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Addressing Cold Climate Challenges for Offshore Energy Systems: A Review of Relevant Literature and Gap Analysis for Atlantic Canada

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Executive Summary

In alignment with global efforts, Canada has implemented robust strategies to harness offshore resources as part of its commitment to achieving Net-Zero carbon emissions by 2050. As the nation explores developing offshore energy capacity in locations that experience harsh winter conditions, addressing icing risks becomes a strategic imperative for sustainable development in cold climates.

This research addresses these challenges by investigating two primary types of icing risks that can affect offshore structures: atmospheric icing and sea spray icing. Although decades of study have been devoted to this subject, many key parameters and associated physics remain insufficiently understood. To characterize these knowledge gaps, a comprehensive literature review is conducted to provide a detailed analysis of icing phenomena, and the complex interplay among meteorological, oceanic, and structural factors. Additionally, the effectiveness of available empirical, semi-empirical, and numerical models in predicting icing events is evaluated, highlighting the necessity of field measurements for more accurate risk assessments.

The insights generated from this analysis will contribute to the development of regional icing risk maps specific to cold climate conditions, as well as the establishment of a consistent and reliable data collection framework for future field campaigns in Atlantic Canada. These findings will be instrumental in supporting the safe, reliable, and efficient deployment of offshore energy systems, including hybrid technologies such as wind, wave, tidal, and floating solar photovoltaic systems.

This project will benefit a diverse range of stakeholders, including government agencies, energy developers, local and Indigenous communities, private investors, researchers, and environmental organizations by enhancing sustainable offshore energy planning. Ultimately, this work sets the stage for achieving energy security and sustainability in Canada's cold climate regions.

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1. Introduction

1.1 Background and Context

Canada's vast coastlines and distinctive climatic conditions provide substantial opportunities to deploy offshore energy systems, particularly in Atlantic Canada. Provinces like Nova Scotia and Newfoundland and Labrador possess immense offshore wind potential, with Nova Scotia committing to offer leases for five gigawatts of wind energy capacity by 2030 [1], and Newfoundland and Labrador being home to some of the highest wind resources in North America [2].

Despite this potential, cold climates pose unique challenges, particularly icing risks such as atmospheric icing, sea spray icing, and the presence of sea ice. These factors significantly impact the safety, feasibility, and efficiency of offshore installations.

While preliminary insights into sea ice and its potential implications for offshore wind have been explored in previous studies by CanmetENERGY-Ottawa [3] and in contributions to the Regional Assessment draft reports for Nova Scotia and Newfoundland and Labrador [4], this report instead focuses on the physical phenomena and modelling practices associated with atmospheric icing and sea spray icing.

1.2 Objectives

The primary aim of this literature review is to explore and address the cold climate challenges that may affect offshore energy systems in Atlantic Canada, with a particular focus on icing risks. The review sets out the following objectives:

- Combine findings from existing studies to provide a comprehensive understanding of how atmospheric and sea spray icing mutually affects offshore energy systems.
- Perform a systematic review of historical and current icing forecast models to identify key knowledge gaps and support the advancement of future cold climate icing risk maps.
- Develop a structured data collection framework to guide future field campaigns, enabling the safe, reliable, and efficient deployment of offshore hybrid energy systems.

1.3 Structure of the Literature Review

The organization of this report is as follows: Chapter 2 outlines the challenges faced by offshore structures in cold climates, beginning with an introduction to the types of icing on offshore platforms. Following this, Chapter 3 examines the key parameters that influence the atmospheric icing process, identifying and prioritizing these factors for future fieldwork and modeling initiatives. In Chapter 4, the review evaluates the risks associated with icing from various sea spray sources, comparing diverse meteorological and oceanic conditions to enhance the accuracy of icing severity forecasts. The report concludes with Chapter 5, which provides a comprehensive discussion and outlines recommendations for future research in this critical area.

2. Cold Climate Challenges in Offshore Structures

2.1 Classification of Icing

Icing poses a significant challenge in colder climates, occurring in various forms such as atmospheric icing and sea spray icing, particularly in offshore settings [5-12]. This challenge is especially evident in offshore wind farms operating in these regions [9, 13].

Past studies show that even minimal ice accumulation on turbine blades can reduce energy output by up to 20%. Power losses caused by icing events have in some cases led to losses of up to 50% of a wind farm's annual production [14–17]. These losses not only diminish wind farm efficiency but also lead to considerable financial setbacks.

Beyond energy production, icing raises public safety concerns, including risks related to platform icing, ice throw, and potential structural failures. The impact of sea ice is primarily associated with foundational failures, the risk of which can be mitigated by conducting rigorous site assessment studies before installation. These assessments help identify suitable locations with minimal risks from icebergs or structural collisions, ensuring that turbines operate safely and efficiently.

Figure 2.1 and Table 2.1 illustrate how icing affects offshore structures, detailing impacts on turbine components and overall power production, while showing that sea ice has a negligible effect on the uppermost parts of the structure, such as the blades, nacelle, hub, and anemometers.

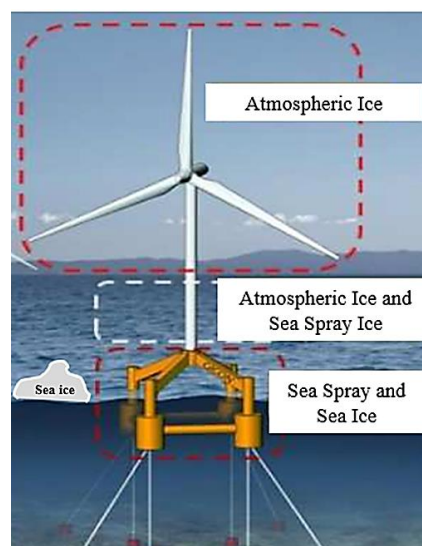


Figure 2.1: Effect of icing on offshore wind turbine structure (adapted from [23]).

Table 2.1: Wind turbine components affected by different types of icing (adapted from [5]).

Types of icing	Wind turbine components or offshore structures				Public safety and risk
	Blades	Nacelle	Tower	Foundation	
Atmospheric icing	✓	✓	✓		✓
Sea spray icing	✓		✓	✓	✓
Sea ice				✓	

Based on these reviews [18–22], Figure 2.2 demonstrates a classification of the different icing types, with each type detailed in the following chapters.

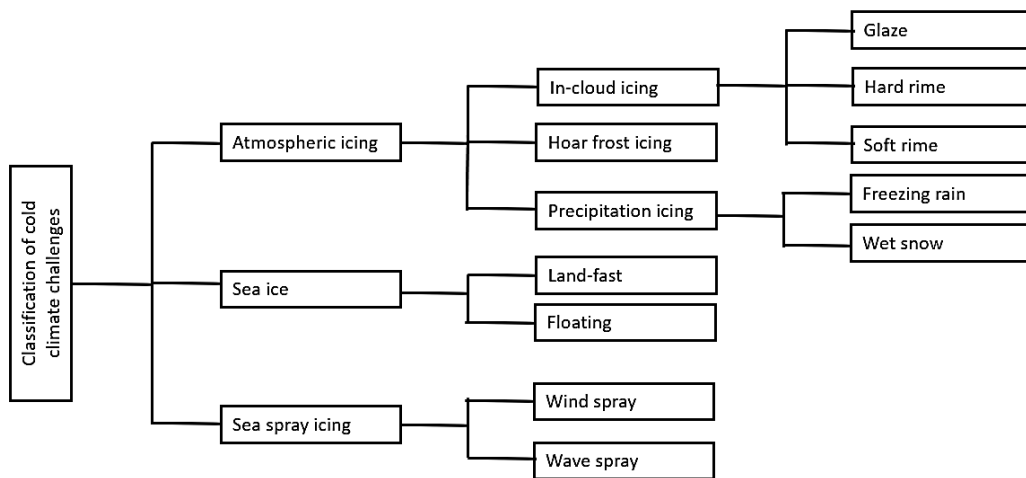


Figure 2.2: Classification of icing phenomena with the potential to affect offshore energy systems.

3. Atmospheric Icing

3.1 Physics of Atmospheric Icing: Background Studies

Atmospheric icing refers to the accumulation of ice or snow on structures exposed to the atmosphere under specific meteorological conditions [24]. This phenomenon is particularly prevalent in cold climates.

In onshore environments, atmospheric icing primarily affects the upper parts of wind turbines, such as the blades and nacelle. However, in offshore settings, icing can also impact the tower and platform structures. This includes the accumulation of ice on the tower, which may lead to increased structural loads and ice formation on platforms, posing operational and safety risks.

In cold climate regions, three primary types of atmospheric icing can occur on wind turbines: in-cloud icing, precipitation icing, and hoar frost [25–29]. Among various influential factors, meteorological conditions are particularly significant in driving atmospheric icing and will be discussed in detail in subsequent sections.

3.1.1 In-cloud icing

In-cloud icing occurs under low atmospheric temperatures when small supercooled liquid droplets in clouds freeze upon impact with a surface [30, 31]. The process is divided into two stages: pre-impact and post-impact. Pre-impact involves droplet movement and cooling during their atmospheric journey, while post-impact includes processes such as spreading, freezing, and runoff after the droplets strike a surface. Droplets may either freeze on the surface or deflect away, depending on various factors. In-cloud icing is further categorized into two forms; rime ice and glaze ice [32, 33, 31, 34].

Rime icing is a dry-growth phenomenon that occurs when supercooled liquid water droplets are transported by airflow and freeze immediately upon impinging on a surface. This type of icing typically forms at higher elevations and can occur at temperatures as low as -20°C . Key factors influencing rime ice formation include droplet size, high levels of supercooling, and the rapid dissipation of the latent heat of fusion [35]. Rime icing is further divided into soft rime and hard rime.

Soft rime forms due to faster heat loss, resulting in a white, opaque coating often deposited on edges and points of objects. Hard rime, caused by slower heat loss, forms a denser, opaque, granular mass, and shoreline structures exposed to supercooled spray often experience hard rime icing [36, 33].

Studies from Japan indicate that rime icing is common on marine structures [37]. Figure 3.1 illustrates the rime icing phenomena.

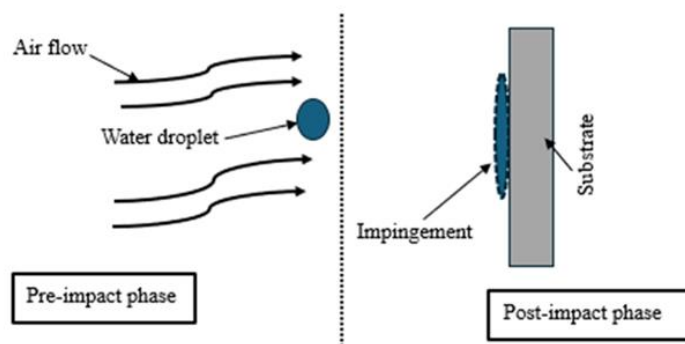


Figure 3.1: Mechanism of rime ice growth.

Glaze icing, also known as wet growth, glaze frost, or clear ice is a type of ice that forms as a smooth, homogeneous, and transparent layer with strong adhesion to surfaces [35, 32, 34]. It occurs when supercooled droplets remain in a liquid state long enough to spread into a thin film before freezing [33]. This type of meteorological hazard typically occurs at lower elevations and forms at temperatures between 0°C and –3°C [38], although the range may extend to –6°C [28].

Glaze ice is denser than rime ice accretion, characterized by relatively larger droplet sizes, slight supercooling, and slower dissipation of the latent heat of fusion [35]. Figure 3.2 illustrates the glaze icing phenomena.

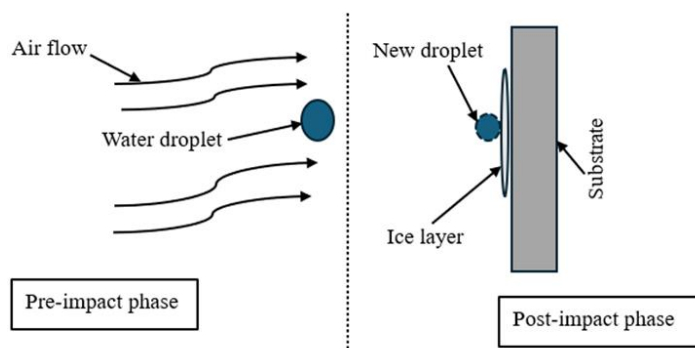


Figure 3.2: Mechanism of glaze ice growth.

A report by the National Research Council of Canada highlights that, unlike many other regions in Canada, the eastern half of Newfoundland and the southern Gulf of St. Lawrence experience frequent and extended glaze icing events. This is primarily due to their exposure to moist Atlantic air masses, which create ideal conditions for prolonged freezing rain and ice accumulation [35].

3.1.2 Precipitation icing

This type of icing results from freezing rain, drizzle, or wet snow [39, 40, 31]. The accumulation rate of this type of icing can exceed that caused by in-cloud conditions.

Freezing rain is made entirely of liquid droplets and occurs when rain falls on a surface with a temperature between 0° and –5°C, leading to immediate freezing [41]. The duration of freezing precipitation events is typically 1–2 hours, though events lasting more than 8 hours are not unusual [41].

In Canada, freezing rain occurs more frequently between October and May [42, 43], with the highest frequency in March [41].

Wet snow consists of partially melted snow crystals containing a small amount of liquid water, where the liquid water content is influenced by the concentration in the surrounding air. Without considering rainfall, the liquid water content (LWC) mainly represents water content in clouds and fog [32]. Wet snow is typically sticky and adheres to surfaces, a phenomenon that commonly occurs when air temperatures range between 0°C and 3°C [31]. In some areas of Canada, particularly in western provinces like Alberta, significant ice loads result from frozen wet snow [44, 45].

3.1.3 Hoar frost icing

This type of icing is commonly referred to simply as frost, forms when water vapor directly solidifies onto a cool surface. This phenomenon typically occurs under conditions of low wind and high relative humidity (above 90%) [32, 46, 33]. Despite its low density and limited persistence, hoar frost can affect wind turbine power production estimates [47]. While icing is not uncommon at air temperatures below –20°C over the sea [48, 49, 50], hoar frost most often forms under these conditions [51].

Although numerous parameters influence atmospheric icing, only a few key factors, including ambient temperature, wind speed, droplet size, and liquid water content have been investigated. Tables 3.1 and 3.2 present a comprehensive summary of the available data [52, 38, 27, 28, 53]. However, significant gaps remain, particularly in defining the ranges of wind speed and droplet diameter for precipitation-induced icing and hoar frost. Additionally, no specific range has been found for liquid water content, underscoring the need for further research in these areas.

Table 3.1: Meteorological conditions during atmospheric icing events.

In-cloud icing	Source	Air temperature (°C)	Wind speed (m/s)	Droplet diameter (µm)
Hard rime	Water droplet	0 to -15	5 to 10	
		-3 to -10		3 to 28
Soft rime	Water droplet	-5 to -25	1 to 5	
		-8 to -14		2 to 20
Glaze	Water droplet	0 to -6	1 to 20	
		0 to -5		8 to 39
Precipitation	Water droplet	0 to -3		
Wet snow	Snowflakes	0 to 3		
Hoar frost	Water vapour	below -20		

Table 3.2 Atmospheric icing as a function of liquid water content in the air.

In-cloud icing	Liquid water content in air
Hard rime	Medium
Soft rime	Low
Glaze	High
Freezing Rain	Medium
Wet snow	Very high

3.2 Atmospheric Icing: Onshore versus Offshore

The environmental conditions that contribute to icing vary significantly between offshore and onshore settings. Figure 3.3 represents an illustration of an offshore environment, highlighting key parameters, such as sea fog, saline water droplets, humidity over the sea, and salt particles in the air.

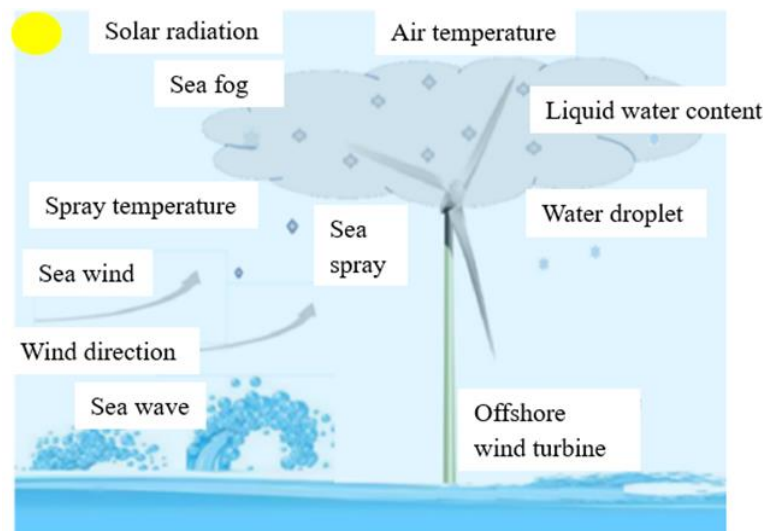


Figure 3.3: Factors affecting environmental icing for offshore wind turbines (adapted from [85]).

Offshore regions frequently experience sea fog, particularly during winter months. Sea fog contributes to a higher concentration of super-cooled liquid water in the atmosphere, which is a critical factor in icing formation. Super-cooled water droplets remain in liquid form below freezing temperatures and can rapidly freeze upon contact with turbine surfaces, leading to ice accretion.

Furthermore, sea winds generate seawater droplets through spray and wave action. These droplets remain suspended in the air, increasing the salinity levels in the atmospheric environment surrounding offshore structures. Elevated salinity can alter the freezing point of water and influence ice adhesion properties [84], potentially leading to more persistent ice formations compared to pure water scenarios typically observed onshore. In addition, humidity over the sea exhibits greater variability across a wide range compared to terrestrial environments. This variability can lead to fluctuating icing conditions, making it more challenging to predict and manage ice accumulation on offshore structures.

Last but not least, the presence of salt particles in the air above the sea surface plays a crucial role in ice formation. These salt particles serve as nucleation sites for ice formation, altering the microphysical processes involved in icing. Additionally, saline air influences phenomena such as sea fog and evaporation fogs, which, in turn, influence precipitation rates and ice accretion patterns on turbine blades [184-185].

3.3 Past Studies on Forecasting Offshore Atmospheric Icing Phenomena

Over the past decade, significant advancements have been made in pre-impact forecasting methods for atmospheric ice accumulation. Research efforts have traditionally centered on onshore wind turbine icing and aviation-related freshwater icing. This section reviews past studies and methodological

approaches to forecasting atmospheric icing, highlighting both their achievements and inherent limitations.

Researchers have utilized an extensive range of climatological datasets, diverse analytical frameworks, and innovative modeling techniques. Collectively, these approaches provide valuable insights into the processes behind atmospheric icing and contribute to a broader understanding of how these phenomena manifest across various meteorological conditions.

3.3.1 Ice forecasting by climatological and regional assessments in Canada

3.3.1.1 Empirical and semi-empirical approaches (1970-2000)

One of the earliest attempts to delineate the spatial distribution of freezing precipitation was conducted by Yip [54], who produced mapping products of freezing precipitation across Canada using a 30-year dataset. This work adopted the semi-empirical model developed by Chaîné and Castonguay [55], assuming a freezing fraction (*e.g.*, percentage of water that freeze after impact) of unity and a clear ice density of 900 kg·m³.

Yip's model for estimating radial ice accretion on cylindrical objects incorporated both horizontal and vertical components, with the horizontal component representing the observed precipitation amount or rate, and the vertical component considered proportional to both precipitation rate and wind speed. While this approach provided a useful early framework, the model's sensitivity to wind speed and precipitation rate, combined with its reliance on simplified assumptions such as fixed ice density and freezing fraction, limited its applicability across diverse environmental conditions. As a result, subsequent research shifted towards empirical modeling approaches to better capture the complexities of ice accretion phenomena.

McComber and Govoni [56] constructed models based on measured parameters such as air temperature, wind speed, and liquid water content to predict exponential growth rates of rime icing. Although these models provided effective predictions under controlled conditions, particularly for rime icing, they encountered difficulties in accurately simulating freezing rain events. Their work underscored the complexity of translating empirical relationships into reliable operational tools, especially under complex and variable meteorological scenarios. Further refinement of understanding came from large-scale climatological studies. Stuart and Isaac [57] developed comprehensive frequency maps of freezing precipitation across Canada using records spanning 1961–1990. Their findings revealed that freezing precipitation occurs across most of Canada during all seasons, with the exception of the Pacific coast and the northernmost regions during colder months. Intriguingly, St. John's, Newfoundland, emerged as the area with the highest frequency of freezing precipitation in North America. Across Newfoundland, the annual cumulative durations for freezing precipitation, freezing rain, and freezing drizzle are approximately 150 hours, 25 hours, and 100 hours, respectively.

In another study at the Hibernia oil field in Canada, Horjen [58] mentioned that the occurrence of supercooled rain is frequent and has led to significant operational challenges in Newfoundland. Although this regional assessment highlighted local meteorological and topographic influences, it fell short of examining broader temporal trends over extended time scales.

3.3.1.2 Empirical and semi-empirical approaches (after 2000)

To enhance the understanding of atmospheric icing, Lamraoui et al. [59] utilized the North American Regional Reanalysis (NARR) dataset to create an updated climatological assessment of in-cloud icing severity index across northeastern Quebec. Their modeling approach considered three weighting factors, including liquid water content, duration of icing event, and icing classess, to effectively characterize the icing risk severity index. The findings identified the Atlantic-facing slopes of the Gaspé Peninsula and the St. Lawrence River valley as regions with particularly high icing severity indices. This heightened severity was attributed to the frequent occurrence of ice storm tracks in these regions, accompanied with a strong winds predominantly blowing from the west and northwest directions.

A representative map of the icing severity index for February, as depicted in Figure 3.4, highlights that areas north of the St. Lawrence valley experience notably high levels of icing severity.

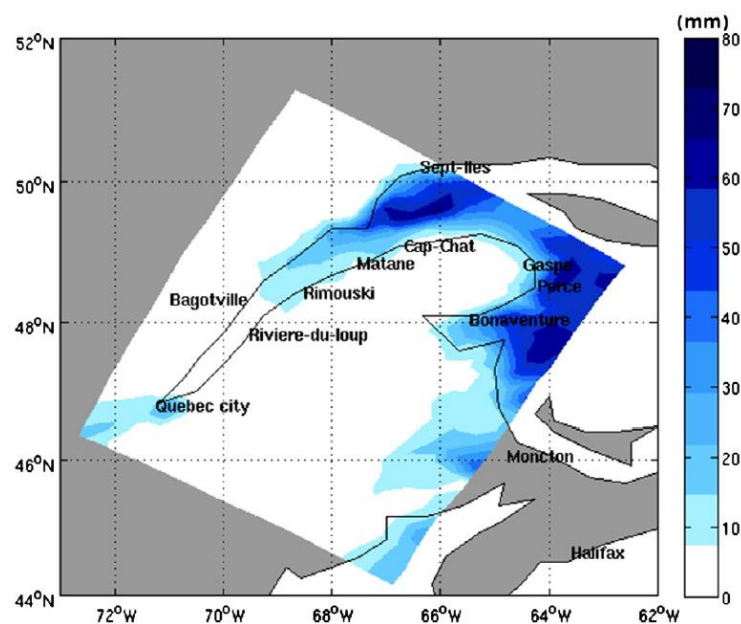


Figure 3.4: Icing severity index map for February (1979-2020) [59].

Tony *et al.* [60] utilized the ERA5 Reanalysis dataset to examine precipitation icing in the northern sub-Arctic and Arctic regions. Their analysis revealed that in the Canadian eastern offshore regions, including Grand Banks, Flemish Pass, and Orphan Basin, precipitation icing was most frequent during winter (25–40% of days), though accretion rates remained relatively low (≤ 0.7 cm/hr).

Later, recognizing the profound implications of climatic change, Bernstein et al. [61] produced a 14-year (1990-2003) climatology report of icing conditions over Canada and the continental United States by integrating balloon-borne sounding data with surface-level observations of temperature, moisture, cloud cover, and precipitation. Building on previously validated methods [62], this approach ensured robust data integration. However, the relatively brief 14-year window restricted its utility for evaluating long-term climatic shifts.

Cheng et al. [63] incorporated future climate scenarios into icing forecasts for eastern Canada by employing a combination of statistical downscaling techniques for general circulation model outputs and synoptic weather typing (*e.g.*, typically associated with freezing rain events). This approach enabled

them to identify atmospheric conditions favorable for freezing rain and to extend these projections into future periods: 2016–2035, 2046–2065, and 2081–2100. Their findings revealed a projected increase in freezing rain events during the winter months of December to February as the century progresses. This groundbreaking research established a vital connection between macro-scale climate predictions and specific meteorological phenomena, offering valuable insights for developing strategies to enhance infrastructure resilience and adapt to changing climatic conditions.

Finally, for a summary of key studies and methodologies, refer to Table 3.3.

Table 3.3: Overview of empirical and semi-empirical models used to predict atmospheric icing phenomena and the required meteorological parameters.

Author (s)	Region	Research Area	Research Type	Parameter Used								
				WS	SAP	AT	RH	CC	DPT	LWC	FF	PR
Tony et al. [60]	Eastern Canada	Precipitation	Climatology									✓
Cheng et al. [63]	Eastern Canada	Freezing rain	Mapping	✓	✓	✓		✓	✓			
Bernstein et al. [61]	Canada	General	Climatology			✓	✓	✓				✓
Stuart & Isaac [57]	Atlantic Canada	Freezing rain, Drizzle	Mapping									
McComber & Govoni [56]	Canada	Rime, Freezing rain	Empirical	✓		✓				✓		
Yip [54]	Canada	Freezing precipitation	Mapping	✓							✓	✓
Lamraoui et al. [59]	Eastern Canada, northeastern Quebec	General	Mapping	✓						✓		

The different notations are defined as follows:

WS=Wind speed; SAP=Sea level air pressure; AT=Air temperature; RH=Relative humidity; CC= Cloud cover; DPT=Dew point temperature; LWC=Liquid water content; FF=Freezing fraction; PR=Precipitation rate

3.3.2 Advancement of ice prediction modeling

3.3.2.1 Empirical and semi-empirical approaches

The risk of atmospheric icing on turbine performance continues to grow as more turbines are deployed in cold-weather regions [64]. As wind turbine designs evolve, featuring larger rotor diameters and taller towers, it therefore becomes crucial to investigate the relationship between hub height and the probability of rotor icing.

$$\text{Rotor icing height} = \text{Hub height of the wind turbine} + \frac{\text{Rotor diameter}}{3} \quad (3.1)$$

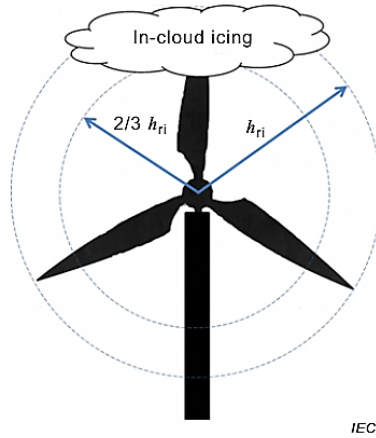


Figure 3.5: Representative ice affected rotor area as defined by rotor icing height, where h_{ri} is the rotor icing height [65].

The relationship between hub height and the probability of rotor icing has been empirically studied and is addressed in the IEC 61400-1 standard for wind turbines [65], which suggests that when cloud heights fall below the rotor icing height, the entire rotor is assumed to be within the cloud layer. While this empirical approach is recognized in the literature [178], comprehensive correlations with key environmental parameters, such as temperature profiles, air speed, and humidity remain limited. Further research is essential to improving the assumption of these estimations and to enhance our understanding of the underlying mechanisms.

To enhance ice projection systems under varying weather conditions, Nergica [87] developed an advanced ice condition monitoring sensor is shown in Figure 3.6. This innovative device not only measures standard meteorological parameters but also detects liquid water content (LWC), setting it apart from traditional sensors. With the ability to assess LWC, the sensor can predict different types of icing (e.g., rime, glaze, wet snow) and determine accumulation rates on surfaces. This information can then be integrated into turbine control systems or de-icing facilities, thereby reducing the impact of icing on wind power production and improving overall system reliability.



Figure 3.6: Ictek's IC-1 ice monitoring sensor [87].

3.3.2.2 Evaluation of computational approaches (after 1970s)

Early investigations into atmospheric icing phenomena initially centered on relatively simple geometries and conditions. Zarling [66] conducted analytical investigations of heat and mass transfer in free-falling droplets, identifying -18°C as a critical temperature for nucleation (*i.e.* early stage of freezing). Later,

Sultana *et al.* [67-68] advanced the understanding of droplet freezing behavior by incorporating temperature-dependent thermophysical properties. Their findings revealed that initial ice formation can occur at temperatures higher than the equilibrium freezing point, depending on droplet size, atmospheric temperature, and water salinity. Such insights are instrumental for elucidating the mechanistic underpinnings of rime icing in free-falling droplets and refining predictive models.

As one of the advancements in modeling ice accretion, Lozowski *et al.* [69] conducted numerical analyses on unheated, stationary, cylindrical surfaces, elucidating variations in ice accretion around the cylinder under both rime and glaze icing scenarios. Subsequent theoretical efforts [70-77] broadened the scope to include transient ice growth processes and more complex phenomena such as icicle formation. Continuing this line of inquiry, Szilder and Lozowski [78] introduced a three-dimensional random walk model to further elucidate icicle growth behavior. By incorporating critical parameters, namely droplet motion, freezing probability, and droplet shedding, their work facilitated a more nuanced understanding of how various factors influence icicle geometry and freezing efficiency. Building upon these foundations, Makkonen *et al.* [79] advanced the modeling framework through a quasi-three-dimensional, flexible-frame model. This refinement subsequently provided the underlying conceptual basis for numerous empirical icing models used in later studies.

Concurrently, various two- and three-dimensional icing simulation tools have emerged where icing environments predominantly involve pure water droplets [81-83]. Commercial software such as LEWICE, FENSAP-ICE, and TURBICE represent an evolution in computational modeling capabilities. LEWICE, a two-dimensional model commonly employed in aviation contexts, provides a fundamental icing analysis on isolated aerodynamic surfaces. TURBICE offers quasi-three-dimensional modeling with a principal focus on wind energy generation, simulating icing on a single representative blade section. In contrast, FENSAP-ICE, a three-dimensional tool, can model the entire blade, incorporating fully three-dimensional flow effects. However, increasing the dimensional fidelity of icing simulations often comes at the cost of substantially greater computational demands. Two-dimensional and quasi-three-dimensional methods simplify this complexity by modeling only a single airfoil or using reduced-order approaches, while fully three-dimensional methods capture more realistic blade geometries and spatial flow variations, albeit at higher computational expense.

Table 3.4 provides a summary of these modeling approaches, their primary application domains, and key parameters, serving as a comparative guide to the state-of-the-art in icing simulation methodologies.

Table 3.4: Overview of icing simulation models and their required meteorological parameters.

Modelling	Application	Parameter Used										
		WS	AOA	RV	DD	AT	WT	AP	RH	LWC	S	IT
Makkonen model [144]	Power Line	✓		✓	✓	✓	✓			✓	✓	
ice Blade model [180]	Aviation	✓		✓	✓	✓	✓			✓	✓	
LEWICE model [181]	Aviation	✓			✓	✓	✓	✓	✓	✓		
TURBICE model [79]	Wind Turbine	✓				✓	✓	✓		✓		✓
FENSAP-ICE model [182]	Aviation, Wind Turbine	✓	✓	✓	✓	✓	✓	✓		✓		✓

The different notations are defined as follows:

WS= Wind speed; AOA= Angle of attack; DD= Droplet diameter; AT= Air temperature; WT= Water temperature; RV= Relative velocity; AP= Air pressure; RH= Relative humidity; LWC= Liquid water content; Subs= Substrate; IT= Icing times

4. Sea Spray Icing

4.1 Physics of Sea Spray Icing: Background Studies

When ocean waves interact with semi-submersible structures, they generate sea spray that can lead to icing. Two principal processes are responsible for spray formation: one induced by wave impacts and the other driven by wind.

4.1.1 Wave-generated spray

Wave generated spray also known as wave-induced spray, this process occurs when breaking waves impact fixed or floating structures, such as platforms, turbines, and ships. The resulting droplets can be lofted to considerable heights above the sea surface, significantly contributing to ice accretion [88, 89]. Figures 4.1 and 4.2 depict the wave–structure interaction and the spray generation process.

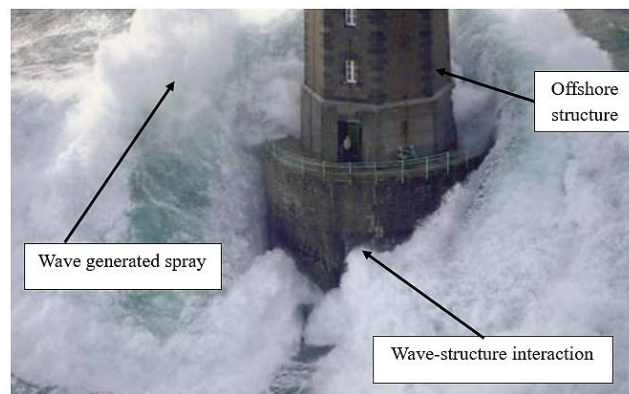


Figure 4.1: Wave structure interaction in North Sea (adapted from [179]).

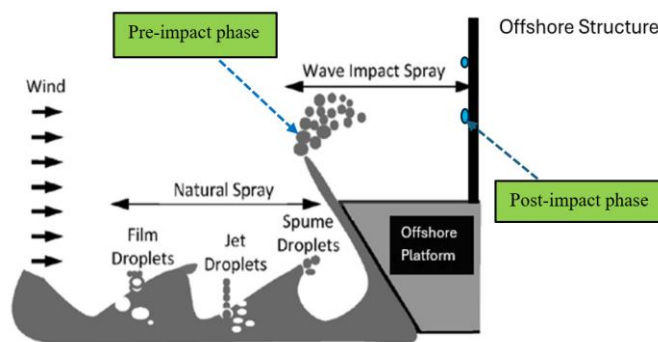


Figure 4.2: Spray generation and transportation physics in the platform (adapted from [90]).

Researchers typically separate the phenomenon into two stages: pre-impact (spray generation and atmospheric transport) and post-impact (contact with a surface and icing process) phases. This segmentation helps identify critical variables at each stage, allowing for targeted strategies, such as splash-zone shielding and anti-icing measures, as well as improved meteorological monitoring to forecast icing events [91-94].

4.1.2 Wind-generated spray

Wind-generated or natural spray is generated primarily by the influence of wind and other environmental factors. Although it tends to play a secondary role compared to wave-induced spray in the icing process [91, 93-94], understanding its formation is essential, especially for stationary offshore platforms.

Figure 4.3 provides an example of wind spray on an offshore oil rig where sprays are generated and travelling to the atmosphere.

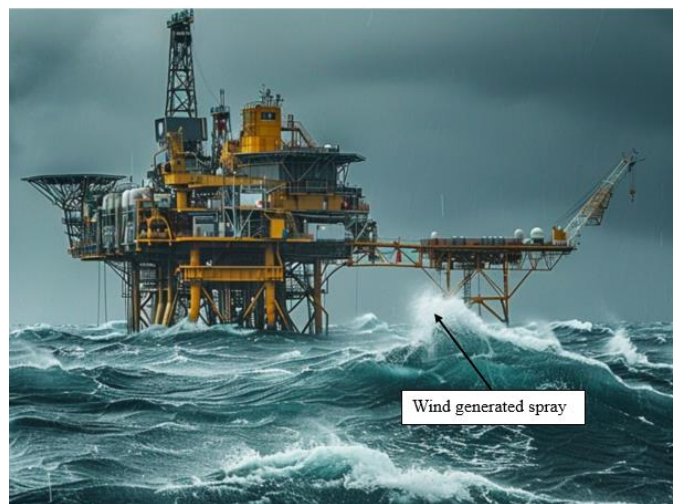


Figure 4.3 Wind spray on an offshore oil rig (adapted from [183]).

4.2 Past Studies on Pre-Impact or Sea Spray Generation

Research on the impact of waves on solid objects has long been a focus in this field. The process that leads to sea spray is divided into distinct stages: initial wave impact, sheet formation, sheet breakup, droplet breakup, and droplet trajectories [95-98]. Given the intermittent and time-dependent nature of these processes, accurate modeling is essential for predicting icing events.

Past research on spray generation spans analytical, empirical, and modeling approaches. Based on these studies, Figure 4.4 summarizes the key parameters involved in the pre-impact phase of wave-induced spray, with detailed descriptions provided below.

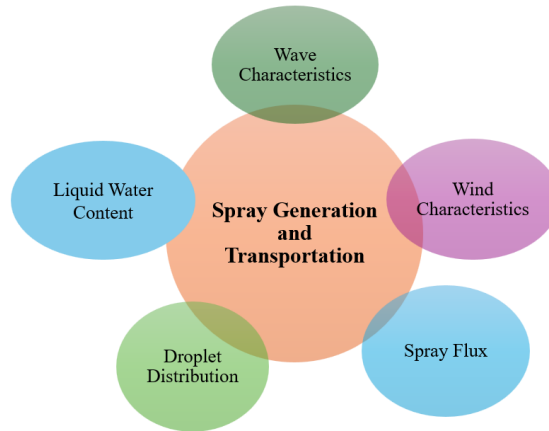


Figure 4.4: Significant parameters for spray generation and transportation process.

4.2.1 Wave characteristics

Wave characteristics are crucial factors in determining sea spray droplet characteristics. Larger and longer waves tend to produce more powerful wave-breaking events (*e.g.*, wave hitting the offshore structures), leading to increased droplet formation.

The type of wave breaking; whether spilling, plunging, or surging, further influences the size and energy of the resultant droplets. Plunging breakers create larger, more energetic droplets, while spilling breakers generate smaller, less energetic droplets. Based on past studies, wave characteristics are classified into several parameters as described in Table 4.1.

Table 4.1: Parameters included in wave characteristics.

Effective factor	Parameters include
Wave	Wave height (m)
	Wavelength (m)
	Wave spectra (m^2/Hz)
	Wave propagation direction (degrees)
	Wave speed (m/sec)

In the area of spray dynamics, the frequency of wave breaking events plays a significant role. Higher-frequency waves produce more frequent droplet generation events, increasing spray volume, especially in consistent wind conditions.

A field study conducted from December 2012 to January 2013 by Jones and Andreas [99] produced data on wind-generated spray and observed that the spray droplet concentration gradient (dC/dr) is dependent on both the significant wave height ($H_{1/3}$), wind speed (U_{10}) at 10 m and wind direction. Figure 4.5 illustrates the outcomes.

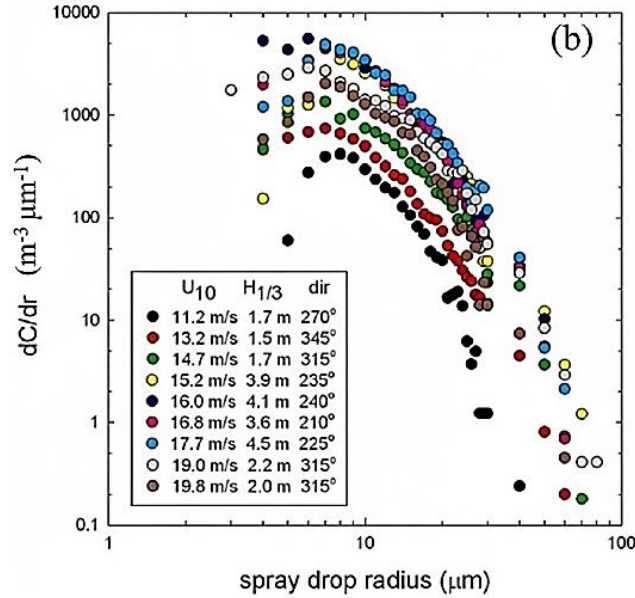


Figure 4.5: Spray droplet concentration distribution function (dC/dr) [99].

For stationary drill rigs, sea spray usually is concentrated from 5 to 20 m over the water surface [100]. However, in regions with frequent large wave events, such as the North Atlantic, sea spray can reach heights of 15 to 60 m above sea level.

4.2.2 Spray flux

The water flux from waves is generally brief and localized near the base of offshore structures, whereas wind-induced spray offers a continuous, though lesser, flux [91, 93-94].

The amount of the total mass flux of seawater spray on an object located on a marine platform per unit area for wave spray during a single spraying event is given by (Horjen, 1983; Zakrzewski, 1987 [101-102]):

$$M = EU_h w(z)_{\text{wave}} \Delta t \quad (4.1)$$

where E is the collision efficiency, U_h is the droplet velocity upon impact, w is the LWC, and Δt is the splash duration. Under certain conditions, measured spray fluxes on horizontal and vertical surfaces range from 0 to $3 \times 10^{-2} \text{ g/cm}^2/\text{s}$ [103].

Besides empirical modeling, past researchers have employed several field measurements with a diverse array of instruments, including sensors and even unconventional tools such as toilet paper rolls and baby diapers. For instance, Muzik and Kirby [104] recorded spray measurements during the 1982 open-water season on Tarsiut Island—an artificial caisson-based island in the Beaufort Sea [105]. Their goal was to map the horizontal distribution of sea spray and quantify the volume produced during high-wind and wave events, with the results summarized in Table 4.2. The authors measured average wind speed at a height of 34 m.

Table 4.2: Overview of wind, wave and spray data measured on Tarsiut island [104].

Date	Maximum recorded significant wave height (m)	Maximum recorded spray rate (cm/h)	Average wind speed (m/s)	Maximum wind speed (m/s)
20-21 August 1982	25	61	16.6	18.9
6-8 September 1982	2	31	10.6	17.3
17 September 1982	1.75	6	5.1 (estimated)	5.1 (estimated)

These findings were later used by Lozowski et al. [106] to refine the liquid water content (LWC) and spray frequency algorithms in the RIGICE model, which estimates ice loads on drilling rigs in Canadian waters. Building on this work, Forest *et al.* [107] further enhanced the model to RIGICE04 by incorporating improved spray data.

More recently, advanced tools such as cloud imaging probes (CIP), high-speed cameras, and LiDAR systems have been introduced, providing high spatial and temporal resolution for a more detailed capture of sea spray dynamics [108, 109].

4.2.3 Liquid water content (LWC)

Liquid water content, defined as the mass of water per unit volume of dry air, is primarily determined by wave height. There are various suggested formulae for LWC due to wave-impact sea spray, but many are intended for marine vessels. The field observations of Forest *et al.*, [107] are the most relevant data that can be used in this context of stationary object. Empirical relations derived from field data include:

Instantaneous LWC [107]:

$$\text{LWC}(z) = 1.35 H_{1/3}^2 \exp(-0.53z) \quad (4.2)$$

where $H_{1/3}$ is the significant wave height, and z (m) is the elevation above mean sea level, and LWC for a single spray cloud in kg/m^3 .

Time-averaged LWC [110]:

$$w = 0.1H \exp(H - 2z) \quad (4.3)$$

where w is the time-averaged spray cloud liquid water content, and H is the wave height (m).

Empirical results show that at a constant wind speed (7 m/s), increasing LWC is correlated with greater ice thickness. This underscores the need for precise LWC measurements using direct sensors and numerical models.

4.2.4 Droplet size distribution

Wind and wave impacts create a broad range of droplet sizes. For example, under conditions where wind speeds exceed 4 m/s, droplets typically measure between about 1 μm and 25 μm [111-112]. In addition, Jones and Andreas [113] observed that wind spray acting on fixed marine structures generates three distinct droplet types with sizes spanning from approximately 0.5 μm to 500 μm , as detailed in Table 4.3. In particular, larger spume droplets (those above 37 μm) have been linked to increased icing rates on these platforms [114].

Table 4.3: Droplet generated by wind spray.

Droplet types	Droplet size in radius (μm)
small film droplets	0.5 - 50
jet droplets	1 - 100
spume droplets	20 - 500

Wave breaking, independent of wind-driven spray, produces its own range of droplet size distributions. Earlier investigations on ships [115]; offshore structures [116-118]; and islands [119]] have yielded valuable field data, although complete records of vertical droplet distributions or velocities were often not captured. Drawing on these past studies, a new plot was developed in Figure 4.6 that suggests a recommended droplet size for modeling ice accretion on offshore structures.

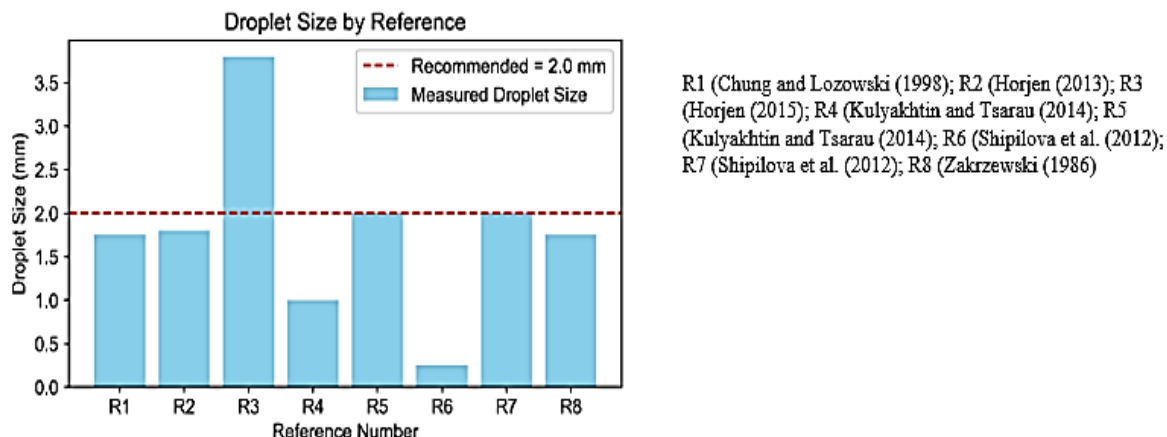


Figure 4.6: Recommended size for the wave spray droplet.

To overcome past challenges, recent field studies have employed a range of instruments, including high-speed cameras, Spray Particle Counters (SPC), CIP, Marine Rain gauge-type Spray gauges (MRS), and Digital Particle Image Velocimetry (DPIV), to measure droplet sizes and velocities. For instance, Ozeki et al. [121] introduced specialized gauges that simultaneously capture droplet size distribution and spray volume (Figure 4.7). However, because sea spray droplets can vary dramatically, from as little as 0.02 μm to as much as 7.7 mm in diameter [123-124], no single instrument is capable of capturing the entire spectrum.

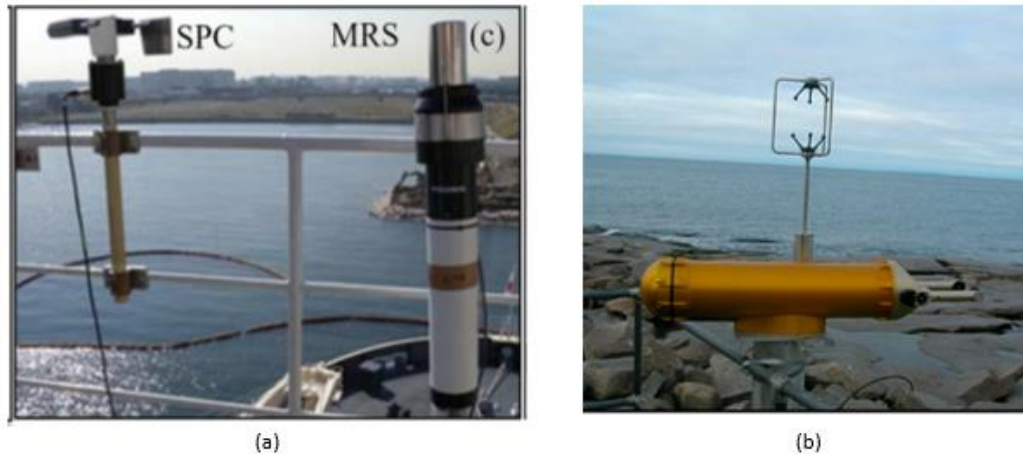


Figure 4.7: (a) SPC (Left) and MRS (Right) mounted on a vessel [121], (b) CIP and the sonic anemometer [122].

Since most measurement techniques sample only a small fraction of the spray cloud, potentially misrepresenting its overall distribution, advanced numerical methods, such as Smoothed Particle Hydrodynamics (SPH) and Discrete Phase Modeling (DPM) have been applied to simulate the complex interactions involved in spray generation and transport.

4.2.5 Wind direction and turbulence

Variations in wind speed and direction, commonly known as wind shear, generate turbulence that critically influences the trajectories of sea spray droplets. This turbulence disrupts the predictable path of droplets, causing them to disperse unevenly as they travel through the air. As a result, the deposition of droplets on offshore structures becomes highly non-uniform, leading to irregular and asymmetric ice formation.

Research indicates that significant droplet entrainment typically begins at wind speeds exceeding 9 m/s [125, 126], with major spray formation occurring around 19 m/s [127]. Jones and Andreas [99] further demonstrated that even minor variations in wind conditions can markedly affect droplet concentration and deposition patterns. Additionally, studies [94, 91] reveal that such unpredictable dispersion not only increases localized ice loads but also poses substantial risks to the structural integrity and operational functionality of offshore installations.

4.3 Past Studies on Post-Impact or Marine Icing Phenomena

Marine icing is a complex, multifaceted phenomenon driven by harsh environmental interactions between wind, water spray, and marine infrastructure. When wind speeds exceed approximately 9 m/s, impact-generated spray droplets are propelled onto marine platforms [128]. Upon impingement, these droplets are rapidly exposed to cold ambient conditions that trigger a series of phase changes by the modes of heat transfer (conduction, convection, and radiation), which collectively contribute to the ice accretion process [129-130]. A detailed explanation of these equations will be found in past studies [128, 131-147].

Ice accumulation rate, or icing intensity, is a critical aspect of marine icing, typically measured on an hourly basis on marine structures. This rate is influenced by a variety of parameters, and drawing on

visual measurements and weather severity factors, a simplified equation (4.4) for sea spray icing growth on offshore structures has been suggested by Overland *et al.*, [148] and Overland [149].

$$I = \frac{v_a(T_f - T_a)}{1 + 0.4(T_s - T_f)} \quad (4.4)$$

where I is the icing intensity, v_a is wind velocity, T_f is the temperature threshold, T_a is the air temperature, and T_s is the sea water temperature.

Although Equation 4.4 incorporates several key parameters, it omits certain important factors. One such limitation is the simplified treatment of relative humidity. To enhance the predictive accuracy of icing intensity, future modeling efforts and measurement correlations should address this gap. Figure 4.8 presents an example of potential future modeling parameters, which are further described below.

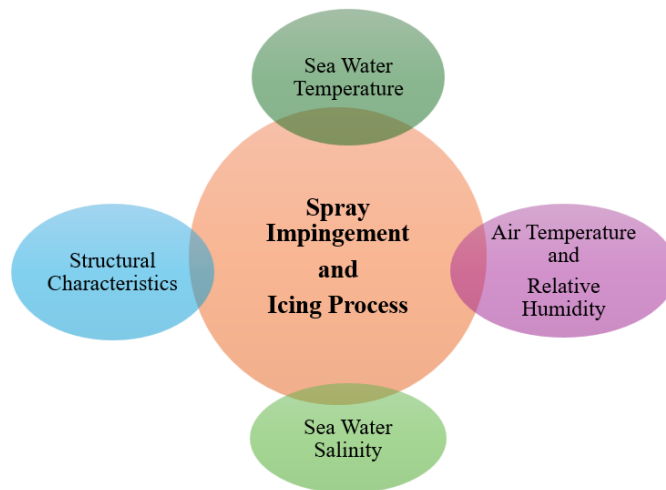


Figure 4.8: Key variables influencing the sea spray icing process.

4.3.1 Air temperature and relative humidity

Atmospheric conditions, particularly air temperature and relative humidity, play a crucial role in determining how water droplets behave on offshore structures. Lower temperatures accelerate droplet cooling, increasing the likelihood of freezing upon impact, while high humidity slows evaporation, allowing droplets to retain their size and enhancing their potential to freeze. Historical research supports these observations.

For instance, ice accumulation is observed to begin at an air temperature of $-2\text{ }^{\circ}\text{C}$, with the most rapid growth occurring around $-17\text{ }^{\circ}\text{C}$ [150-151]. Similarly, Lundqvist and Udin [152] found that ocean water icing requires temperatures below $-2\text{ }^{\circ}\text{C}$, and Cammaert [153] noted that sea spray icing initiates when air temperatures drop below the freezing point of seawater ($-2\text{ }^{\circ}\text{C}$). Interestingly, some Russian studies indicate that at temperatures lower than $-18\text{ }^{\circ}\text{C}$, spray icing does not occur because droplets freeze mid-flight into ice crystals, preventing adhesion to vessels and structures [154, 155, 156].

Regarding relative humidity, the vertical profile near the sea surface remains poorly characterized. While previous research often assumed values above 80% [186], significant gaps in our understanding persist.

These discrepancies underscore the need for region-specific analyses in areas with highly variable weather conditions, such as the Arctic and other cold regions. Furthermore, understanding the long-term impacts of climate change on these atmospheric influences will require comprehensive statistical analysis.

4.3.2 Water temperature

The rate of icing is strongly influenced by sea water temperatures, as demonstrated in Figure 4.9.

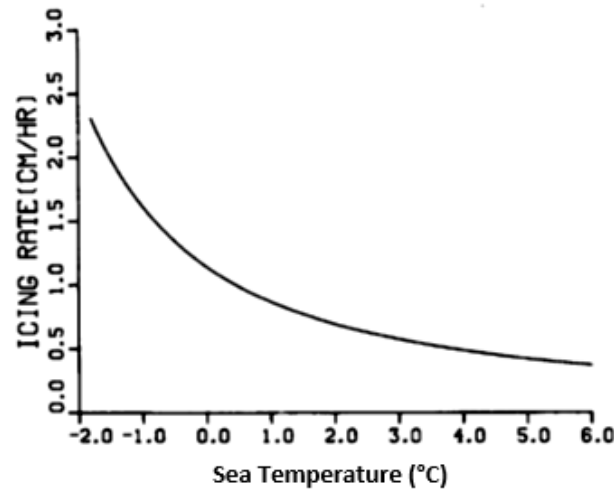


Figure 4.9: Effect of sea temperature on rate of icing [149].

Past studies have shown that spray droplets are more likely to supercool when the sea surface temperature falls below 7 °C, provided the air temperature remains under the freezing point for saline ocean water (−1.7 °C) [157, 158, 159].

Sea surface temperatures vary by region; for example, in areas such as the Aleutian Islands, the Gulf of Alaska, the Bering Sea, and the Arctic, the critical temperature range for marine icing is between −2.2 and 8.9 °C [153, 157; 160]. Furthermore, research suggested that in most Canadian waters, freezing spray is uncommon when the sea surface temperature exceeds 5 °C, with typical temperatures ranging from −1.7 to 5 °C [161-163].

4.3.3 Water salinity

Water salinity presents a significant challenge in marine icing, leading to phenomena such as supercooling, sponginess (a composite structure of pure ice interspersed with brine pockets and air bubbles), and salt rejection. Higher salinity extends the freezing process by maintaining droplets in a cooled state for a longer period. Consequently, marine icing models rely on the equilibrium freezing temperature to account for the salinity-dependent supercooling process [161]:

$$T_{eq} = -0.002 - 0.0524S_w - 0.00006S_w^2 \quad (4.5)$$

where T_{eq} is the equilibrium freezing temperature, and S_w is the water salinity.

Although past studies have often used an average salinity value of 34 ppt for modeling purposes, actual salinity can vary considerably across different regions, illustrated in Table 4.4.

Table 4.4: Information about salinity in seawater [163-166].

Location	Salinity (%)
Atlantic Ocean	36-37
Arctic	20-35
Black Sea	3-15
Baltic Sea	8
Gulf of St. Lawrence	32-34
Mediterranean Sea	37-39
Red Sea	34-41
Average salinity of the ocean considered	34.7

As the climate changes, future research should incorporate region-specific field studies through water sampling or sensor-based measurements at various depths. Moreover, the challenges posed by sponginess and salt rejection further complicate marine icing applications, and a more detailed understanding of these phenomena is still needed.

4.3.4 Surface roughness and topography of offshore structures

The geometry [80, 86] and surface properties [167, 168] of offshore platforms are essential in determining the behavior of spray droplets and their subsequent ice accretion upon contact. The shape and configuration of the surfaces, whether flat, sharp-edged, cylindrical, or spherical, play a pivotal role in influencing droplet adhesion and interaction. For example, sharp edges may enhance ice shedding due to aerodynamic forces, while flat surfaces tend to retain ice more easily. Additionally, the angle at which wind interacts with the structure significantly impacts ice deposition patterns. Structures oriented perpendicular to prevailing winds may exhibit distinct icing dynamics compared to those aligned with the wind, ultimately affecting the distribution of ice loads across the platform.

Moreover, studies highlight that smooth surfaces are more prone to rapid and extensive ice accretion compared to rough or coated surfaces [167-168]. These phenomena are visually represented in Figure 4.10, illustrating the differences in ice accumulation across various surface types.

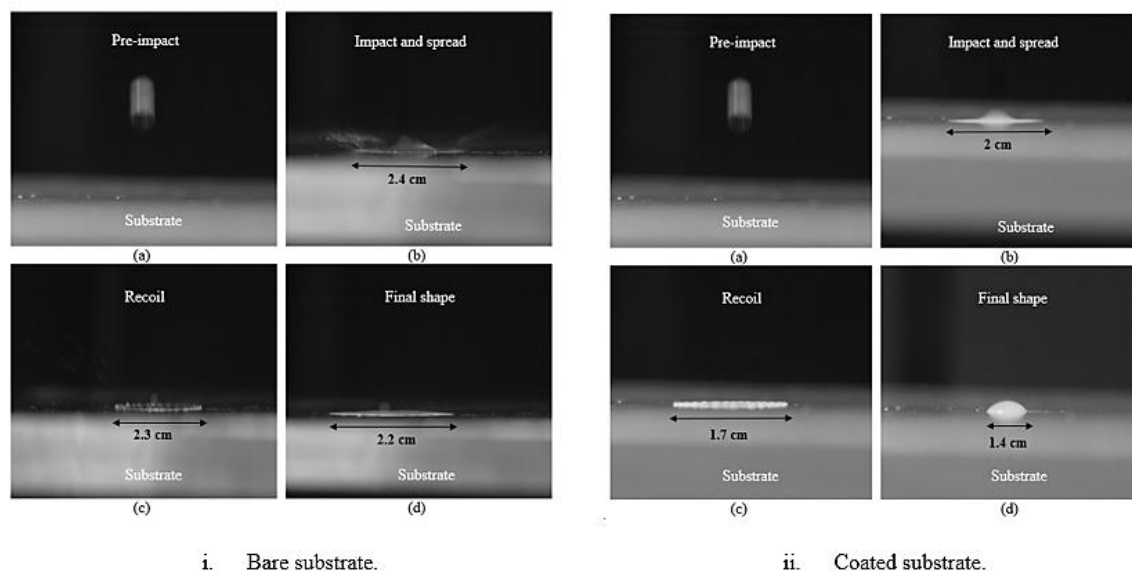


Figure 4.10: Droplet freezing process on (i) bare substrate (ii) coated substrate [167, 169].

Beyond empirical studies, advanced computational models have been developed to simulate ice accretion processes by integrating sea spray dynamics. These models are categorized into fully stationary models, quasi-steady models, and fully time-dependent models, based on how they handle spray mass flux input and calculate icing rates.

Fully stationary models, such as RIGICE and MINCOG, assume a constant spray mass flux throughout the icing period, relying on time-averaged flux without requiring specific spray frequency or duration inputs. In contrast, quasi-steady models, such as the Midgett vessel model, allow spray mass flux to vary over time. Lastly, fully time-dependent models, like ICEMOD, fully account for temporal variations in the icing process. While stationary models primarily depend on average flux, these types of models require detailed inputs regarding spray frequency and duration when employing liquid water content (LWC).

Over time, these models have been enhanced with new data, interpretations, and algorithms. Despite these advancements, spray sub-models still face limitations. Current versions often simplify key aspects, such as assuming a constant droplet size and overlooking complex airflow dynamics, leading to uncertainties in input data [107, 176]. For further insights, refer to the summarized comparison of these models in Table 4.5.

Table 4.5: Analysis of existing marine icing models.

Model	Country	Application	Dimension	Conditions	Numerical Technique	Factors Used			Validation	Accuracy
						Spray generation	Spray distribution	Heat transfer modeling		
ICEMOD	Norway	OV	2D	FTD	FDM	x	x	x	x	Moderate
RIGICE	Canada	OS	2D	MT	FORTAN-77	x	x	x	x	Moderate
RIGICE04	Canada	OS	2D	MT	ESS	x	x	x	x	Moderate
MARICE	Norway	OS	3D	FTD	FVM	x	x	x	x	High

The different notations are defined as follows:

OS=Offshore structure; OV=Offshore vessel; FTD=Fully time dependent; FDM=Finite difference method; MT=Mean time; ESS=Excel spread sheet; FVM=Finite volume method

5. Conclusions and Recommendations

The successful deployment of offshore energy systems in cold climates requires a thorough understanding of icing phenomena. This chapter summarizes knowledge gaps, key contributions, and strategic recommendations for the effective implementation of offshore energy solutions.

5.1 Contributions and Knowledge Gaps

5.1.1 Comprehensive classification of icing risks for offshore energy projects

This review presents a comprehensive framework for classifying icing risks in cold climate conditions, specifically tailored to offshore energy projects in Atlantic Canada. The classification encompasses both atmospheric icing and sea spray icing, reflecting the full spectrum of icing conditions relevant to these systems. As illustrated in Figure 2.2, the framework is structured into clearly defined main and sub-categories, providing an organized and in-depth understanding of the various icing phenomena encountered in offshore environments. This integrated approach fills a notable gap in the existing literature, where such risks have often been examined in isolation or without a cohesive structure.

5.1.2 Atmospheric icing characterization

Chapter 3 provides a comprehensive state-of-the-art review aimed at advancing the understanding of atmospheric icing and identifying the key factors influence ice accretion on offshore energy infrastructure. Review of existing literature reveals that most of the prior research has predominantly focused on onshore environments, leaving offshore conditions significantly underexplored. To address this gap, this review investigates offshore-specific icing phenomena, such as sea fog, saline water droplets, and airborne salt particles. These parameters will be support the assessment of icing risk for offshore energy applications, with a focus on conditions specific to Atlantic Canada.

This review also examines the parametric dependencies associated with various types of atmospheric icing and identifies data gaps, particularly the absence of threshold values for wind speed, droplet diameter, and liquid water content in relation to precipitation-induced icing and hoar frost formation. Parametric limitations are also observed in previously developed empirical models. For instance, one simplified correlation used in wind energy applications estimates the rotor icing height based on atmospheric cloud height. It assumes that if the cloud base falls below the rotor height, the entire rotor is subjected to icing conditions. While this model may offer a preliminary approach for tall turbines, it fails to account for small to medium-sized structures and lacks integration with other atmospheric factors such as temperature profiles and humidity levels.

To contextualize the Canadian offshore environment, the review also explores regional icing patterns, with a particular focus on Atlantic Canada. Freezing precipitation is identified as a recurring and impactful climatic hazard in the region. Local topography, moisture advection, and prevailing wind conditions significantly influence icing severity. For example, eastern Newfoundland frequently experiences persistent glaze icing due to exposure to moist Atlantic air masses, while the Atlantic-facing slopes of the Gaspé Peninsula and the St. Lawrence River Valley exhibit high icing severity indices, driven

by recurring ice storm tracks and strong westerly to northwesterly winds. Although these regional insights offer valuable meteorological and topographic context, there is a lack of comprehensive analyses that explore broader temporal trends and long-term implications. In particular, this review identifies the limited understanding of how climate change may affect icing patterns across extended time scales.

In addition to empirical and semi-empirical models, advanced computational tools were also evaluated. Models like TURBICE and FENSAP-ICE provide valuable insights but demonstrate limitations in accurately representing the transient dynamics of icing events and challenges related to salt rejection. There is a need for long-term, region-specific field data to deepen our understanding of offshore atmospheric conditions and support the development of more reliable icing prediction models.

5.1.3 Sea spray icing characterization

To improve the understanding of sea spray icing in offshore environments, this review categorized the phenomenon into two primary stages, spray generation and the subsequent icing process. This integrated perspective offers a more comprehensive view and addresses a notable gap in previous literature, where such a structured approach has not been well-documented.

In the context of spray generation, past studies found that frequent and intense wave events are common in the North Atlantic. However, significant data gaps remain regarding wave characteristics such as height, frequency, and impact dynamics, limiting our ability to accurately assess spray formation and its contribution to marine icing. Spray droplets are a major contributor to sea spray icing, making it essential to accurately characterize their size, distribution, and behavior. To aid future modeling efforts, this review offers a recommendation for the minimum droplet size in Figure 4.6, derived from empirical correlations in existing studies. Nonetheless, substantial uncertainties remain, particularly in understanding droplet velocity and distribution under varying environmental conditions.

Further complexity arises from oceanic and meteorological parameters, such as sea surface temperature, salinity, and relative humidity, which complicate the direct application of semi-empirical models in the diverse settings of Atlantic Canada. The location-specific nature of these variables limits the generalizability of existing models, reinforcing the need for region-specific data inputs.

In addition to empirical and semi-empirical approaches, a range of computational modeling tools has been developed to simulate spray generation and icing formation. These models benefit from advances in computing power and hold significant promise for capturing the intricacies of real-world conditions. However, comparing model outputs remains difficult due to variations in scope and application. For example, RIGICE, developed in Canada, is designed for stationary offshore structures, while ICEMOD, from Norway, is tailored for marine vessels and operates as a time-dependent model. This contrast highlights the necessity of selecting or developing case-specific modeling frameworks suited to the unique operational and environmental conditions of offshore energy systems in cold climates.

5.1.4 Development of a comprehensive cold climate data collection framework

Through an assessment of atmospheric and sea spray icing mechanisms, a comprehensive data collection matrix has been developed and represented in Table 5.1. This matrix will serve as a valuable resource for future NRCan field campaigns in Atlantic Canada, and will support the development of regional cold-climate icing risk maps, ultimately contributing to the safe and efficient deployment of offshore energy systems in the region.

Table 5.1 Intergrated data collection matrix for cold climate risk assessment.

Category	Serial number	List of parameters	Unit	Icing types	
				Atmospheric icing	Sea spray icing
Meteorological	M1	Wind speed	m/sec	●	●
	M2	Wind direction	degrees	●	●
	M3	Wind shear	m/sec/km	●	●
	M4	Wind turbulence	N/A	●	●
	M5	Air temperature	°C	●	●
	M6	Atmospheric pressure	Pa	●	
	M7	Solar radiation	W/m ²	●	
	M8	Relative humidity	%	●	●
	M9	Density of freshwater	kg/m ³	●	
	M10	Liquid water content for fresh water	g/m ³	●	
	M11	Rate of freezing rain	mm/hr	●	
	M12	Total time of freezing rain	Sec or hour	●	
	M13	Rate of wet snow	mm	●	
	M14	Precipitation type	N/A	●	
	M15	Total precipitation time	sec or hour	●	
	M16	Sea fog	visibility reduction	●	
	M17	Cloud cover	okta	●	
Ocean	O1	Sea surface or water temperature	°C		●
	O2	Salinity of sea water	ppt	●	●
	O3	Density of salt water	kg/m ³	●	●
	O4	Liquid water content for sea water	g/m ³		●
	O5	Wave height	m		●
	O6	Wave period	sec		●
	O7	Wave breaking types	N/A		●
	O8	Sea state	N/A		●
	O9	Wave frequency	Hz		●
Structure	S1	Structure of substrate	N/A	●	●

The different notifications are defined as follows: ● = Pre-impact phase; ● = Post-impact phase; ● = Both phases

5.2 Recommendations for Future Research

To support the successful deployment and long-term resilience of offshore structures in cold climate regions such as Atlantic Canada, future research must place greater emphasis on understanding atmospheric and sea spray icing conditions. These phenomena, along with their influencing parameters, pose significant operational risks in sub-zero marine environments and require in-depth investigation to enhance the safety and reliability of offshore infrastructure. Figure 5.1 illustrates the future applications of integrated data collection matrix.

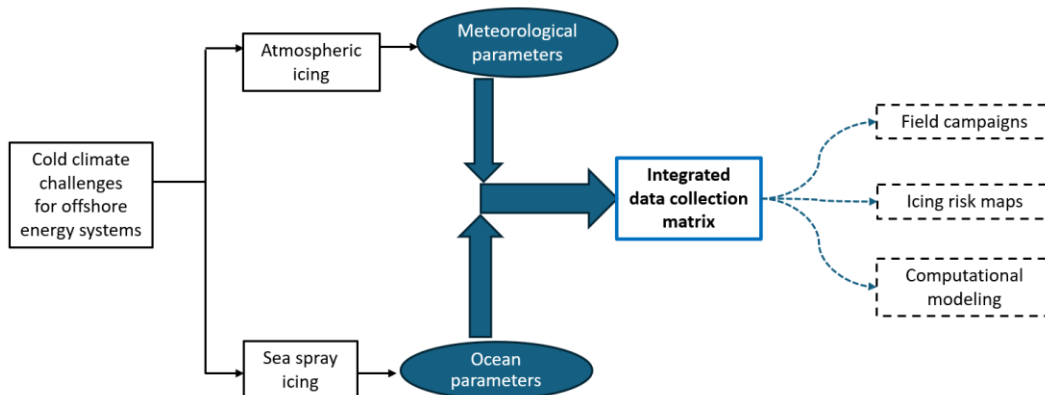


Figure 5.1: Framework desired of cold climate research outcomes.

A key step toward mitigating icing-related risks involves the development of regional cold climate icing risk maps. This will require a comprehensive analysis of integrated atmospheric and oceanographic datasets over extended timescales, ideally twenty to thirty years. Such long-term projections can reveal evolving climate trends, facilitate the identification of regions with increased icing potential, and serve as early warning tools for developers. To reduce uncertainty and increase the robustness of these assessments, comparative evaluations using outputs from multiple climate models are recommended.

In terms of modeling ice accretion, the Canadian-specific RIGICE model serves as a valuable tool for fixed offshore structures. However, to effectively forecast climate change scenarios, the integration of long-term historical datasets into the model is essential. For model validation, scaled laboratory experiments, such as wave-tank testing and controlled cold chamber studies can yield significant insights into ice formation. These experiments can be further enhanced by sequential video recordings, which improve the accuracy of droplet distribution data and offer visual confirmation of icing events.

Despite the benefits of laboratory studies, long-term field measurements remain essential for capturing the complexity of real-world icing phenomena. Field monitoring campaigns spanning a minimum of two years are recommended to gather high-resolution, site-specific data necessary for comprehensive model validation and refinement. The integration of advanced technologies, such as LiDAR, drones, and machine learning algorithms will be essential for the automated detection and characterization of complex spray events and transient ice accretion processes.

Together, these research approaches and technologies will contribute to building a comprehensive, high-fidelity dataset. This, in turn, will support more accurate risk assessments and the development of effective mitigation strategies, ultimately enhancing the operational resilience of offshore structures in cold climate marine environments.

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