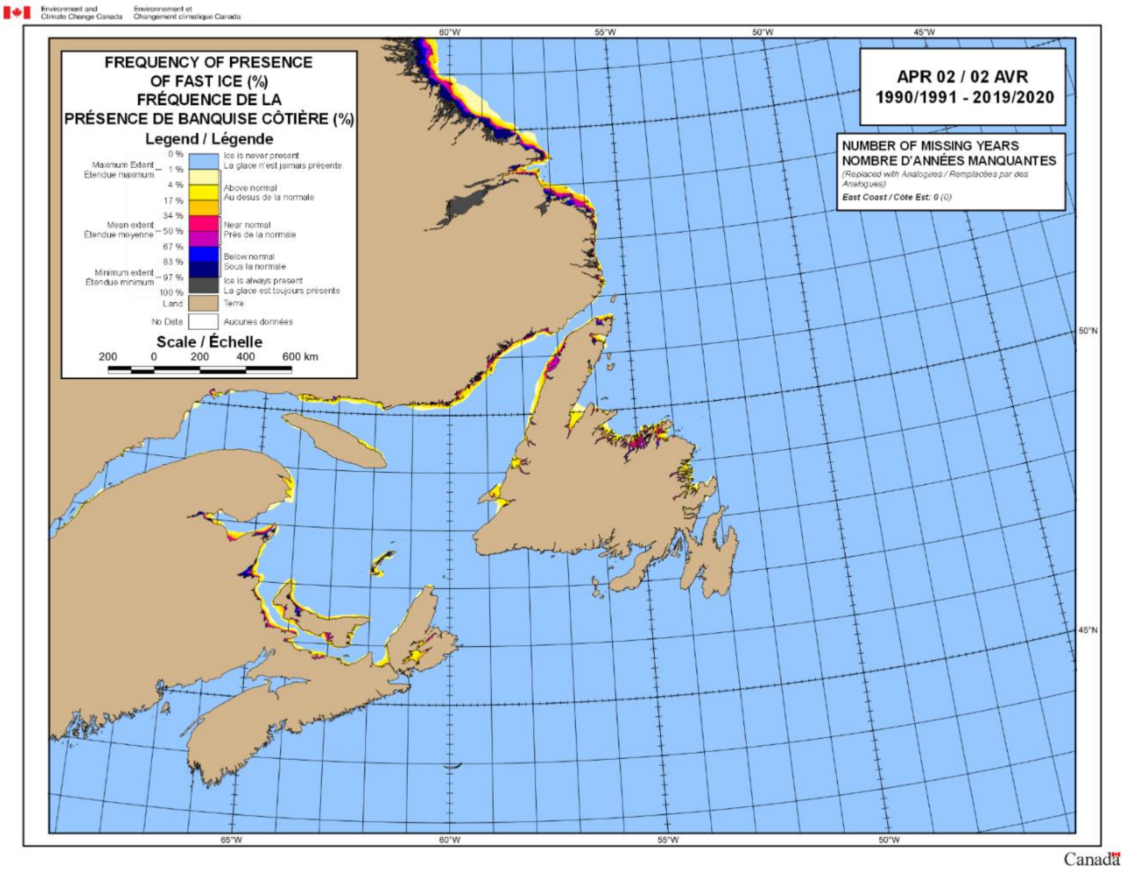

Figure 3-18 - Extent of fast ice for the Canadian East Coast at the time of maximal land fast ice in early April over the years 1991-2020 (Canadian Ice Service, 2023).

The vertical load from fast ice cover is subject to water level fluctuations: this is an ice-engineering specific parameter that is not widely available and would need to be calculated from relevant parameters from field datasets for a given location. Important parameters for this calculation are ice thickness, ice density, ice pressure (internal stresses) in addition to water level. These parameters should be assessed as a time series, with ice loading calculated at regular intervals so that the full range of ice loading values can be assessed for a particular site, throughout a full ice season.

For determining the horizontal load of moving ice, the key parameter arises from moving sea ice is changes in momentum (p), which is a function of mass (m) and velocity (v), where $p = mv$. The availability of data on sea ice velocities is very limited in areas having short duration ice seasons and comparatively thin ice, e.g. the Gulf of St. Lawerence and the southern limits of sea ice on the Newfoundland Shelf. Satellite-imagery derived sea ice velocities is very limited in these areas due to problems in detecting the ice, for radar and radiometric satellites, and atmospheric conditions such as clouds and fog which can impede the use of radiometric satellite data sets.

Pressure from hummocked ice and ice ridges due to subduction and ridging processes: this parameter will vary considerably between the different sub-regions presented in Figure 3-17. The thickness, highest concentrations of sea ice move southeastwardly along the Labrador coast, driven by wind and currents. Much of the mobile sea ice is of Arctic origin and can include thick first-year and multi-year floes, that have undergone deformation and ridging. Some information is available on ice draft and momentum via existing upward-looking sonar datasets, but this is largely limited to a single Labrador inner shelf location, and some previous studies undertaken prior to the construction of the Confederation bridge across the Northumberland Strait between Prince Edward Island and New Brunswick. For most areas, high-resolution sea ice draft and thickness data availability is insufficient for engineering design purposes to properly assess ice thickness, maximum ice velocities, and resulting ice-derived momentum stresses on potential offshore structures.

Limit stress, Limit force, and Limit energy are engineering-specific mechanisms that would need to be assessed for extreme sea ice features that may be present (albeit infrequently) at a given wind farm location if it is determined that limit stress mechanisms are a design risk. These extreme sea ice features are much more prevalent in the areas of the Labrador and northern Newfoundland shelves than in other areas. The limit force mechanism represents an important factor for evaluating the ice interaction scenarios.

Additional information on climate change and its impact on future sea ice climatology within all of the sub-regions can be gleaned from the CMIP-6 database (Stockhause et al., 2021).

3.11.2 ICEBERGS

Iceberg areal densities vary considerably by over three orders of magnitude within Atlantic Canada waters (Figure 3-19).

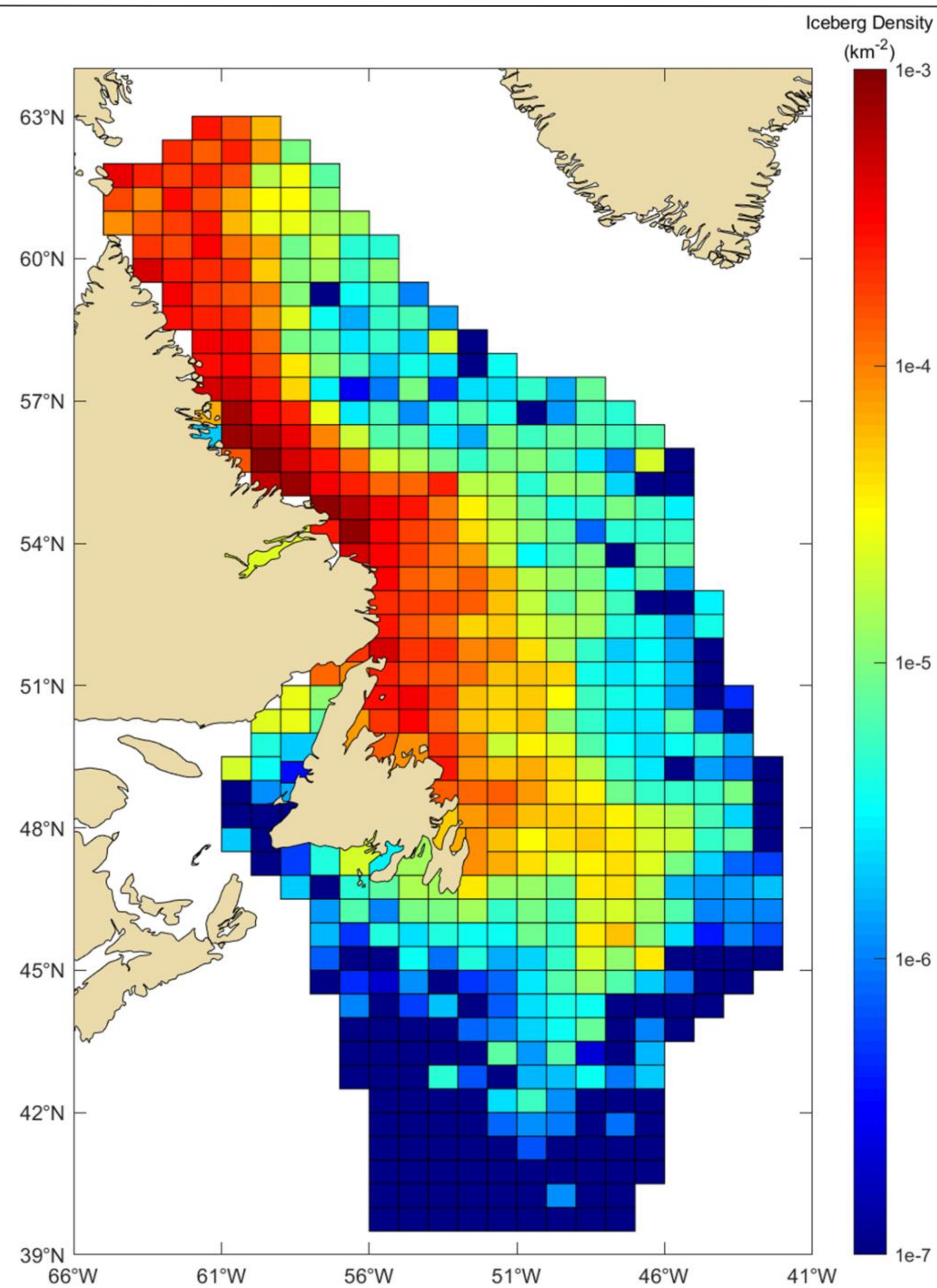

Figure 3-19 - Average annual open water iceberg areal densities (in counts per km ^{2}) based on combined areal and satellite data, 2003-2020 (Turnbull et al., 2022)

The largest iceberg densities occur in the iceberg regions of Davis Strait (S.Dav.St.), the inshore waters of the Labrador Shelf (LAB-In) and the inshore waters of the N. Newfoundland shelf (N. NF-In), with densities of >~ 10^{-4} (Figure 3-19). In the central waters of the N. Newfoundland shelf (N.NF-Cen) and the SE. Newfoundland shelf (SE.NF-Off), the densities are also relatively high at 3-10 x 10^{-5}. The densities in the far offshore waters of the Labrador and Newfoundland shelf (LAB-Off, N.NF-Off, S.NF-E), the N. portion of the Gulf of St. Lawrence (N.GSL, west of the Strait of Belle Isle) and the inshore waters S. of Newfoundland (S.NF-In) are considerably lower at 10^{-6} to 10^{-5}. The very lowest densities of < 10^{-6} occur in the Western and Eastern portions of the Gulf of St. Lawrence (W.GSL, E.GSL) and to the south and southwest of Newfoundland (S.NF-Off). In these latter areas, occurrences of icebergs are extremely rare.

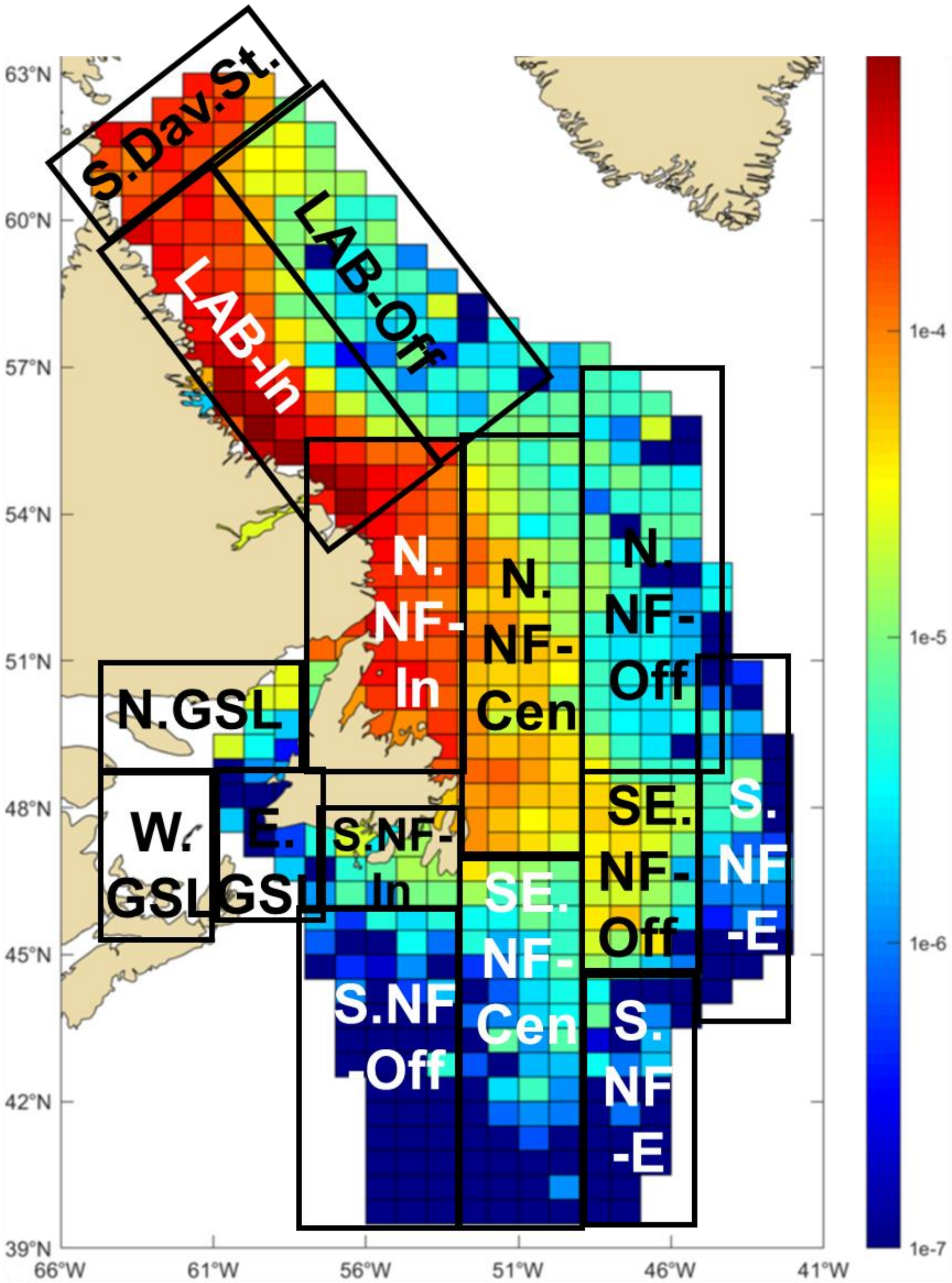

Figure 3-20 - Different regions of iceberg densities (km^2) in Atlantic Canada waters (C-CORE, 2017).

Iceberg densities for gridded regions are presented in Figure 3-19, which can be used to infer occurrence probabilities of iceberg occurrence and guide developers to areas that are less at risk of having offshore turbines interact with offshore wind turbines. The availability of physical sampling-derived datasets for icebergs varies enormously among the various areas in Atlantic Canada. On the Labrador and northern Newfoundland shelf, there is reasonably robust availability of historical data, but this is not the case in other areas which have much lower iceberg densities.

The key challenge with iceberg dataset collection that introduces a significant data gap is it is very difficult and expensive to physically sample icebergs at offshore locations. The placement of a simple tracking beacon requires a considerable cost in helicopter time, and as such, is only conducted at limited intervals, mostly in the academic sense. The lifespan of these beacons can be limited as icebergs are known to roll over, thereby submerging, or losing installed ice beacons and other scientific equipment.

There is a satellite-based ship and iceberg monitoring product (Coresight) available through C-Core based on a semi-automated tracking system with manual quality control (Coresight, 2023). This software is presently licensed to International Ice Patrol and the Canadian Ice Service (CIS) to support operational services. This service has also provided iceberg detection services to the offshore oil and gas sector, tourism sector, and maritime traffic. While this service offers a data product that identifies and tracks icebergs, there may be limited information on iceberg mass, density, momentum, and motion which is tracked at the time interval between satellite images. Iceberg velocities are of particular concern and would need to be better assessed with further field papers.

Climate change and its impact on iceberg formation is a dynamic variable that requires ongoing study and data collection. There have been several academic studies conducted of ice islands originating from the Petermann Glacier Calving events (e.g. (Crawford, et al., 2018)), and these studies have a focus on meltwater inputs and their impacts on ocean currents in the North Atlantic. Additional work could expand upon iceberg frequency studies (e.g. (Marko, et al., 1994)) to better understand the changing nature of the iceberg extinction zone in the North Atlantic. A large gap in future climate is the frequency and transport of icebergs southward from Greenland may change over time (King & Turnbull, 2022).

3.11.3 FREEZING SPRAY AND ICE ACCRETION

The occurrence of freezing spray is dependent on a combination of atmospheric and oceanic variables and may be calculated when required. Climate change data, such as sea surface and air temperatures and wind data from the CMIP-6 database (Stockhause, et al., 2021) may be used to determine future projections of freezing spray within all the sub-regions. A site-specific forward-looking estimation of freezing spray parameters and risks can be assessed using downscaled future metocean climate projections.

Direct in situ measurements of icing on structures and vessels with corresponding meteorological and sea state data is infrequently collected. Methods appropriate to the site and situation for assessing freezing spray which have been reviewed (Dhar, et al., 2023) and should be applied in developing in situ measurement programs as part of baseline data collection activities.

3.11.4 REGIONAL DATA GAP OPPORTUNITIES

The following tools may offer opportunities to address some of the above-noted data gaps, with respect to supporting safe designs for wind turbines may be explored further.

These tools represent existing information, technologies and statistical tools developed for the offshore oil and gas sector in Newfoundland and are considered to be invaluable for offshore wind developers. These tools offer spatial coverage that aligns with the scope of this study and are accessible online.

3.11.4.1 C-CORE RAPID ICEBERG PROFILING SYSTEM

In June 2017, C-CORE conducted a successful iceberg data collection program in Bonavista Bay, NL, showcasing its Rapid Iceberg Profiling technology. The research team employed a Light Imaging, Detection, and Ranging (LIDAR) sensor above the waterline and a multibeam SONAR sensor below it, completing three circuits around icebergs to generate 3D models within an hour. This innovative approach eliminated the time-consuming process of photogrammetry and provided comprehensive above-water and below-water iceberg profiles. The collected data, including metocean conditions, was processed through C-CORE's Ice Management Decision Support software, which offers insights and recommendations for deployment and towing strategies. Beyond the immediate applications, the 3D profiles contribute to an understanding of iceberg drift and melt factors and enable accurate simulations of iceberg-infrastructure interactions, which aids engineers in developing safer designs for vessels, platforms, pipelines, and subsea cables.

3.11.4.2 C-CORE PIPELINE ICE RISK ASSESSMENT AND MITIGATION (PIRAM)

The Pipeline Ice Risk Assessment and Mitigation (PIRAM) Joint Industry Program, led by C-CORE from 2007 to 2009 with a budget of nearly $5 million, addressed the crucial need for environmentally appropriate transportation solutions in ice environments. Funded by C-CORE, seven oil and gas companies, and the Atlantic Innovation Fund, PIRAM aimed to advance safe and reliable pipeline infrastructure for field developments. The program developed methodologies to assess contact frequency and impact loads from gouging ice keels, determined pipeline mechanical behaviour in response to ice keel loading events, and created engineering models and procedures for industry best practices related to risk mitigation and pipeline protection from ice keel loading. PIRAM significantly enhanced pipeline routing and burial optimization approaches, leading to substantial cost reductions, and its models, initially focused on the Beaufort Sea, are adaptable to various ice-prone regions requiring export cables. The program's findings emphasized the importance of multiple fingered keels and conducted groundbreaking ice keel tests, contributing to a better understanding of ice limits and enhancing overall knowledge in this field.

3.11.4.3 ECCC SEA ICE TRACKING SYSTEM

The Environment and Climate Change Canada automated sea ice tracking system (Howell et al., 2022), is an excellent resource for sea ice motion. As Arctic Sea ice diminishes, the significance of remote sensing observations for monitoring and comprehending sea ice becomes increasingly crucial. The introduction of synthetic aperture radar (SAR) satellites operating at C-band, such as Sentinel-1A, Sentinel-1B (S1), and RADARSAT Constellation Mission (RCM), has ushered in a new era in the sea ice community. This study introduces and validates the Environment and Climate Change Canada's automated sea ice tracking system (ECCC-ASITS), which utilizes SAR imaging from S1 and RCM to routinely generate large-scale sea ice motion (SIM) data over the pan-Arctic domain. Applying ECCC-ASITS to the image streams from March 2020 to October 2021, the study produces new SIM datasets with improved coverage, particularly in regions like Hudson Bay, Davis Strait, Beaufort Sea, Bering Sea, and the North Pole. Validation against data collected from buoys demonstrates the robustness of ECCC-ASITS, providing comprehensive and accurate large-scale SIM data entirely from SAR imagery across the pan-Arctic domain.

This product could hypothetically be extended further south to cover much of Atlantic Canada where sea ice is a concern; however, an assessment of the frequency and coverage of necessary satellite information would need to be conducted to determine its feasibility (Personal Comm. Dr. Alexander Komarov, November 21st, 2023). It is likely that for some areas, including much of the Gulf of St. Lawrence and the southern limits of the Newfoundland Shelf waters, this ECCC ice tracking system would be effective in detecting and measuring iceberg velocities and momentum.

3.11.4.4 C-CORE ICE RISK ANALYSIS FOR FLOATING WIND TURBINES, OFFSHORE NEWFOUNDLAND AND LABRADOR

King & Turnbull (2022) have conducted an analysis on the risk of ice impact on floating wind turbines in the offshore waters of Newfoundland and Labrador. The imperative to reduce greenhouse gas emissions in the offshore hydrocarbons production sector has spurred interest in exploring offshore wind as an alternative to on-platform power generation. While certain offshore regions are moving forward with plans to electrify hydrocarbon-producing platforms using offshore wind, they do not face the specific challenges inherent in the offshore environment of Newfoundland and Labrador.

The latter region is susceptible to icebergs and pack ice incursions, posing a potential threat to offshore wind turbines. The analysis methodology employed by King & Turnbull (2022) to evaluate these risks, along with initial findings, is outlined for floating offshore wind turbines (FOWT). An Area of Interest (AOI), spanning from 45°N to 51°N and 45°W to 51°W, was designated, covering all development licenses in the Grand Banks, Flemish Pass, and Orphan Basin.

Calculations of iceberg and pack ice contact rates and loads utilized data from the Nalcor Energy Exploration Strategy System (NESS) Metocean database, Canadian Ice Service (CIS) ice charts, and satellite imagery. Assessment of ice loads corresponding to 50-year return periods, both with and without ice management, provides a foundation for determining the necessity of ice management and/or disconnection capabilities. Furthermore, the study includes modelling of the frequency and severity of atmospheric icing on turbines using available data and models.

4. WP3: Waves, Ocean Currents, Water Levels, and Marine Growth Data Collection

In the following section, an example of the terms of reference (TOR) document required ahead of a data collection campaign of wave, current, and water level data is provided. The TOR provides a basis of recommendations for collecting new metocean data in the Atlantic Canada region. The outcome of the gap analysis of these key variables is that there are minimal physical measurements available for currents and water levels in the study area. However, there is partial coverage of wave datasets across the same region.

It is important to note that detailed recommendations regarding the placement of instruments are not provided. Ideally, these considerations should be taken into account once the lease areas have been defined by the Client. The following figure displays a suggested survey grid for waves and wind data collection. The locations are high-level and based on the availability of physical measurements presented Figure 3-2. An equidistant grid (0.5-degree) was placed in the regions outside of the 0.5-degree radius around the existing datasets provided by DFO. Data collection efforts should be aligned with the outcomes of the two ongoing regional assessments of offshore wind (Government of Canada, 2022).

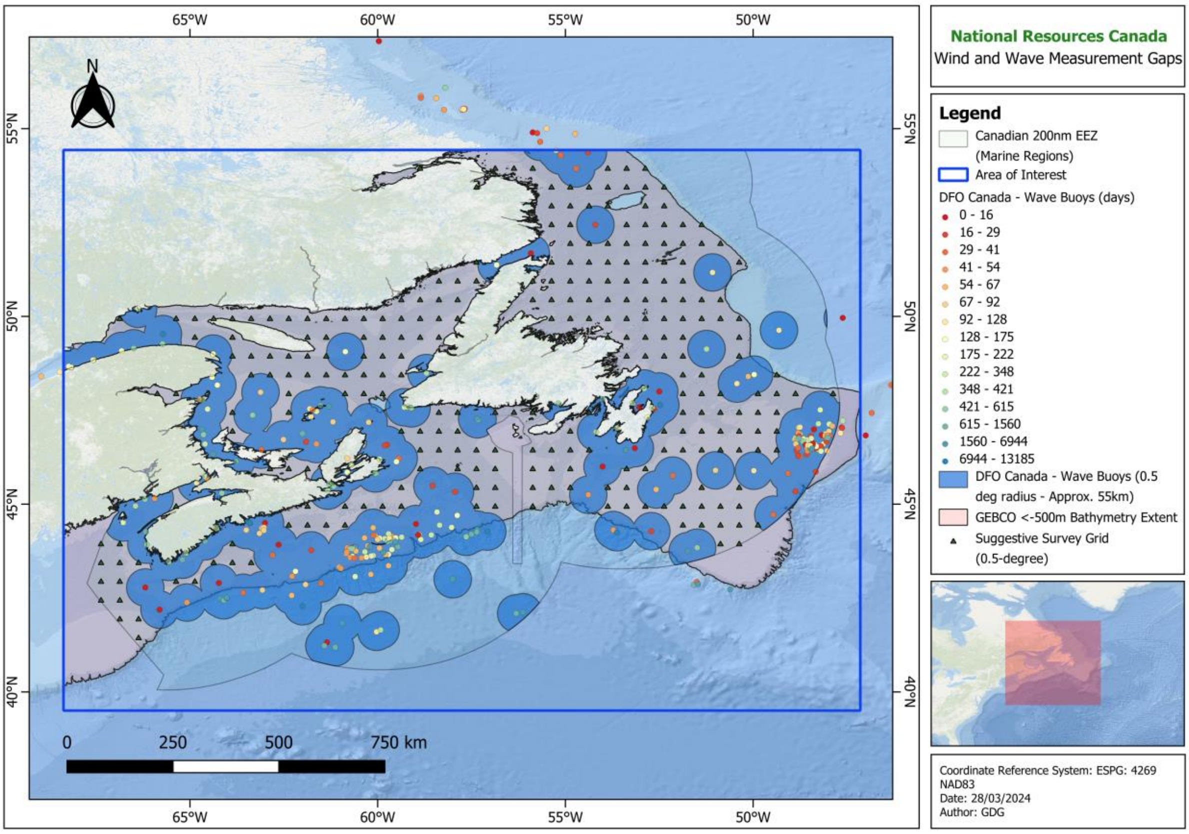

Figure 4-1 – Proposed positioning of survey equipment is recommended based on the availability of physically measured wind and wave data.

4.1 Background and Project Area

Background

Interest and support for offshore wind power in Atlantic Canada has grown considerably over recent years, and policymakers are increasingly recognizing that Canada has vast offshore wind resources that can contribute to its clean energy and climate objectives. The Impact Assessment Agency of Canada (IAAC) is undertaking Regional Assessments for offshore wind in both Nova Scotia and Newfoundland (Guilbeault, 2022), and the Government of Nova Scotia has announced a target of 5 GW of offshore wind capacity by 2030 (Government of Nova Scotia, 2022).

To support the cost-effective, and environmentally and socially responsible deployment of offshore wind power in Canada, an improved understanding of meteorological and ocean conditions relevant to existing and emerging offshore wind technologies is required.

Various European countries, and more recently the United States, have conducted metocean data needs and gap assessments before deploying offshore wind in their respective jurisdictions, as a means of synthesizing existing relevant information and ensuring that future data collection could be carried out in an efficient and organized manner (DNV, 2018; AWS Truepower et al., 2015).

Project area

The study area covers the region highlighted in Figure 1-1. Once the Client has defined the Offshore Wind Farm lease areas, further refinements to the project area and device placement can be investigated.

4.2 Objectives

The main purpose of a metocean survey campaign is to collect accurate wind, wave, current and water level information within the area of interest, that will be used to:

- Feed into structural design, and
- Estimate workability range at offshore sites, for defining the construction and O&M strategies.

The recommended survey methods are outlined in the following sections.

As a general guideline, the minimum duration of a measurement campaign should not be less than 24 months to account for seasonal variability.

A separate term of reference (TOR) is designed for wind measurements (Section 5). However, measurement campaigns should be aligned to ensure simultaneous wind, wave, and current measurements. The measurement campaign timeline should consider planning requirements, any necessary permitting, and set-up and validation periods (such as required for a floating lidar unit).

The next immediate sections (Sections 4.3 to 4.6) address the data collection relevant to ocean currents, water levels and waves, which is the followed by the wind and ice-related measurement activities and recommendations.

4.3 Methodologies

4.3.1 Equipment deployment and recovery vessel

The method for deploying metocean monitoring equipment should involve using a suitable vessel capable of either towing or lifting and deploying the equipment from the vessel deck using an A-frame. All monitoring devices should be collected upon decommissioning by detaching the connection moorings and loading the monitoring devices onto a vessel and transporting all equipment to port. All elements of the mooring systems should be removed at the end of the metocean data gathering campaign and no equipment will be left on the seabed.

4.3.2 Ocean Currents and Water Levels

4.3.2.1 Background

Acoustic Doppler Current Profiler (ADCP) frames should be deployed onto the seabed at positions across the site to collect data on water movements, current speeds, and directions at the project site. The ADCP type will be finalized upon selection of contractor however the following specifications should be considered which are based on the Nortek Signature500 ADCP which is both a current profiler and a wave directional system in one unit:

- Current:
    - Acoustic Frequency: 500 kHz
    - Measurement interval: 600 s
    - Sample duration: 120 s
    - Cell size: 1 m
    - Blanking distance: 0.5 m
- Waves:
    - Measurement interval: 30 mins
    - Frequency: 2 Hz

Ideally, each ADCP placed should be spread evenly across the site, taking into consideration the changes in water depth. The precise placement should be discussed upon appointment of contractor but if the bathymetry is complex, they should be placed at distinct changes in water depth to capture site variability. The deployment duration should be 24 months of continuous recording taking into consideration downtime for the operation and maintenance of the device (see Section 4.3.2.6).

4.3.2.2 Indicative quantity

For a successful measurement campaign, redundancy in instrumentation is required. As a minimum, two instruments measuring simultaneously should be deployed, ideally of a different type (e.g. a wave-rider buoy and an ADCP). If water depths across the site vary significantly (more than 10 to 15 m) and if the bathymetry is complex, additional instruments should be used to capture site variability.

Indicative quantity: 2 to 4.

4.3.2.3 Method

Deployed to the seabed via an A-frame from a survey vessel for at least 24 months.

4.3.2.4 Indicative Equipment

A typical ADCP unit consists of a mechanical measurement instrument housed within a trawler-resistant protection frame. Typical installation layouts consist of the frame being connected to a weighted base with a weight of approx. 300 kg. This should be attached to a ground line, a clump weight, and an acoustic release system carrying a rope retrieval system. The seabed frame should be equipped with conductivity, temperature, depth (CTD), and ADCP.

4.3.2.5 Instrument accuracy and operation performance requirements

Following the ISO 19901-1: 2015 (ISO, 2015b) recommendations, ocean currents should be measured at fixed depths and include at least three depths in shallow waters: near-surface, mid-depth, and near-bottom. The mean speed and direction of ocean currents should be recorded at least once per hour for at least 10-20 minutes, or more often if possible. The recommended instrument accuracy and operational performance from ISO 19901-1:2015 (ISO, 2015b) are given in Table 4-1.

Sea-water temperature, density, and salinity are usually obtained from a CTD (conductivity-temperature-depth) device. Where a CTD is used, the data should be stored at least for every 50 kPA increase in pressure. The requirements for data collection are also set out in ISO 19901-1:2015 (ISO, 2015b) (Table 4-1).

Table 4-1 - Recommended instrument accuracy and operational performance – ocean current, sea-water temperature, and salinity

Variable		Range	Reported resolution	Required measurement uncertainty	Sensor time constant	Output averaging time	Typical operational performance	Remarks
Ocean current	Current speed	$0\ cm\ s^{-1}$ to $250\ cm\ s^{-1}$	$1\ cm\ s^{-1}$	$1\ cm\ s^{-1}$ to $10\ cm\ s^{-1}$	1 s	5 min to 20 min	$2\ cm\ s^{-1}$ to $10\ cm\ s^{-1}$	Achievable accuracy affected by type of measurement; direct or acoustic doppler profilers
	Current direction	0° to 360°	1°	$\pm 5°$	1 s	5 min to 20 min	$\pm 5°$	
Temperature	Air temperature	$-40°C$ to $+40°C$	0.1K	0.1K	20 s	1 min	0.2K	Operational performance and effective time constant can be affected by the design of thermometer solar radiation screen
	Extremes of air temperature	$-40°C$ to $+40°C$	0.1K	0.1K	20 s	1 min	0.2K	
	Sea-surface temperature	$-2°C$ to $+40°C$	0.1K	0.1K	20 s	1 min	0.2K	
Temperature profile		$-2°C$ to $+25°C$	0.1K	0.01K	0.5 s	1 min	0.05K	Achievable accuracy according to commonly used CTD sensors
Salinity profile		0 to 40 PSU	0.1	$\pm 0.01\ PSU$	0.5 s	1s	$\pm 0.05\ PSU$	As per temperature profile unit: PSU (Practical Salinity Unit) according to PSS78.

Tidal level data should be provided through the pressure gauge in the ADCPs. Water levels offshore should be measured with a resolution and instrument accuracy of ± 1 cm. The output averaging time should be 10 minutes, and the sampling frequency at least 1 Hz.

4.3.2.6 OPERATIONS AND MAINTENANCE OF THE DEVICE

Periodic servicing should be carried out every 3 months. This includes recovery to a workboat via crane/A-frame with a winch.

- During each service visit the following should be completed:
    - Shackles should be inspected and replaced as required.
    - Anodes should be inspected and replaced as required.
    - Mooring lines should be replaced as required.
    - Download the recorded data and check to ensure that the equipment is performing correctly.
    - Cleaning of the measurement systems (ADCP and CTD Tu sensor) to remove any biofouling that may have accumulated.
    - Installation of new batteries.
    - Thorough check of the equipment and replacement of any damaged equipment.

Once servicing of the equipment is completed the seabed frame should be redeployed to the seabed at the same location. Mooring systems should also undergo periodic replacement. Over the monitoring period, it is recommended that the mooring is replaced after every six months. This is however variable dependent on the findings of the planned mooring inspections.

4.3.2.7 DEVICE RECOVERY

The recovery methodology for the ADCP should be refined pending further investigation into the suitable deployment method at the site. However, two types of recovery are recommended; an acoustic release method or a grapple recovery method.

4.3.3 WAVES

4.3.3.1 BACKGROUND

In order to capture current and wave data, surface tracking wave buoys with an integrated current profiling unit and satellite-based data transmission system should be deployed at the site. This should enable higher resolution current and wave data as well as near-seabed properties, ensuring higher degrees of accuracy to support project design criteria and logistical planning in the construction, operation, and maintenance phases of the project.

4.3.3.2 INDICATIVE QUANTITY

For a successful measurement campaign redundancy in instrumentation is required. As a minimum, two instruments measuring simultaneously should be deployed, ideally of a different type (e.g. a wave-rider buoy and an ADCP). If water depths across the site vary significantly (more than 10 to 15 m) and if the bathymetry is complex, additional instruments should be used to capture site variability.

Indicative quantity: 2 to 3

4.3.3.3 Method

A surface floating wave buoy should be deployed within the survey area and held in position via a suitable specified mooring configuration comprising a mooring chain/rope and anchor. Wave buoys should be deployed on location for a period of a minimum of 24 months taking into consideration downtime for operation and maintenance time (see section 4.3.3.7). Sampling details are typically finalized with the contractor, but the following specifications should be considered (based on the Triaxys G3 sensor equipped with a downward-looking Nortek current profiler):

- Triaxys G3 sensor:
  - Sampling Frequency: 4 Hz
  - Frequency Range: 0.64 Hz (1.56 seconds) to 0.030 Hz (33.33 seconds)
  - Frequency Spacing: 0.005 Hz
  - Sample Duration: 17 minutes
  - Sampling Interval: 30 – 60 minutes
- Nortek Signature 500 Profiler:
  - Current speed and direction every 10 minutes
  - Profile interval 120 seconds
  - 0.5 to 4 m cells

4.3.3.4 Indicative Equipment

Typical wave measurement buoys such as the Datawell and Triaxys Waves and Currents buoy that provide directional wave spectral information should be deployed. Ideally, the wave buoy should be equipped with a downward-looking current profiler to provide additional current profile characteristics (velocity and direction). The surface buoys should be fitted with an amber flashing obstruction LED light, with a programmable flashing sequence visible from three miles, to mitigate the risk of collision.

4.3.3.5 Instrument Accuracy and Operation Performance Requirements

The requirements for data collection are set out in ISO 19901-1:2015 (Annex A.11, Table A:8, in turn, based on Annex 1.B, pp 19-24, Chapter 1, of WMO-No. 8:2008) (ISO, 2015). These are summarised in Table 4-2. The table presents the required measurement range, resolution, and operational performance to result in suitable data for each type of wave information.

Table 4-2 - Recommended instrument accuracy and operational performance - waves

Waves Variables	Variable Subset	Range	Reported resolution	Required measurement uncertainty	Sensor time constant	Output averaging time	Typical operational performance	Remarks
1.Time series of sea surface elevation	N/A	-15 m to +20 m	0.1 m	N/A	0.5 s	n/a	$\pm 0.2\ m$ for $\leq 5\ m$ $\pm 4\ \%$ for $> 5\ m$	Length of time series 17 min (typical) sampling frequency 2 Hz.
2.Variables from time series (zero crossing analysis)	2A. Significant wave height (H_s)	0 m to 20 m	0.1 m	0.5 m for $\leq 5\ m$ 10 % for $> 5\ m$	0.5 s	20 min (typical)	Depends on averaging time and sea regularity as well as intrinsic instrument accuracy	N/A
	2B. Average zero crossing period (T_z)	3 s to 30 s	1 s	0.5 s	N/A	20 min (typical)		N/A
	2C. Maximum wave height (H_{max})	0 m to 35 m	N/A	N/A	N/A	20 min (typical)		Observed value at location of sensor. New value every 30 min (typical)
3.Wave spectrum	3A. 1-D spectral density	N/A	0.1 m² Hz^{-1}	N/A	N/A	Minimum 17 min	Depends on averaging time and sea regularity as well as intrinsic instrument accuracy. Should be sufficient to achieve number 4. requirements	Instruments may include wave buoys, altimeter, microwave doppler radar, HD radar, navigation radar etc. (1 Hz sampling frequency is sufficient).
	Frequency	0.035 Hz to 0.3 Hz	<0.01 Hz	N/A	N/A	N/A		N/A
	3B. 2-D spectral density		0.1 m² $Hz^{-1}rad^{-1}$	N/A	N/A	N/A		N/A
	Frequency	0.035 Hz to 0.3 Hz	< 0.01 Hz	N/A	N/A	N/A		N/A
	Direction	0° to 360°	10° (see remark)	N/A	N/A	N/A		2-D spectrum may be based on parameterized directional distribution and reported as direction and spread parameters.
	4A. Significant	0 m to 20 m	0.1 m	N/A	0.5 s	20 min	N/A	N/A

Waves Variables	Variable Subset	Range	Reported resolution	Required measurement uncertainty	Sensor time constant	Output averaging time	Typical operational performance	Remarks
4.Variables from wave spectrum	wave height (H_{mo})							
	4B. Average period (T_{m02})	3 s to 30 s	0.1 s	N/A	0.5 s	20 min	0.5 s	N/A
	4C. Peak period (T_p)	3 s to 30 s	0.1 s	N/A	0.5 s	20 min	0.5 s	Period of peak of frequency spectrum.
	4D. Mean direction	0° to 360°	10°	N/A	0.5 s	20 min	20°	May be spectrally averaged or based on angular harmonics
	4F. Direction spread	0° to 360°	10°	N/A	N/A	N/A	20°	

4.3.3.6 MOORING SYSTEM

The mooring design should be based on the supplier's recommended configuration and using mooring equipment (ropes, shackles, ground weights etc.) that exceed the minimum requirements, to ensure continued data recovery.

Certified mooring components should be utilised to ensure moorings are able to withstand the site-specific metocean conditions. Mooring lines should be provided as per the specifications recommended by suppliers and according to the water depths at the deployment locations chosen. Tidal range expected wave and meteorological conditions should also be factored into the final mooring design.

4.3.3.7 OPERATIONS AND MAINTENANCE OF THE DEVICE

The metocean buoys require regular maintenance and inspection to ensure the integrity of the moorings and anodes and ensure battery continuity. All O&M operations should take place onboard the working vessel. During each service visit the following should be completed:

- Inspection of mooring systems,
- Shackles should be inspected and replaced as required,
- Anodes should be inspected and replaced as required,
- Mooring lines should be replaced as required,
- The bungee should be replaced if worn or damaged,
- A spare ground weight should be taken in case of total loss during recovery,
- The outer housing should be inspected and replaced as necessary,
- Battery status should be confirmed and compared to the transmitted battery status report,
- Data should be downloaded, and the memory card checked for capacity,
- Satellite and data transmission should be verified.

Once servicing of the equipment is completed the systems should be redeployed at the same location.

4.3.4 Marine Growth

4.3.4.1 Background

Living organisms attach to offshore structures, and this marine growth can affect hydrodynamic loads, dynamic response, accessibility, and corrosion rate. The magnitude of these effects depends on the thickness and nature (i.e., hard vs soft) of marine growth, which vary based on geography and site-specific conditions. The approach outlined below follows standard recommendations (ISO, 2015c; DNV, 2018; DNV, 2016c; DNV, 2021a) for site-specific studies, which can provide more accurate data to inform engineering decisions and determine the required removal of marine growth. Site-specific studies can include:

(1) A desktop analysis that predicts the thickness and nature of marine growth.

(2) An optional targeted field study that quantifies marine growth on structures deployed locally if there is insufficient existing data to support a desktop analysis.

(3) Inspections that confirm the thickness of marine growth and strategically remove marine growth as necessary and at a frequency informed by the desktop analysis, targeted field study, and previous inspections.

4.3.4.2 Indicative Quantity

The indicative quantity for each site-specific study can include:

(1) The desktop analysis should incorporate existing data, including measurements and observations reported in databases, published in reports, and shared by local people with knowledge of the system.

(2) An optional targeted field study should deploy structures on the benthos and suspended in the water column, ideally with a minimum of three replicate structures for each selected habitat type and depth strata.

(3) Inspections can include a subset of the assets, with a minimum of three assets for each selected habitat type and depth strata. If marine growth approaches engineering limits within a single habitat or depth strata, then inspections should expand to include additional assets to strategically remove marine growth as necessary.

4.3.4.3 Method

The method applied for each site-specific study can include:

1) The site-specific desktop analysis should predict the thickness and nature of marine growth by depth and habitat type, by incorporating empirical observations in an analysis that weights the effect size reported in separate studies by its precision. Additionally, the desktop analysis should generate a list of hard and soft biota that could colonize offshore structures, based on habitat- and depth-specific observations from the region. This list should specify taxa-specific densities, if available.

2) An optional targeted field study should deploy structures composed of the same material that will comprise structures in proposed wind farms; these studies should monitor marine growth on these structures for a minimum of four years.

3) Inspections should assess and possibly remove marine growth in Y0, Y1, Y2, Y3, and Y5, with modifications informed by the desktop analysis, targeted field study, and previous

inspections. If there are insufficient existing data to support a desktop analysis and there was no targeted field study, then initial inspections could occur at an increased frequency (<1 year) to ensure marine growth does not exceed engineering limits and to optimally set frequency of future inspections.

4.3.4.4 Indicative Equipment

The indicative equipment for each site-specific study can include:

1) The desktop analysis should incorporate existing data to predict the thickness of marine growth in millimeters (mm) and specify the associated variance (95% confidence interval), sampling effort (number of locations and studies included in the analysis), and spatial extent of the geographic region included in the analysis.

2 and 3) The targeted field study and/or inspections of offshore structures should evaluate marine growth using ultra-high-definition (UHD) video collected by a camera mounted to a remotely operated vehicle (ROV). In addition to a visual assessment, the inspection can measure the thickness of marine growth and clean targeted areas using a manipulator arm on the ROV. Using the UHD video, the inspection can reconstruct a three-dimensional (3D) model of the structure to identify areas of thicker marine growth on the structure, with potential implications for the center of gravity. Using the measurements collected with the manipulator arm, the inspection can ground-truth measurements made using the 3D models. If the 3D models can quantify the thickness of marine growth with sufficient resolution, future inspections do not need to include these ground-truth measurements.

Some state-of-the-art ROV equipment is available on the market, some examples specifically for offshore structure and marine growth inspection may be found in (McLean, et al., 2020).

4.3.4.5 Accuracy and Operation Performance Requirements

Typically, marine growth predictions are reported in 10 mm intervals, although for some regions, predictions are reported at a higher resolution (DNV, 2016c, 2021a). Depth-specific predictions should distinguish marine growth in shallow water (<40 m) and deeper water (>40 m) (DNV, 2016c, 2021a). If taxa-specific densities are available, then these values can provide a more accurate estimate of weight, instead of using the standard density of 1325 kg/m^3. Typically, marine growth increases within the first two years of installation and can require strategic removal after four years, however, marine biota do not always recolonize cleared space. As possible, site-specific studies should specify the dominant marine biota, the settlement season, growth rates, coverage (%), terminal thickness, and depth range.

4.3.4.6 Multi-purposed inspections

In addition to engineering considerations, marine growth requires inspections that can evaluate potential environmental impacts. If the same inspection and dataset can meet engineering and environmental requirements, then the industry can reduce costs, risks, and demand for vessels by planning multi-purposed inspections. In addition to ROV video, inspections can non-invasively evaluate the potential environmental impact using non-extractive tools such as Sediment Profile and Plan View Imaging (SPI/PV) to monitor the recovery of soft sediments and Baited Remote Underwater Video (BRUV) to characterize spatial and temporal variation in fish populations.

4.3.4.7 METHODS FOR MARINE GROWTH REMOVAL

Following an assessment of marine growth, teams can remove excessive marine growth using a remotely operated vehicle (ROV) (Pedersen et al. 2022). However, marine growth removal campaigns can become a time-consuming task. Therefore, campaigns should focus on areas with excessive growth and select appropriate instrumentation to efficiently remove marine growth.

Removal campaigns can focus on areas with excessive growth by first conducting assessments that capture spatial variation using spot checks or image-based methods that virtually reconstruct the 3D surfaces using video or images captured from a camera mounted to the ROV (Gormley et al 2017, Massot-Campos and Oliver-Codina, 2015). Image-based approaches can also increase efficiency and consistency, particularly, when using algorithms to automate image analysis (Gormley et al 2017).

Appropriate instrumentation encompasses the necessary tools and features to adequately control and position the ROV, and to remove marine growth (Pedersen et al. 2022). To be most effective, the campaign should select a tool based on the type of marine growth (i.e., hard versus soft biota). Then, ROVs can remove marine growth using a high-pressure water jet or mechanically with a tool attached to a manipulator arm (Sivčev et al 2018, Oil and Gas UK).

4.4 QUALITY CONTROL AND DATA MANAGEMENT

4.4.1 QC TECHNIQUES

Data quality control includes the assessment of the communication and operation of data acquisition systems, power supplies, and measured data. These should be reviewed every six months to help ensure high-quality data. Data reviews should include:

- Visual inspection of the data to ensure it lies within the sensor measurement range and expected range for the climate and time of year. The visual inspection is used to identify erroneous spikes, dropouts, or nonsensical trends in the data. At a minimum, a visual inspection should include:
  - Time series and scatter plots of data from redundant sensors.
  - Time series and scatter plots of data at different elevations.
  - Time series and scatter plots of data between measurement locations (if available).
  - Time series review of data from power systems, such as battery voltage, to ensure adequate power is being supplied.
- Correlation tests
- Examination of data coverage of the number of valid records within the averaging periods and the availability of the entire data record over time. Poor data coverage is an indication of either a systematic sensor or recording error, or the inability of the sensor to operate at the climatic conditions at the site.
- Check that the data acquisition system is not omitting or duplicating timestamps.
- Identify and exclude sensor failures or periods of erroneous data.
- Test for trends and inconsistencies.

4.4.2 Storage and Access

The data acquisition system should be able to store all recorded data between site inspections. If applicable, it should also be operated remotely or accessed to modify programming, synchronize the clock, or download data. It is highly recommended that the data be autonomously transmitted by the device to a secure location on a daily basis.

4.4.3 Metadata

Documentation should include commissioning reports, inspection and maintenance logs, and decommissioning reports. Reporting requirements are provided in Annex A of MEASNET ESSWC and are summarised in Table 4-3.

Table 4-3 - Required documentation for a measurement campaign

No	Report contents	Details to include
1	Location	• Coordinates, coordinates system and accuracy of position • Photo documentation of position and bearing, surroundings • Magnetic declination
2	Measurement equipment	• Type and dimensions • Specify the height and orientation • Photograph of installed and replaced equipment (if possible) • Serial number(s) • Calibration report(s) • Distance to obstacles such as nearby turbines, platforms or masts (if applicable) • Power supply and/or heating (if applicable)
3	Measurement data	• Start and end dates of calibration factors or offsets applied • Sampling rate and averaging periods
4	Measurement history	• Date and time of installation/maintenance/decommissioning • Changes to equipment, datalogger programs or firmware (include data and time) • Log of observed equipment failure, power supply problems etc. Start and end dates of these events should be noted in the log • Equipment location changes (if applicable)
5	Other documentation	• Validation report for remote sensing devices

4.4.4 Relevant Standards and Guidelines

The relevant standards and guidelines for the previously mentioned data collection activities are listed in this section.

The survey contractor and vessels should comply with international and national statutes as appropriate. A non-exhaustive list of examples includes:

- S.I. No. 372/2012 - Sea Pollution (Prevention of Pollution by Garbage from Ships) Regulations 2012.
- S.I. No. 492/2012 - Sea Pollution (Prevention of Pollution by Sewage from Ships) (Amendment) Regulations 2012
- S.I. No. 507/2012 - Merchant Shipping (Collision Regulations) (Ships and Water-Craft on the Water) Order 2012.

Relevant standards and guidelines are outlined in Table 4-4.

Table 4-4 – Relevant standards and guidelines

Reference	Title
API RP 2MET	API Recommended Practice 2MET – Derivation of Metocean Design and Operating Conditions (modified version of ISO 19901-1:2015); November 2014 https://www.techstreet.com/api/standards/api-rp-2met?product_id=1886618
CTC870	Carbon Trust Offshore Wind Accelerator Recommended Practice for Floating LiDAR Systems, October 2016 https://www.carbontrust.com/media/673560/owa-floatinglidarrecommendedpractice-25oct2016-final.pdf
DNVGL-ST-N001	Marine operations and marine warranty https://rules.dnvgl.com/docs/pdf/dnvgl/st/2016-11/DNVGL-ST-N001.pdf
DNVGL-ST-0119	Design of Floating Wind Turbine Structures http://rules.dnvgl.com/docs/pdf/dnv/codes/docs/2013-06/os-j103.pdf
DNV GL 10039663-HOU-01	Metocean Characterization Recommended Practices for U.S. Offshore Wind Energy https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Renewable-Energy/Metocean-Recommended-Practices.pdf
DNVGL-SE-0190	Project certification of wind power plants https://rules.dnvgl.com/docs/pdf/DNVGL/SE/2015-12/DNVGL-SE-0190.pdf
DNVGL-ST-0437	Loads and site conditions for wind turbines https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-11/DNVGL-ST-0437.pdf
IEC 61400-12-1	Power performance measurements of electricity producing wind turbines https://webstore.iec.ch/publication/60076
IEC 61400-3	Wind Turbines – Part 3: Design requirements for offshore wind turbines https://webstore.iec.ch/publication/5446
ISO 19901-1	Petroleum and natural gas industries -- Specific requirements for offshore structures – Part 1: Metocean design and operating considerations https://www.iso.org/standard/60183.html
ISO/IEC 17025	General requirements for the competence of calibration and testing laboratories https://www.iso.org/publication/PUB100424.html
MEASNET ESSWC	MEASNET Procedure: Evaluation of Site-Specific Wind Conditions. Version 2, April 2016

Note suppliers are required to create risk management plans for each of the required surveys.

4.5 Reporting and Deliverables

4.5.1 Reporting requirements

The report for a metocean study involving the collection of metocean data through in-situ measurements should as a minimum (in addition to any data result reported) contain:

- Specification of the requirements set out at the beginning of the metocean measurement campaign.
- Choice of instrument selection to fulfill the requirements, including an explanation of the choice and comparison with other options available.
- Details of the instrumentation, including as a minimum the provider, key data facts of each instrument, calibration, and expected performance.

- Instrumentation deployment report, including details and photos of the vessel and operation.
- Maintenance record of the instrumentation as appropriate.
- Instrumentation recovery report, including details and photos of the vessel and operation and any observed failures or damage to the instrument.
- Measured dataset details, including data return achieved and overall success of data collection campaign.
- Any post-processing or quality control procedures undertaken after data collection.
- Any other information not mentioned above relevant to the end-user of the datasets.
- Report detailing survey results at all locations:
  - Significant wave heights, maximum wave heights and crests, wave periods and directions for normal and extreme conditions including joint probability of various wave conditions.
  - Joint probability distribution of various wind and wave conditions.
  - Current speeds and directions for normal and extreme conditions are crucial. This includes breaking down various components of sea current velocity into sub-surface currents, wind-generated currents, near shore currents, and total current velocity.
  - Water levels including tides, extreme water levels, and sea level change.
  - Water density, water salinity and water temperatures.

4.6 SCHEDULE / PROGRAMME

Table 4-5 – Example Deployment Schedule

Activity	Typical Time Period Required for Activity	Days	Total Time for SIs
ADCP	24 months in any one location At least 24 months total	365 to 730	Actual deployment at each location will include 1 day to deploy and 1 day to retrieve. May be deployed at same time as wind resource survey.
Wave Rider Buoy	24 months in any one location At least 24 months total	365 to 730	Actual deployment will include 1 day to deploy and 1 day to retrieve. May be deployed at same time as wind resource survey.

5. WP3: Wind Data Collection

5.1 Background and Project Area

Background

Please refer to the Section 4.1 for additional background information.

This work is focused specifically on the metocean characteristics of Atlantic Canada and the metocean data collection efforts necessary to support offshore wind development. The proceeding text (Section 4) provides an example of the terms of reference documents (TOR) required to support the collection of wind data. The information follows IEC 61400-15-1 guidelines (IEC, 2023).

Project Area

The study area covers the region highlighted in Figure 1-1. Once the Client has defined the Offshore Wind Farm lease areas further refinements to the project area and device placement can be investigated.

5.2 Objectives

The objective of the wind resource survey campaign is to precisely characterize the wind conditions at the project site, which will serve the following purposes:

1. Conduct energy yield assessments, and
2. Feed into turbine selection, operational planning, and structural design.

Recommendations regarding survey methods are detailed in the preceding sections.

The minimum duration of a floating lidar measurement campaign should be not less than 24 months to cover seasonal variability.

A separate TOR is designated for metocean surveys; however, the measurement campaigns should be synchronized to ensure simultaneous wind, wave, and current measurements. The timeline for the measurement campaign should accommodate planning requirements, any necessary permitting, and set-up and validation periods, as required for a floating lidar unit.

5.3 Methodologies

5.3.1 Equipment Deployment and Recovery Vessel

The methodology for the deployment of floating lidar wind resource monitoring equipment should be with a suitable vessel to either tow and/or lift and deploy from the vessel deck via an onboard crane. All monitoring devices should be collected upon decommissioning by detaching the connection moorings, loading the monitoring devices onto a vessel and transporting all equipment to port. All elements of the mooring systems should be removed at the end of the data-gathering campaign and no equipment should be left on the seabed.

5.3.2 Wind Resource (Floating Lidar)

One of the common approaches to wind data collection in the offshore industry is using floating lidars. The objective of a floating lidar campaign is to gather precise wind and metocean data from the project site. This data will be utilized for conducting energy yield assessments, informing structural design decisions, and, considering the significance of weather downtime at offshore sites, defining construction, operation, and maintenance strategies. Specific data requirements are outlined in Section 5.5.1.

A surface and self-powered floating lidar buoy should be deployed within the survey area and held in position via a suitable specified mooring configuration comprising a mooring chain/rope and anchor.

5.3.2.1 INDICATIVE QUANTITY

Indicative quantity per OWF site: 1 to 2.

Although, this depends on the size and geometry of the Offshore Wind Farm area.

5.3.2.2 INDICATIVE EQUIPMENT

Floating lidar devices are lidar sensors that are installed on a floating platform and a motion compensation system. The motion of the buoy presents six degrees of freedom (DOF). The measurement of DOF is used to correct lidar measurement to be equivalent to a mast height measurement at sea level. There are several commercially available FLD models for sea level measurements within an acceptable level of accuracy. Only FLDs that have reached a 'Commercial maturity stage as defined by the 'OWA roadmap for the commercial acceptance of floating LiDAR technology" (CTC, 2018) should be used without undergoing a validation period with a trusted reference measurement system. However, it is recommended that a validation period is undertaken as described in (CTC, 2018) and the 'Offshore Accelerator Recommended Practice for Lidar Systems' (CTC, 2016).

5.3.2.3 INSTRUMENT ACCURACY AND OPERATION PERFORMANCE REQUIREMENTS

Measurement of wind conditions (and other meteorological data) should be performed in accordance with IEC 61400-12-1 (IEC, 2022a) and should follow MEASNET ESSWC (MEASNET, 2016) procedures.

An offshore wind measurement campaign at minimum should include measurements of horizontal wind speed and wind direction from blade tip to at least hub height, 3-second maximum wind gust at hub height, and measurements of temperature and pressure at ideally hub height.

5.3.2.4 MOORING SYSTEM

The mooring design will be based on the supplier's recommended configuration and using mooring equipment (ropes, shackles, ground weights etc.).

Certified mooring components will be utilised to ensure moorings are able to withstand the site-specific metocean conditions. Mooring lines will be provided as per the specifications recommended by suppliers and according to the water depths at the deployment locations chosen. Tidal range expected wave and meteorological conditions will also be factored into the final mooring design.

5.3.2.5 OPERATIONS AND MAINTENANCE OF THE DEVICE

Maintenance should take place every six months, lasting up to two days. Visual inspection should be performed to ensure buoyancy, stability, absence of damages and overall condition. It may be required that the buoy is brought onshore to perform additional corrective maintenance works. Once servicing of the equipment is completed, the systems should be redeployed at the same location.

5.3.2.6 DEVICE RECOVERY

The recommended device recovery methodology is either an Acoustic Release Recovery or Grapple Recovery.

5.4 QUALITY CONTROL AND DATA MANAGEMENT

Please see the Section 4.4.4 for relevant standards and guidelines.

5.4.1 QC TECHNIQUES

Data quality control should include the assessment of the communication and operation of data acquisition systems, power supplies, and measured data. These should be reviewed every six months to help ensure high-quality data. Data reviews should include:

- Visual inspection of the data to ensure it lies within the sensor measurement range and expected range for the climate and time of year. The visual inspection is used to identify erroneous spikes, dropouts, or nonsensical trends in the data. At a minimum, a visual inspection should include:
  - Time series and scatter plots of data from redundant sensors.
  - Time series and scatter plots of data at different elevations.
  - Time series and scatter plots of data between measurement locations (if available).
  - Time series review of data from power systems, such as battery voltage, to ensure adequate power is being supplied.
- Correlation tests.
- Examination of data coverage of the number valid records within the averaging periods and the availability of the entire data record over time. Poor data coverage is an indication of either a systematic sensor or recording error, or the inability of the sensor to operate at the climatic conditions at the site.
- Check that the data acquisition system is not omitting or duplicating timestamps.
- Identify and exclude sensors failures or periods of erroneous data.
- Test for trends and inconsistencies.

5.4.2 STORAGE AND ACCESS

The data acquisition system should be able to store all recorded data between site inspections. If applicable, it should also have the ability to be remotely operated or accessed to modify programming, synchronize the clock, or download data. It is highly recommended that the data be autonomously transmitted by the device to a secure location on a daily basis.

5.4.3 METADATA

Documentation shall include commissioning reports, inspection and maintenance logs, and decommissioning reports. Reporting requirements are summarised in the table below.

Table 5-1 -Required documentation for a measurement campaign.

No	Report contents	Details to include
1	Location	• Coordinates, and coordinate system and accuracy of position.

		• Photo documentation of position and bearing, surroundings • Magnetic declination.
2	Measurement equipment	• Type and dimensions. • Specify the height and orientation. • Photograph of installed and replaced equipment (if possible) • Serial number(s). • Calibration report(s). • Distance to obstacles such as nearby turbines, platforms or masts (if applicable). • Power supply and/or heating (if applicable).
3	Measurement data	• Start and end dates of calibration factors or offsets applied. • Sampling rate and averaging periods.
4	Measurement history	• Date and time of installation/maintenance/decommissioning. • Changes to equipment, datalogger programs or firmware (include data and time). • Log of observed equipment failure, power supply problems etc. Start and end dates of these events should be noted in the log. • Equipment location changes (if applicable).
5	Other documentation	• Validation report for remote sensing devices.

5.5 Reporting and Deliverables

5.5.1 Reporting requirements

The report for a wind resource study involving the collection of wind resource data through in-situ measurements should as a minimum (in addition to any data result reported) contain:

- Specification of the requirements set out at the beginning of the measurement campaign.
- Choice of instrument selection to fulfill the requirements, including an explanation of the choice and comparison with other options available.
- Details of the instrumentation, including as a minimum the provider, key data facts of each instrument, calibration, and expected performance.
- Instrumentation deployment report, including details and photos of the vessel and operation.
- Maintenance record of the instrumentation as appropriate.
- Instrumentation recovery report, including details and photos of the vessel and operation and any observed failures or damage to the instrument.
- Measured dataset details, including data return achieved and overall success of the data collection campaign.
- Any post-processing or quality control procedures undertaken after data collection.
- Report containing the accuracy, sensitivity, and uncertainty of wind speed, wind direction, and wind shear exponent.
- Report/data package characterizing normal wind conditions at each location:
    - The long-term 10-minute average wind speed at hub height; monthly, all-year and omnidirectional.
    - Wind speed distribution; omni-directional and directional.
    - Wind speed vertical profile.
    - Wind shear.
    - Ambient turbulence intensity and standard deviation as a function of average wind speed.
    - Turbulence including wave effects from neighboring turbines; the wave effects can only be estimated when the type of turbine has been decided in the design process.
    - Air density.

    - An appropriate interval of wind speed bin and wind direction sectors used in the above should be chosen. As an example, 2 m/s or less for wind speed bins and 30° or less for wind direction sectors is consistent with DNVGL-ST-0437 (DNV-GL, 2016) and IEC 61400-3 (IEC, 2019).

- Report/data package characterizing extreme wind conditions at each location:
    - Extreme 10-minute average wind speed at hub height with specified recurrence periods
    - Extreme 3-second average wind speed (gust) at hub height with specified recurrence periods
    - Extreme wind shear
    - Extreme turbulence intensity
    - Air density
    - Extreme deterministic wind events such as extreme gust events and extreme direction change events.

- Any other information not mentioned above relevant to the end-user of the datasets.

5.6 SCHEDULE/PROGRAMME

Table 5-2 – Example deployment schedule

Activity	Typical Time Period Required for Activity	Days
Floating LiDAR	The duration is 24 months in total. If feasible within the project development timeline, the equipment can be relocated from one location to another after 12 months at the initial site, extending its operation for an additional 12 months at the new location.	730

6. WP3: Sea ice, Icebergs, and Ice accretion

The data collection recommendations to guide pre-leasing activities to support offshore wind development in Atlantic Canada are presented here. These recommendations are based on ASL's experience working with sea ice, iceberg, and freezing spray inputs for offshore oil and gas structures in ice-infested waters, following ISO 19901-1:2015 (ISO, 2015b) guidelines, integrated with the assessment of guidelines presented in IEC 61400-3-1:2019 (IEC, 2019b). These recommendations are presented in the form of terms of reference.

6.1 Background and Project Area

To identify ice data needed to enable offshore wind development in Atlantic Canada, recommendations are provided for collecting new data sets. As discussed in the Data Gap Analysis section (Section 4), the needs for the acquisition of new data depend on the characteristics of the ice regime and the availability of historical data, which varies enormously from one area to another in Atlantic Canada offshore waters.

6.2 Objectives

The objective of each recommended data collection program is to provide ice datasets that are required, at least in some areas within the offshore waters of Atlantic Canada, to enable offshore wind development in these areas.

6.3 Methodologies

In this document, we provide the Terms of Reference for two types of data collection activities that would be warranted for some areas in the Atlantic Canada offshore waters. These two types of data collection are:

1. Measurement of sea-ice momentum which consists of simultaneous measurements of sea-ice thickness and sea-ice velocity.
2. Measurement of iceberg velocities along with estimates of the physical dimensions and mass of the iceberg

6.3.2 Sea ice draft and velocities (upward-looking sonar and ADCP)

Measurements of the momentum of sea ice require simultaneous measurement of ice thickness (required for computing ice mass) and the velocity of the sea ice.

6.3.2.1 Equipment deployment and recovery vessel

The two upward-looking sonar instruments are mounted to the seabed using subsurface moorings (see Figure 6-1). These moorings can be readily deployed and recovered with a small vessel such as a fishing vessel. The deployment is carried out prior to the presence of sea ice and the recovery operation is carried out after the sea ice has cleared.

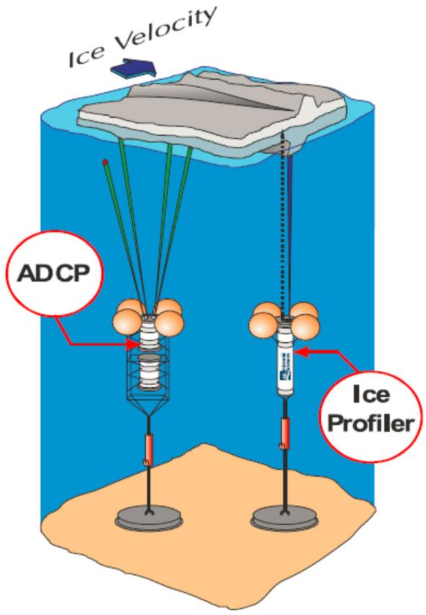

Figure 6-1 - A typical deployment arrangement of an ice profiling sonar and ADCP on separate sea floor-based moorings (Fissel et al., 2008).

6.3.2.2 INDICATIVE QUALITY

The upward-looking sonar instrumentation "has been and continues to be the primary source of data with volumes and accuracy sufficient for meaningfully monitoring ice thickness. The accuracy achieved combined with high horizontal resolution of the sea ice topography (1 m) meets the requirements for engineering design in offshore waters for renewable and non-renewable offshore energy sources" (Fissel et al., 2008).

6.3.2.3 INDICATIVE EQUIPMENT

The required equipment is two bottom-mounted upward-looking sonar instruments: an Ice Profiler Sonar (IPS) to measure the underwater thickness of the sea ice and an Acoustic Doppler Current Profiler (ADCP) that measures the sea ice velocity using its "Bottom Tracking" mode.

6.3.2.4 INSTRUMENT ACCURACY AND OPERATIONAL PERFORMANCE

The resolution of the IPS-derived underwater ice thickness is 1 m horizontally (Fissel et al., 2008) with an accuracy of about 5 cm the vertically, according to the knowledge of the average speed of sound in the water column above the instrument. A high sampling rate of 1-2 Hz is used to ensure that each ice keel is resolved. The accuracy of the ADCP-derived ice velocities is 0.01 – 0.03 cm/s at measurement intervals of 5 to 20 minutes (Fissel, et al., 2011).

6.3.2.5 MOORING SYSTEM

The mooring system is simple consisting of the ULS instruments, subsurface flotation for the instruments, acoustic release(s) to allow retrieval of the equipment, and mooring lines and weights that are on the seabed (see Figure 6-1).

6.3.2.6 Operations and Maintenance

The upward-looking sonar measurement system is operated unattended for the duration of the sea ice season, which ranges from < 2 to 6 months in Atlantic Canada waters. No maintenance is required.

6.3.2.7 Device recovery

The upward-looking sonar instruments are activated through an acoustic release deck unit operated from the recovery vessel which activates the release of the instruments and flotation from the mooring weights.

6.3.3 Iceberg characterization and velocities

Measurements of the iceberg momentum require simultaneous measurement of iceberg volume (required for computing ice mass) and the velocity of the iceberg.

6.3.3.1 Equipment deployment

The satellite-tracked ice beacons are attached to the iceberg via helicopter operations through lowering the beacons onto the upper surface of the iceberg.

6.3.3.2 Indicative value

The data collection consists of the operation of a satellite-tracked iceberg beacon deployed onto the beacon by helicopter. During the helicopter operations, the above-water dimensions of the iceberg are also measured using range finding and photography tools operated from the helicopter. The above water dimensions are then used to estimate the total iceberg volume based on the isostatic principle. This total volume is then converted to an iceberg mass using a typical value for iceberg density.

6.3.3.3 Indicative equipment

The satellite-tracked iceberg beacons use a GPS satellite location module to determine successive positions of the iceberg which are relayed by a satellite (e.g. Iridium or System Argos) to a central data system where the positions and their measurement times are stored. The satellite-tracked beacons are available from many vendors including Geoforce, Canatec, Metocean Telematics, and others.

6.3.3.4 Instrument accuracy and operational performance

As described above, the satellite-tracked iceberg beacon positions obtained by GPS are accurate to about 5 m. This results in very accurate iceberg velocities at frequent time intervals. For example, at one-minute measurement intervals, the velocity accuracy is < 0.1 m/s.

6.3.3.5 Device recovery

The satellite-tracked iceberg beacons are generally not recovered. The beacon is lost at sea when the iceberg deteriorates to the point that the beacon is no longer attached to the iceberg.

6.3.3.6 Operations and maintenance of the device

There is no requirement for operation and maintenance of the equipment.

6.4 Quality Control and Data Management

6.4.1 Quality Control Techniques

The quality control techniques for the IPS datasets are well understood through many scientific reports and papers, which are supported by purpose-designed software packages developed and operated by ASL Environmental Sciences Inc. and the Woods Hole Oceanographic Institution (e.g. ASL Ice Toolbox (ASL Environmental Services, n.d.), (Krishfield & Proshutinksy, 2006). A simplified ice draft calculation is included as part of the software which is provided with the IPS. The calculation of ice draft to the 5 cm accuracy noted earlier; however, requires highly trained analysts who can synthesize data streams from several sources to evaluate the average sound speed between the surface and the IPS. This cannot be measured directly as it is often inhomogeneous, and instruments placed within this region are at high risk of being damaged by ice or lost. ADCP data processing is widely conducted by nearly all oceanographic organizations.

The processing of satellite-tracked ice beacon data sets has been widely conducted for many decades. The computations are simple leading to very straightforward quality control techniques.

6.4.2 Storage and Access

The IPS/ADCP and the iceberg velocity data sets are flat ASCII data files as time series of underwater ice thickness and sea ice velocity and spatial (distance files at 1 m horizontal intervals of underwater ice thickness).

6.4.3 Metadata

The metadata is straightforward, being the mooring geolocation and time information along with the data channels described above for the upward-looking sonar/IPS/ADCP datasets.

6.4.4 Relevant Standards and Guidelines

The IPS/ADCP and iceberg data sets are widely used in polar studies for cryosphere scientific studies and for offshore energy applications. These data are in conformity with the standards for both offshore renewable and non-renewable energy (e.g. ISO 19901-1:2015 (ISO, 2015b), IEC-61400-3-1:2019 (IEC, 2019b)).

6.5 Reporting and Deliverables

6.5.1 Reporting Requirements

The reporting is driven by reports used to address environmental conditions at a particular offshore location as used for engineering purposes. The processed data is provided in support of the report(s).

6.6 Schedule/Programme

For the ULS measurement program, the recommended measurement schedule is for a continuous measurement period spanning each sea ice season. The equipment should be deployed before the onset of the ice season and the equipment should be recovered after the ice season ends. The time required for the preparation of the measurements is 2-3 months and the time required to process, analyze, and prepare data sets for archival purposes is about 3 months.

For the iceberg measurement program, the recommended measurement schedule is to deploy beacons and conduct geometric surveys by helicopter on a few to several icebergs located upstream by tens of kilometers from the offshore wind site. The duration of the beacon measurements will likely be a few weeks or several days in areas that are at the downstream limits of areas of iceberg activity, and longer in upstream areas. The data processing and reporting can be completed in a few to several weeks from the time that the iceberg data collection ends.

7. WP3: Hydrographic Survey

7.1 Background and Project Area

Please refer to the Section 4.1 for additional background information.

This work is focused specifically on the hydrographic characteristics of Atlantic Canada and the metocean data collection efforts necessary to support offshore wind development. The proceeding text provides an example of the terms of reference documents (TOR) required to support the collection of bathymetric data across an Offshore Wind Farm lease area.

7.2 Objectives

The Natural Resources Canada agency requires the successful contractor to gather a comprehensive hydrographic survey data set which enables the understanding of the site conditions within the proposed Offshore Wind Farm lease area.

The Hydrographic survey programme will involve a non-intrusive, multi-disciplinary approach designed to acquire a full suite of data which includes the collection of Multi Beam Echosounder and associated backscatter data.

The collected data will be used to better understand the water depths, topography, and relief structure of the seabed.

The objectives of the hydrographic survey are:

- To obtain up-to-date high-resolution water depth measurements across the site.
- To obtain information on the seabed surface (type, texture, variability, etc.) and to identify any seabed features that may be of interest to the overall project.
- Identify any seabed geohazards and man-made hazards (including but not limited to outcropping, boulders, wrecks, debris, etc.).
- Identify marine habitat areas as the basis for the benthic survey to be carried out.
- Identify sensitive marine habitats which will need to be avoided during geophysical/geotechnical and environmental sampling.

7.3 Methodologies and Data Requirements

7.3.1 Survey Coverage and Line Spacing

Full coverage of the site area and export cable route area shall be achieved. Survey line spacing shall be proposed by the survey contractor.

7.3.2 Multibeam Echosounder (MBES) Including Backscatter

Full, 100 % coverage of high-resolution MBES and backscatter data is required across the array site area and export cable route area. A target vertical resolution of ± 0.5 m is required.

Data shall be vertically reduced to the project's vertical datum.

In order to meet the project objectives, it is expected that the MBES swathe bathymetry should meet or exceed IHO Standards for Hydrographic Surveys Order 1a.

The system should incorporate a sound velocity probe to monitor the speed of sound in water in real time at the receiver, to provide a constant comparison against a vertical Sound Velocity Profile (SVP) through the entire water column. The sound velocity probe should have an accuracy of ±0.15 m/s and a calibration certificate will be available that has been performed within the last six months.

Table 7-1 – Multibeam echosounder system requirements

Multi Beam Echosounder - System Requirements	
System Operating frequency	200 - 400kHz or greater
Acquisition frequency is to be defined at mobilization and remain at the defined frequency for the entire survey period.	
Absolute gridded surface accuracy	+/- 0.25 m at 2 standard deviations
DTM cell size	0.5 m for the Array Site and Export Cable Route areas
Minimum soundings in each cell	10
Swathe overlap between lines	minimum of 10%
Total Vertical Uncertainty (TVU)	0.25 m at 2 standard deviations or better.
Total Horizontal Uncertainty (THU)	0.5 m + 2% of water depth at 2 standard deviations.
Backscatter	Required
Water column data	Required for any identified wreck locations or potential obstructions

7.4 QHSE and Guidelines

The survey contractor and vessels will comply with international and national statute as appropriate. A non-exhaustive list of examples includes:

- S.I. No. 372/2012 - Sea Pollution (Prevention of Pollution by Garbage from Ships) Regulations 2012.
- S.I. No. 492/2012 - Sea Pollution (Prevention of Pollution by Sewage from Ships) (Amendment) Rand regulations 2012
- S.I. No. 507/2012 - Merchant Shipping (Collision Regulations) (Ships and Water-Craft on the Water) Order 2012.

7.5 Reporting and Deliverables

7.5.1 Field Reporting

All field reports and charts will be provided in draft for Employer review and comment. On receipt and implementation of Employer comments, the Contractor will issue a Final version of all deliverables in accordance with the agreed scope.

Daily reporting

The Contractor shall submit Daily Progress Reports (DPR), detailing all aspects of the work undertaken, to the Client Representative and Client-requested distribution list daily before 0900 throughout the offshore campaign.

Mobilisation report

Prior to the Client's approval of mobilization, the Offshore Client Representative(s) shall complete a Mobilisation Checklist with the Contractor. A mobilization report will be submitted by the contractor within 48 hours of completion of the vessel and equipment mobilization, calibration, and verification activities. The Mobilisation report will be presented to the Offshore Client Representative for review and acceptance.

Survey operations report

A Survey Operations report will be completed and issued within one week of the completion of the survey work (to be taken as the start of vessel and equipment demobilization). The report will be presented to the Employer for review and acceptance.

7.5.2 FINAL REPORTING AND DELIVERABLES

Final data interpretation shall focus on using the acquired data to deliver the objectives of the survey. Interpretation and correlation of data sets are necessary to fulfill these requirements and produce a robust picture of the seabed conditions throughout the survey area.

Data processing and interpretation results report

The Contractor is to provide a report that includes full details of the Data Processing and interpretation results. The Draft and Final report will be issued for review to the Employer, in digital (*.pdf) and hard copy form.

Report deliverables

All reports will be provided to the Employer in digital form (PDF and MS Word).

Drawings

All GIS maps and drawings shall be supplied in both ESRI ArcGIS format (.mxd) and PDF. The data sourced within the .mxd file should be set to relative paths to the data delivery. CAD drawings shall be supplied in AutoCAD format (.dwg).

All data used in drawings must be covered by the appropriate data licenses and the relevant copyright information displayed.

The Employer will approve drawing templates of the Contractor before the commencement of charting and reporting.

7.5.3 DIGITAL DATA DELIVERABLES

A full list of GIS data deliverables and types will be agreed upon between the Employer and the Contractor prior to survey commencement.

The collected survey data and interpreted data shall be provided by the Contractor in digital format on completion of the final reports. All data must have an appropriate coordinate system defined or the associated projection file supplied and be accompanied by metadata to the standard conforming to the Marine Environmental Data Information Network (MEDIN) discovery standard for metadata. Digital data provided shall use Vector or Raster formats where appropriate and be compatible with ESRI ArcGIS v10.

7.6 SCHEDULE AND PROGRAMME

Table 7-2 – Example hydrographic survey schedule

Activity	Typical Time Period Required for Activity
Provision of contractor's project QHSE documents	30 days before mobilisation
Mobilisation, Survey Systems Calibration & Data Acceptance Report	48 hours after completion of mobilization
Hydrographic Surveys	8-10 weeks (weather dependent)
Draft Survey Operations Report	1 weeks after demobilisation
Draft Data Processing and Interpretation Report	10 weeks after completion of survey (de-mobilisation

8. CONCLUSIONS AND RECOMMENDATIONS

In this report three distinct work packages have been delivered to the Client to support the development of offshore wind in the Atlantic Canada region and the decision-making processes of the Client, they are as follows:

Work Package 1:

Key metocean variables and phenomena essential for developing Offshore Wind Farms in the Atlantic Canada region have been identified and furnished to the Client. Compliant with relevant standards and best practice guidelines, comprehensive details regarding requirements, units, notation, and the responsible party for collecting these datasets are provided. The considered variables span across atmospheric, wave, current, and tides, encompassing extreme variations necessary for design purposes.

Work Package 2:

A list of datasets, both modeled and measured, which provide the identified metocean variables and phenomena, and meet the requirements for offshore wind design and analysis, has been documented. The list provides the specifications and properties of each of the sources, including the spatial and temporal coverage, extent, and availability.

In addition, a gap analysis has been conducted to identify gaps in existing data holdings in the area of interest versus what is required for the successful deployment of offshore wind. At this stage, the key metocean variables required by the Client to support Pre-FEED and lease area definition initiatives are wind, wave, currents, water levels and tides, bathymetry, and those related to ice phenomena. The gap analysis investigates numerous parameters in those categories.

Following discussions with the Client, it was agreed that part of the offshore study area is not suitable for installing Offshore Wind Farms due to the high levelized cost of energy (LCOE) associated with installing turbines in deep waters. For deeper areas (greater than -250 mLAT), the installation of floating offshore wind turbines poses significant technical challenges, such as increased engineering complexity and higher maintenance costs. These challenges can substantially escalate the overall project expenses, rendering installations in such depths economically unfeasible. Allowing for future technological advancements, the extent of the area considered in the gap analysis was limited to depths less than -500 mLAT, as shown in Figure 3-1.

Additionally, considering the many geotechnical, metocean, and social factors that influence the feasibility of offshore regions for installing wind turbines, the suitable zones are likely smaller than those considered here.

The gap analysis has drawn the following conclusions:

- For wind and wave datasets, specifically wind direction and speed, peak wave period, significant wave height, and wave direction, there is good temporal and spatial coverage provided by numerical models across the region. Namely, the MSC50, ERA5, and NARR models provide 1-hour averages, and 3-hour averages for the latter, in varying grid dimensions across the study area. The temporal extent ranges from 1979 to 2024 providing sufficient duration to capture the seasonal variations.

  While the aforementioned datasets provide the means for the Client to progress in the initial phases of development, analysis of the available physical measurements shows gaps in a number of regions, including:

  - The Scotian Shelf, Northwest of Sable Island and Southwest of Nova Scotia
  - The southern coast of Labrador in the Gulf of St. Lawrence and around the Anticosti Island

  - The Labrador Shelf
  - The Northeast Newfoundland Shelf
  - The Grand Banks of Newfoundland

  At this stage specific recommendations on where to locate survey equipment to address the gaps would result in a significant number of surveys and cost. When the Client defines the Offshore Wind Farm lease areas, they then should consider the placement of survey equipment to address these needs to further enhance the value in each lease area to offshore wind developers.

- For ocean current datasets, our analysis concludes that there is good temporal and spatial coverage provided by numerical models. GDG recommends that the Client utilize the HYCOM model to provide the surface current speeds and directions at this stage. It provides a 3-hour average current speed and directions for various water depths throughout the area of interest. There is a notable absence of physical current measurements throughout the offshore areas. SmartAtlantic provides several datasets measured at coastal stations, which may be useful for future offshore wind developments located nearby, however, these should be carefully analyzed as local topological effects can influence the current speeds and directions and may not be representative of nearby locations.
- Analysis of the available water level and tides datasets in the region shows the HYCOM model is the most useful numerical model at this stage. The HYCOM model provides historical water level data across a 0.08 x 0.04-degree grid between the years 1994 – 2015, which is sufficient to capture the long-term variations in water levels. The CHS-DFO provides historical water level data at numerous locations along the coast of Newfoundland, Nova Scotia, and Labrador, and a small number are located around Sable Island and the eastern side of the Grand Banks of Newfoundland. The temporal duration for each CHS-DFO station varies, and the local effects may influence the measured water levels, therefore not all may be suitable for development at this stage.
- In terms of bathymetric datasets, there is sufficient publicly available data that will enable the Client to proceed with preliminary Offshore Wind Farm zonation. The GEBCO dataset provides 500 x 500 m resolution bathymetry data throughout the area of interest. Other sources which are less comprehensive but higher in resolution include the CHS NONNA 10 and NONNA 100, and NOAA NCEI MBES datasets. A substantial amount of the available MBES data is located beyond the continental shelf in areas where turbines are not likely to be installed, while much of the SBES data, which is less useful for providing detailed information about the seafloor, is located along the continental shelf.
- Existing sea ice concentration and stage of development datasets are well developed by the Canadian Ice Service, however, there is a significant data gap in regional ice thicknesses, and dynamic ice feature formation (i.e. keels, pressure ridges, stress zones). This gap can be addressed with additional time series of ice draft measurements and subsequent statistical analysis with higher-density observation networks in areas most likely to see offshore wind development that may be affected by momentum transfer from sea ice.
- Freezing spray and ice accretion on offshore structures can be modeled, however, in situ observations represent a significant data gap. It is recommended that an in-situ assessment of ice accretion should be conducted as part of baseline metocean data collection activities.
- Existing iceberg datasets relevant to offshore wind activities are sparse in many sub-regions, especially in the Gulf of St. Lawrence and adjoining waters. Additional direct observations should be carried out if and when feasible in site-specific areas. Historical databases should be assembled and made more accessible through readily available online information sources.

In WP3, TORs have been provided as a basis of recommendation for collecting new metocean data. GDG recommends that the Client focus on the primary metocean variables that are typically collected in metocean survey campaigns for Offshore Wind Farms, and those that can be used to derive other key variables and enable the Client to perform preliminary lease area definition. Those variables include wind, waves, currents, water levels and tides, bathymetry, and ice-related phenomena.

The TORs provide general recommendations on survey objectives, indicative equipment and quantity, deployment and retrieval methodologies, quality control, data management, and reporting requirements. These are provided as general guidance to the Client and may be subject to change when the Client defines the OWF lease areas.

In terms of data collection activities, this should ideally be carried out prior to a call for bids. GDG recommends that the Client collect the primary variables outlined above. By doing so, more detailed metocean side condition assessments can be conducted which will help verify initial estimates of wind resources and strengthen the assessment of environmental conditions at the OWF site.

Recommendations:

As a result of this study, GDG recommends the following for consideration:

- Preliminary Offshore Wind Farm Lease Area Zonation:

  GDG recommends that the Client proceeds with zoning the preliminary Offshore Wind Farm lease areas to define them accurately for subsequent planning of metocean survey campaigns. It's advisable to align the positioning of survey instruments with the outcomes of ongoing regional assessments of offshore wind potential in Newfoundland Labrador, and Nova Scotia.

- Integration of Weather Analysis:

  It is advised to integrate weather window and weather downtime analysis into existing metocean data analysis. This analysis should be synchronized with a typical Offshore Wind Farm transportation and installation schedule. The objective is to gain deeper insights into the suitability of regions in Atlantic Canada for Offshore Wind Farms. Delays in transportation and installation activities due to unfavorable weather conditions can lead to additional costs and render certain regions unfeasible for Offshore Wind Farm developments.

- Additional Data Needs from Regional Assessments:

  GDG suggests extracting additional data needs and monitoring responsibilities from the ongoing regional assessments of offshore wind in Nova Scotia and Newfoundland and Labrador. This will ensure that comprehensive data requirements are met for successful offshore wind project development.

- Coordination of Metocean Data Collection Efforts:

  Given the extensive data requirements for offshore wind projects, GDG recommends coordinating metocean data collection efforts with existing offshore marine energy developers and relevant organizations such as the Canadian Ice Service, National Research Council, and C-Core. This collaboration will address various factors including environmental, social, and economic considerations, ensuring a holistic approach to data collection and project development.

- Extension of C-Core Pipeline Ice Risk Assessment Program:

  It is recommended to extend the existing C-Core pipeline ice risk assessment and mitigation program to include offshore wind projects. This extension should assess risks to export and inter-array cables, floating wind turbine anchor lines, and sub-structures, ensuring comprehensive risk management for offshore wind installations.

These recommendations aim to streamline the planning and execution of offshore wind projects in Atlantic Canada while addressing key considerations for successful development and risk mitigation.

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APPENDICES

APPENDIX A – WORK PACKAGE 2 DATA SOURCES

Additional information on available datasets may be found in the following excel workbook:

23200_Metocean_Canada_WP2 - Data Sources.xlsx

For each of the identified data sources, where possible and information is publicly available, the following information is provided:

1. Category: The overarching category that the data source variable or phenomenon belongs.
2. Variable/phenomenon: The specific phenomenon that the data source provides. Variables identified in work package 1.
3. Data source: The name or title of the data source.
4. Reference: The proprietor or owner of the data source and/or link to the data source.
5. Data source type: The type of data that the source provides (eg. reanalysis, hindcast or measurements)
6. Spatial resolution: The spatial resolution of the dataset, either in degrees or meters, or location of the measurement station(s).
7. Temporal resolution: The temporal resolution of the dataset (eg. 1-hour average, 3-hour average, 10-minute average).
8. Temporal extent: the duration over which the data was measured.
9. Geographic extent: the area which the dataset covers. In the case of gridded data, the coordinates of the corner points of the area covered by the dataset is provided. In the case of non-gridded datasets, the region or locality of the dataset is listed.
10. Availability: the availability of the dataset, either publicly or commercially available, or privately owned.
11. Cost: where information is publicly available the cost has been indicated.

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