OCS Study
BOEM 2018-032

US Outer Continental Shelf Oil Spill Causal Factors Report (2018)

US Department of the Interior
Bureau of Ocean Energy Management
Alaska OCS Region

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List of Abbreviations and Acronyms

ABSG	ABS Group Consulting, Inc.
API	American Petroleum Institute
bbl	Barrel; 1 barrel =42 US gallons, 0.159 kiloliters, 0.159 m3, or 0.136 metric tonnes
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CSB	US Chemical Safety and Hazard Investigation Board
DPS	Dynamic positioning system
GOM	Gulf of Mexico
GPS	Global positioning system
HEP	Human error probability
IMO	International Maritime Organization
LOWC	Loss of well control
MMS	Minerals Management Service
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPS	Nominal pipeline size
NSIDC	National Snow and Ice Data Center

OCS	Outer Continental Shelf
OSV	Offshore supply vessel
PAC	Pacific Ocean
PSS	Practical salinity scale
PWOM	Polar Water Operations Manual
SWH	Significant wave height
USACE	US Army Corps of Engineers
USCG	US Coast Guard
USGS	US Geological Survey

1 Introduction

On 26 September 2017, the Bureau of Ocean Energy Management (BOEM) contracted ABS Group Consulting, Inc. (ABSG) in an Indefinite Delivery/Indefinite Quantity contract to develop oil spill occurrence frequencies for determined size ranges of crude oil, condensate, and refined petroleum spills. These frequencies are for use in environmental analyses related to proposed oil and gas leasing, exploration, development, and production activities in the Alaska Outer Continental Shelf (OCS) Arctic Planning Areas. Task 1 of the first task order in contract produced oil-spill occurrence rates for these regions. Task 2 of the first task order in the contract involves a literature search and analysis of potential causal factors of oil spills of 50 barrels (bbls) or more in Arctic regions and differences in oil spill occurrence factors among the Arctic, Gulf of Mexico (GOM), and Pacific (PAC) OCS. The oil-spill occurrence rates and causal factors will provide information for further work to be performed regarding fault tree analysis of oil spills in the Arctic OCS.

To enhance understanding of the origins of oil spills of 50 bbls or more in the OCS, this report identifies and analyzes historic and potential causal factors in the GOM and PAC OCS to identify causal factors in the Arctic OCS that are not inherent to the Arctic environment. The intent is to capture both actual and potential causes of spills and examine similarities or differences between regions.

The environmental conditions and remote locations in the Arctic OCS require additional safeguards; innovative and tested designs; and careful operation of oil and gas facilities such as pipelines, platforms, or rigs. Over the last few years, work has been initiated to investigate ways to deal with the unique challenges to operating and transiting through Arctic regions, particularly the extreme cold temperatures and ice loads. The federal government, including cooperation with the Bureau of Safety and Environmental Enforcement (BSEE) and BOEM, has acknowledged this unique frontier in energy development in its passing of the Arctic Rule in 2016 (BSEE & BOEM 2016). As the Arctic continues to undergo changes and as industries expand to the region, further research will be necessary to ensure the best available technology and science are utilized in offshore operations. The operational, technological, and monetary challenges of overcoming the Arctic environment have historically proven to be too great for many companies. For example, Shell launched a $7 billion Arctic environmental studies and drilling program only to abandon the project years later after marginal discoveries and regulatory difficulties (Macalister 2015). Economic and market studies of oil development indicate that Arctic operations are likely to be costlier compared to other regions; though some parts of the world have had relative success in oil production, Arctic oil projects typically require longer construction times and production schedules (Kleinberg, et al. 2018). The excessive cost of Arctic exploration may be preventative enough to preclude new operations or to impose a delay in technological and scientific development for countries that have already dedicated initial resources (Dvorak 2017). The cost of the operations reducing investments in research may influence the likelihood of oil spills if oil companies are not utilizing best available technologies.

1.1 Scope of Report

The literature search and analysis of causal factors in the Arctic and other regions include oil spills of 50 bbls or more at different facility types associated with offshore oil and gas operations. This report is intended to inform future fault tree analysis of oil spills of 50 bbls or more related to offshore exploration and development activities on the US Arctic OCS. The analysis considers oil spill causal factors in the GOM and PAC OCS as well as factors in Arctic regions within and outside of the US.

This report assumes any analysis conducted using this literature review will be specific to the US Arctic region. The literature review may identify information that related to the Arctic region or Polar regions outside of the US; however, if the information is not also relevant or applicable to the US Arctic, then it is considered outside the scope of this project.

The historical causal factors within the US OCS are informed primarily by ABSG's 2016 oil spill analysis study for BSEE. The study estimated statistics for spill occurrence for a broad scope of spill volumes as well as additional facility types (ABSG 2016).

1.2 Outline of Report

This report discusses the causal factors of oil spills of 50 bbls or more in the GOM and PAC OCS and Arctic OCS through three sections. Section 2 of the report discusses the GOM and PAC OCS causal factors based on the US OCS Oil Spill Statistics Report (ABSG 2018). Section 3 considers the climate and conditions of the Arctic that may be oil-spill causal factors on the Arctic OCS. Section 4 analyzes the influence of Arctic factors on the causal factors of the GOM and PAC OCS.

The comparison of the GOM, PAC, and Arctic OCS and the associated causal factors of oil spills includes the discussion of uniquely Arctic circumstances and how Arctic factors may modify GOM and PAC OCS causal factors. The causal factors of oil spills in the GOM and PAC OCS are organized according to the facility type (platforms and pipelines) and include: hurricanes, equipment failure, human error, weather, collisions, natural hazards, third-party impacts, corrosion, operational impacts, and mechanical failure. The causal factors discussed for the Arctic OCS include: Arctic weather, low temperatures, ice forces, ice gouging, strudel scouring, upheaval buckling, and thaw settlement.

This report will utilize Kent's words of estimative probability (Kent 2008) to describe the likelihood of oil spill causal factors occurring in each of the discussed OCS regions. The categorical estimations of probability are qualitative descriptions for ranges of certainty in Error! Reference source not found. This l anguage does not guarantee the quantitative probabilities associated with the descriptions, but it frames the factors for discussion on relative likelihoods. For example, causal factors described as "chances about even" are those that are just as likely or unlikely to occur and lead to an oil spill after an event.

Table 1. Kent's words of estimated probability

Estimated Probability	General Area of Possibility	Qualitative Description
100%	Certainty	Certain
93%	Give or take about 6%	Almost certain
75%	Give or take about 12%	Probable
50%	Give or take about 10%	Chances about even
30%	Give or take about 10%	Probably not
7%	Give or take about 5%	Almost certainly not
0%	Impossibility	Impossible

2 Oil Spill Causal Factors in the Gulf of Mexico and Pacific Outer Continental Shelf

Oil spills of 50 bbls or more in the GOM and PAC OCS are heavily studied from environmental, engineering, regulatory, and business perspectives. Understanding the causes and impacts of historic oil spills is crucial for prevention and mitigation of future spills, particularly as the oil and gas industry ventures into new territories and technologies.

This section of the report focuses on offshore oil spills of 50 bbls or more in the US OCS. BOEM's past oil spill analysis studies consider a broad range of facilities and spill volumes, but most of the research focuses on spills of 50 bbls or more. These spills are better documented and studied, allowing greater confidence in the causal factor identification. This report organizes the causal factors for GOM and PAC oil spills by facility type (i.e., platforms and pipelines), then by causal category.

For the purposes of this report, ABSG defines small, medium, large, and huge oil spills according to the limits outlined in **Table 2Error! Reference source not found.** below.

Table 2. Platform and pipeline spill size definitions

Category	Size (bbls)
Small	50 to <100
Medium	100 to <1,000
Large	1,000 to <10,000
Huge	>10,000

The categorical breakdown by facility type and causal factor allows for the analysis in this report to provide information for future fault tree analysis of oil spills in the different size categories. Failures in a singular factor or any combination of several factors do not guarantee an oil spill. These categories and the causal factors within them capture the areas that are most likely to cause concern for offshore operations as evidenced by historical oil spill occurrence rates in the GOM and PAC OCS. The influence of the Arctic OCS environment on each of these causal factors will be discussed in Section 4 of this report.

2.1 Platform Spills

Offshore platforms are subject to a wide range of variables, including the natural environment, building materials, and personnel. Each of these variables includes individual factors that all contribute to the success or failure of offshore operations. Oil spill causal factors for GOM and PAC OCS include:

- Hurricanes
- Equipment failure
- Human error
- Weather
- Collisions

2.1.1 Hurricanes

Since 1972, hurricanes have caused the most oil spills of 50 bbls or more (ABSG 2018). The Minerals Management Service (MMS), now BOEM, was historically tasked with the responsibility of recording hurricane-related spills from US OCS oil and gas facilities. The records included spills that were observed and generally required intervention following the storms.

In 2002, MMS identified petroleum losses from tanks on platforms and rigs destroyed by Hurricane Lili and counted those as spills even though no evidence of a release was observed, and no response was required. Hurricane Ivan in 2004 marked the first case for which unrecovered petroleum amounts on destroyed, heavily damaged, and/or missing structures (platforms, rigs, and pipelines) were effectively inventoried and reported as spills. This record collection of unseen and passive spills was performed to calculate spill estimates for Hurricanes Katrina, Rita, Gustav, and Ike, with changes in hurricane-related spills generating an increase in the number and size of spills, primarily due to the destructiveness of hurricanes (MMS 2009). Hurricanes not only can have dramatic effects on the number of spills occurring in the OCS, but they can also cause spills that are large and long lasting if wells are not shut in properly or timely. After Hurricane Ike in 2008, thousands of platforms in the GOM were damaged or destroyed. One of the failed platforms was the result of a foundation failure, making it the first foundation failure in an offshore platform from a hurricane (Chen, et al. 2013). The offshore industry is still learning from past hurricane incidents, making this causal factor unlikely to diminish in influence (API 2017). No industry-wide methodology has been established to effectively measure the direct impacts of hurricanes on offshore infrastructure (Ilbeigi and Dilkina 2017). Though hurricanes are unlikely in the Arctic OCS, other severe storms like polar lows may act similarly as causal factors of oil spills.

2.1.2 Equipment Failure

Equipment failure alone is more likely to cause small and medium oil spills than large spills, but equipment failure may act as a contributing factor to larger spills (ABSG 2016). The 1970 Shell Platform 26 spill in the GOM is officially considered to have been caused by various equipment failures. The 21-B well, with a 424-bbl-per-day capacity, had ruptured 12 ft above the water, thus releasing an estimate of 20 bbls per day for five months (NOAA c2018).

More recently, equipment failure and other factors were cited as the causes for the 2010 *Deepwater Horizon* oil-spill incident. The investigation report identified a well blowout as one of the contributing factors for the incident (USCG 2011). The US Chemical Safety Board (CSB) identified one of many technical failures at the Macondo well in the Gulf of Mexico as a buckled drill pipe caused by inconsistent internal and external pressures (CSB 2016). This pressure scenario is also a concern in the Arctic OCS, though shallower depths of Arctic drilling may reduce the likelihood of an incident similar to the Macondo events. Incidents such as Shell Platform 26 and *Deepwater Horizon* are extreme examples of low probability events, but equipment failure is also the cause of more typical small and medium oil spills. For example, a 2009 small pollution event from the Transocean *Discoverer Spirit* in the GOM was attributed to equipment failure when a leak occurred in the kill line connection between two joints, and 196 bbl of synthetic base mud was released (MMS 2010). In the Arctic OCS, equipment failure is likely to be a more influential causal factor due to the additional stresses and pressures on equipment from the harsh environment.

2.1.3 Human Error

Human error is a relatively stable predictive causal factor as rates of human error do not tend to vary substantially over time. The contribution of human error is comparable for different sizes of oil spills (ABSG 2016). Despite the relative reliability of human error as a stable causal factor, human error is an important additive causal factor. Along with equipment failure, human error contributed to the *Deepwater Horizon* incident in 2010 as the rig crew failed to observe and respond to the critical indicators before the explosion (Dittrick 2011). Human error also contributes to more typical medium oil spills, not just low probability, large events such as *Deepwater Horizon*. A medium spill aboard ENSCO 29 in 2001 was attributed to human error when an employee inadvertently manually opened the overboard drain line to the mud pit reserve storage tank (MMS 2001). Though human error is a predictable contributing causal factor to GOM and PAC OCS oil spills, its influence may be greater on oil spills in Arctic operations. Certain conditions, such as adverse Arctic weather, which will be discussed further in Section 3, can impact the performance of employees in offshore environments and potentially make oil spills more likely (Balindres et al. 2016).

2.1.4 Weather

After hurricanes and equipment failure, weather is the most common causal factor for medium and large oil spills on GOM and PAC OCS platforms. Weather as a causal factor identifies spills caused by standard weather events, such as strong tides, rough seas, and waves, and not by extreme events such as hurricanes or other natural hazards. Weather factors that may cause oil spills include rate and frequency of significant wave heights (SWHs), which are most likely to impact platforms on the OCS. During the period of 2004-2008, the maximum number of SWHs exceeding 10 m in the GOM region had increased in comparison to the previous 46 years of collected data (Panchang et al. 2013). SWHs do not necessarily imply platform damage or oil spills, but an increase in their frequency may increase the stress to platforms. In the PAC OCS region, data collected from offshore deep-water buoys indicate the annual average of SWHs have increased at a rate of approximately 0.015 m per year since the collection of SWHs data in 1970s, in addition to the increase of five highest SWHs per year at 0.0071 m per year (Ruggiero et al. 2010). This trend of increasing SWHs is present in the Arctic as well, making weather a likely causal factor for Arctic OCS oil spills (Waseda et al. 2017).

2.1.5 Collisions

Collisions in the GOM and PAC are most likely to occur between tankers or offshore supply vessels (OSVs), but collisions leading to oil spills are likely between vessels and platforms. Studies on collisions with offshore platforms are numerous, and this causal factor was once a primary concern (Furnes and Amdahl 1980). Over time, other causal factors have proven their greater potential for causing an oil spill, as the likelihoods of collisions have decreased with advanced technology of ships, particularly dynamic positioning systems (DPS) (Faÿ 1990). As more vessels have incorporated the use of DPS, the potential risk of collision is now higher for those who have do not operate with this system (Verhoeven et al. 2004). Though the likelihood of this causal factor is relatively low in all regions of the OCS, the consequences could be severe (Pengfei et al. 2016).

2.2 Pipeline Spills

Pipeline size, as measured by pipeline diameter, appears to have a slight correlation with spill frequency (ABSG 2018). Larger pipelines, with a nominal pipeline size (NPS) of 10 inches or more, have a slightly higher spill frequency. Larger pipelines also have higher spill rates in the medium, large, and huge spill size categories while smaller pipelines have the higher rate in the small spills category. The causal factor categories for pipeline spills of 50 bbls or more include:

- Natural hazards
- Third-party impacts
- Corrosion
- Operational impacts
- Mechanical failure

2.2.1 Natural Hazards

Many natural hazards can impact pipelines, but mud slides and hurricanes are most notable. Hurricanes are not considered separately for pipelines because their impacts are not substantial enough to warrant an individual category. However, hurricanes may still be a primary causal factor for pipeline-based oil spills, as well as to platform-based oil spills. The strong winds and currents of hurricanes and storms can threaten the structural integrity of pipelines (Tian et al. 2015). Mudslides threaten pipelines as they remove supporting sediment and pose external forces from moving sediment (ABSG 2018). Natural hazards may be a causal factor of oil spills in the Arctic OCS, but the hazards will likely differ from those on the GOM and PAC OCS such as mudslides and hurricanes.

2.2.2 Third-party Impacts

The influence of external impacts on pipelines is similar to the influence of collisions on platforms in causing oil spills. Third-party impacts threatening pipelines may include vessels, anchor drags, and trawl nets. Longer pipelines present a greater chance of accidental contact with third parties and thus oil spills (National Research Council 1994). Third-party impacts may be a causal factor of oil spills in the Arctic OCS, but the influence of this factor is dependent on trends in maritime traffic and the burial depth of the pipeline.

2.2.3 Corrosion

Internal and external corrosion can act as causal factors for oil spills for pipelines. Corrosion is typically a causal factor for small or medium spills (ABSG 2018). Corrosion can be a contributing factor to oil spills, along with other causal factors. For example, external corrosion may lead to mechanical failures (National Research Council 1994). Corrosion may be a causal factor in the Arctic, but it will likely manifest differently than in the GOM or PAC OCS as materials react differently at different temperatures.

2.2.4 Operational Impacts

For pipelines, operational impacts include rig anchoring and workboat anchoring. This causal factor is distinct from third-party impacts because rigs and workboats are necessary parts of the offshore exploration and development operations and must be managed accordingly. When hurricane-related spills are removed from oil spill data, a declining trend appears for operations-related spills (ABSG 2018). Operational impacts is likely to be a causal factor in the Arctic due to the lack of existing infrastructure and subsequent need for additional support vessels (BSEE & BOEM 2016).

2.2.5 Mechanical Failure

Mechanical failure of a pipeline may include connection failures or material failures. Connection failures most likely occur at the source or end of the pipeline where the pipeline meets the platform or onshore facility, and material failures may occur throughout the entirety of the pipeline (DNV GL 2017).

Mechanical failure may include failure of bends, bolts, connectors, fittings, clamps, joins, valves, or other features of the pipeline (DNV GL 2017). The concern of mechanical failure in the Arctic OCS prompted BSEE and BOEM to require auditing of mechanical integrity more frequently on the Arctic OCS than on the GOM or PAC OCS (BSEE & BOEM 2016).

2.3 Loss of Well Control

Loss of well control (LOWC) spills are oil spills on an exploration or development well. Spills resulting from an LOWC event have the potential to be large due to the free-flowing nature of the oil after the event, but LOWC spills are historically small spills (ABSG 2018). Oil spills associated with the loss of well control do not necessarily need to be categorized separately because an LOWC event is likely the result of causal factors that have been discussed in previous sections, such as equipment failure or human error (Holand 2017).

3 Oil Spill Causal Factors Unique to the Arctic Outer Continental Shelf

The Arctic poses unique environmental and technological challenges that offshore oil and gas stakeholders must address when drilling, producing, or transporting in Arctic regions. The harsh environmental conditions and remote locations require the design and construction of innovative and reliable primary and secondary systems. This report analyzes the following potential causal factors of oil spills in the Arctic, focusing on the US Arctic OCS:

- Arctic weather
- Low temperatures
- Ice forces
- Ice gouging
- Strudel scouring
- Upheaval buckling
- Thaw settlement

The causal factors of oil spills in the GOM and PAC OCS are still present in the Arctic, but this section will discuss Arctic-specific factors. The history and understanding of oil spills in the GOM and PAC OCS are often categorized by their source: pipelines and platforms. This distinction is not entirely appropriate for categorizing the potential of oil spills in the Arctic. The potential causal factors of oil spills in the Arctic do not directly align with pipelines and platforms because the factors are likely to influence oil and gas operations in multiple stages of operations. However, platforms are more likely to be influenced by ice forces, low temperatures, and Artic weather, while pipelines are more likely than platforms to experience oil spills under the influences of ice gouging, scouring, upheaval buckling, and thaw settlement.

3.1 Background

Offshore oil and gas development and activities are relatively new to the US Arctic OCS, and the scientific community is still researching the relationships between and challenges to the industry and the environment. Further research is needed on the geography, climate, and challenges of the US Arctic region. The US Geological Survey (USGS) publishes data and results, such as their assessment of undiscovered conventional oil and gas resources in all areas north of the Arctic Circle as seen in **Figure 1**. Scientists are developing models to understand the potential impacts of offshore activities on the Arctic environment and the influences of the Arctic environment on offshore development. Some of these models focus on the Arctic environment itself, such as sea ice modeling (Rees Jones and Worster 2014), or the relationships between the atmosphere, ice, and ocean as in the Louvain-La-Neuve single-category model and the Los Alamos multicategory model (Roy et al. 2015).

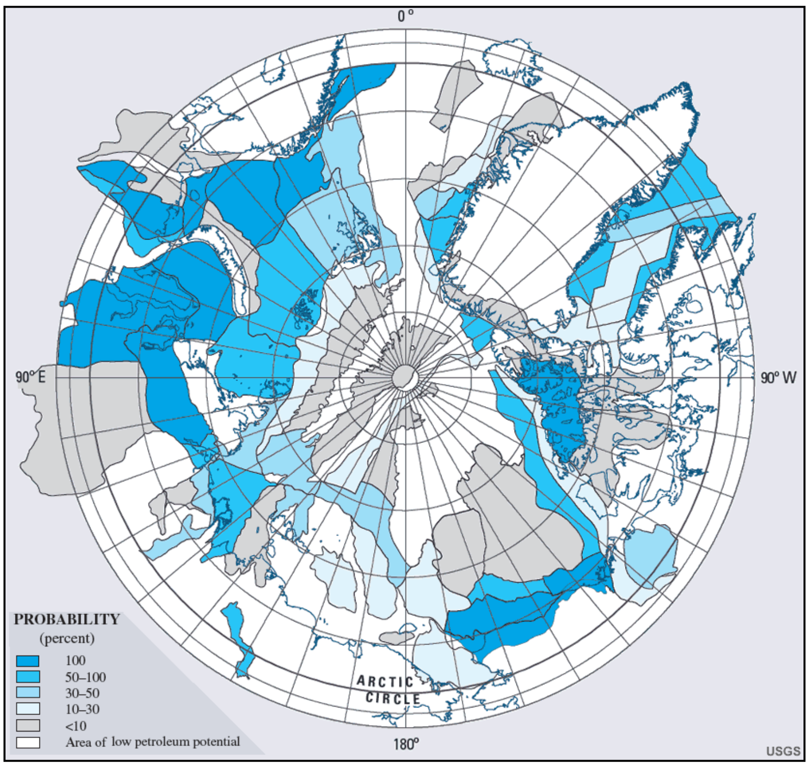

Figure 1. Probability map of globally undiscovered Arctic oil and gas (Gautier 2008)

Other scientific research takes a more applied approach and considers how the Arctic environment is influenced or how influences develop, often with a focus on the oil and gas industry. Throughout all this research, consideration of how both the Arctic environment and oil and gas industry are changing is necessary. Understanding the natural environment and its challenges in the Arctic is crucial to preventing, mitigating, and responding to oil spills.

Because the number of oil spills is limited in the Arctic, a global analysis of historical oil spill incidents may provide insight to the probability of such events occurring (Nuka Research and Planning Group and LLC & Pearson Consulting, LLC 2010). The international nature of the issue requires consideration of research and data from other nations with similar regional and regulatory environments to the US Arctic

OCS. This report considers international sources that can lend insight to the US on modeling sea ice, estimating oil spill occurrence rates, and structural design.

3.2 Arctic Climate

The following sections describe conditions that are inherent to the Arctic climate. These conditions will influence the causal factors of GOM and PAC spills described in Section 2 and will make spills in the Arctic either more or less likely compared to those in the GOM or PAC.

3.2.1 Arctic Weather

Adverse weather conditions in the Arctic have the potential to cause oil spills on platforms, pipelines, or other offshore vessels. Arctic weather in this report refers to Arctic-specific weather patterns or events that are not common elsewhere on the OCS. While traditional hurricanes do not form in the Arctic, similar storms called “arctic hurricanes” or “polar lows” do occur (Smirnova et al. 2015). These storms are characterized by blizzard conditions and low-pressure systems. Research on polar lows is expanding as interest in the Arctic grows. A study of the Nordic and Barents seas identified a total of 637 polar lows in 14 extended winter seasons (Smirnova et al. 2015). In November 2011, western Alaska experienced a polar low with winds reaching 93 mph, comparable to a Category 1 hurricane, and storm surge equal to that of a Category 3 hurricane (NSIDC 2011). Some early research suggested the frequency of polar lows would decline with warming seas (Zahn and von Storch 2010), but recent literature is less conclusive on the effects of a changing climate (Smirnova et al. 2015). More targeted research may help identify trends, such as projections of storm frequency in specific areas of the Arctic (Romero and Emanuel 2017). The impact of polar lows may be substantial on platforms or other offshore oil vessels and structures. The threats of polar lows include snow, sea spray, and icing, which could impact the stability and operations of offshore structures (Orimolade et al. 2017). Polar lows may cause instability and lead to failure directly, but they may also lead to unsafe or dangerous working conditions vulnerable to human error.

Weather factors that may cause oil spills include the rate of Arctic sea ice retreat and increase in wave height. As of 2016, wave heights in Arctic OCS region have reached 4.9 m during significant storms. By 2050, studies indicate that the entire Arctic Ocean may be ice-free, thus the highest observed waves in the OCS region are likely to increase over time (Waseda et al. 2017). Weather conditions in the Arctic may become more influential on OCS operations in the future as the expected increase in significant wave height evolves into a greater threat with the reduced sea ice. Without appropriate construction and design considerations of these maximum wave heights, platforms may be damaged by the waves.

Beyond severe storms, the adverse weather conditions in the Arctic also include considerations of seasonality, air pressure, humidity, wind patterns, precipitation, and cloud cover. The high latitude of the Arctic causes the sun to be low, particularly in the winter, creating a very short operational timeframe during the day without the use of artificial lighting or other established support systems (Det Norske Veritas 2012). In the summer, the sun may remain up all day at varying levels in the sky. The extensive sunlight may pose additional challenges to employees as the surrounding ice creates reflected glare (Det Norske Veritas 2012). The Beaufort Sea high pressure system governs the winds and may help inform when and where strong winds are likely to occur and impact offshore operations (Barrett 2011).

While the daily weather patterns in the Arctic present a harsh operating environment, the high latitude and remoteness of the Arctic region present additional challenges to maritime infrastructure and development. The limited availability of port infrastructure and support directly influences the level of risk associated with transiting a particular waterway or conducting off-shore drilling activities (Arctic Council 2009). The high latitude of the Arctic poses a communication disruption hazard due to limited shore-based infrastructure and satellite coverage; the electronic systems are more susceptible to interference from "space weather events" such as solar flares (Clement et al. 2013). This interference may decrease the ability of operators in the Arctic to coordinate safe vessel movements, contact search and rescue authorities, and access weather and ice forecasts. In addition to communication systems disruptions, global positioning system (GPS), DPS, and other navigational systems may experience electromagnetic interference at the higher latitude (Canadian Coast Guard 2013).

3.2.2 Low Temperatures

The Arctic environment is typically categorized by its high winds and low temperatures. These low temperatures create threats and challenges in oil and gas development and activities in the Arctic. The low temperatures may increase the risk of operational error through fault of labor and machinery. Manual tasks are impaired due to cold-related discomfort, reduced mental alertness, and joint and muscle pain (Det Norske Veritas 2012). The risk of increased human error probabilities (HEPs) is positively correlated with cold and harsh working environments. The primary factor affected by the low temperatures is reduced cognitive performance, which could negate any additional training provided for staff in the Arctic (Balindres et al. 2016).

In addition to impacts on employees and manual operations, low temperatures may influence the technological and mechanical features of platforms. Structural design must account for the low temperatures at various stages of the offshore drilling process, but platforms and rigs are most likely to be impacted because they are exposed to a wider variety of elements (Wood Group Kenny 2016). Arctic temperatures can influence the chemical and mechanical properties of steel and concrete used on offshore platforms (Yan et al. 2016). If not carefully considered, these effects can cause safety critical failures. One design option that presents additional challenges is creating enclosed or sheltered areas to protect certain processes of offshore activities from the harsh climate. Enclosures and weather protection safeguards may prevent some technical failures due to cold, but they also increase potential risks of explosions or other complications from vapor collection areas or lack of ventilation. Low temperatures cause a need for additional heating and mechanical ventilation. These systems can be safety critical for certain functions, and this must be considered when setting requirements and guidance (Det Norske Veritas 2012). Non-metallic materials have been developed, tested, and approved for low temperatures, but metals cannot always be replaced by synthetic materials. If the metals cannot be replaced with non-metallic materials, the brittle fracture and fatigue life of metallic materials must be considered in Arctic conditions (Wood Group Kenny 2016).

3.3 Ice Forces

As the Arctic climate continues to change, the presence of sea ice will be more unpredictable. The trends in sea ice indicate lesser amounts, if any, of multi-year ice across the entire Arctic OCS region (Coastal Frontiers Corporation and Vaudrey & Associates Inc. 2017). Newer, weaker sea ice is more susceptible to cleavage and drifting, but it may be less forceful in collisions with offshore platforms (Juricke et al. 2013). Given the transition from old to new sea ice, impacts with structures may be more frequent but the severity of ice force impacts is likely to be less. As seen in **Figure 2**, the proportion of sea ice coverage with a high concentration of ice is low compared to the historical median ice edge in the Beaufort and Chukchi sea region, as sea ice coverage in 2017 had shrunk to 4.64 square kilometers. Within the decline in overall Arctic sea ice concentration, the National Aeronautics and Space Administration (NASA) identified the fastest sea ice retreat occurred in the Beaufort Sea region based on satellite imagery (NASA 2017).

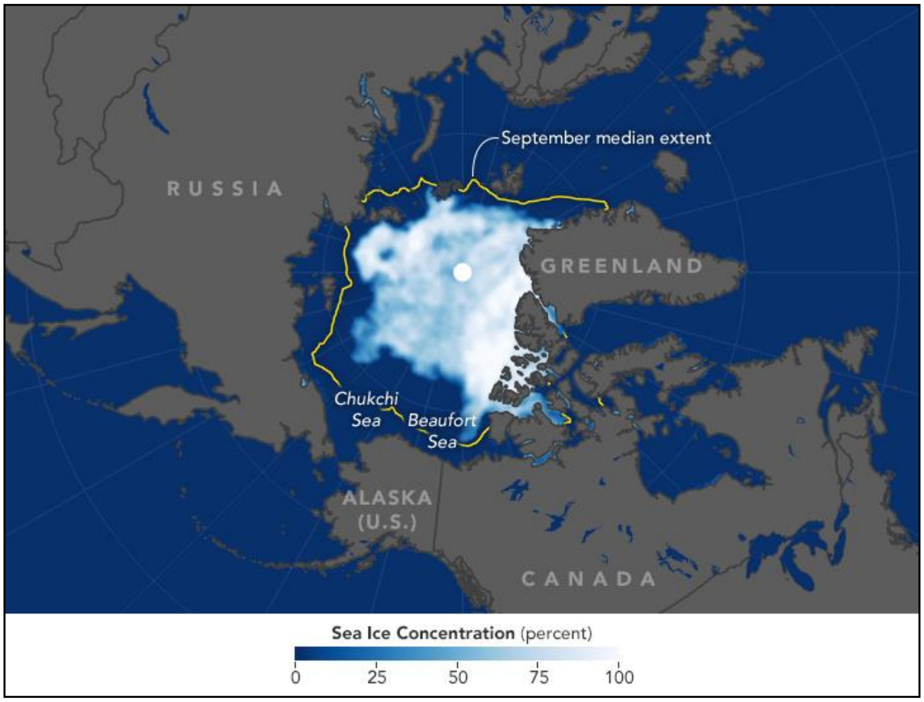

Figure 2. Map of Chukchi and Beaufort Sea ice concentration in September 2017 (NASA 2017)

The relationship between Arctic ice and offshore activities is reciprocal. Several studies show that the design of Arctic structures may influence the ability to withstand or succumb to ice forces. One study examined the pitch motion of fixed and compliant cones and found that the compliant cone reduced the ice forces of drifting level ice (Dalane 2014). Though pitch motion is primarily a concern for container ships at sea, the science and technology discovered through research may be applicable across offshore structures (Reguram et al. 2016). This type of research can help understand the causes of past structural failures from ice forces and provide information for future design to prevent structural failures that may lead to oil spills.

The interactions of level ice with platforms and vessels are distinct and must be considered appropriately. Interactions between ships and level ice have a history of research that is apparent in the modern development of icebreakers (Zhou et al. 2018), but the impact of ice on other structures is not as heavily researched. Engineering research for Arctic structures is considering ice loads and forces to provide information for future design strategies and test existing ones, such as platforms with inclined sides. One study ran simulations of slanted structural designs against a variety of ice features to identify peak ice loads that structures can withstand (Ranta et al. 2018). Designing fixed offshore structures with an incline is a strategy to withstand ice loads, but the force from the ice can vary with the age and thickness of the ice (Juricke et al. 2013). Design strategies such as these may be powerful mitigation tools against oil spills from ice force damage to platforms. Though sea ice is likely to pose challenges to Arctic offshore operations, the likelihood of ice forces causing oil spills will likely be easily mitigated with appropriate planning and response plans.

3.4 Ice Gouging

When sea ice with sufficient keel depth moves through the ocean, the ice may penetrate the sea bottom in areas where the seabed is uneven. The penetration of the seabed from ice features is generally referred to as ice gouging or ice scouring (Barrette 2011). This can damage pipelines that are installed on the seabed. The onset of ice gouging or scouring within the Beaufort Sea region have produced gouges varying from 2 m to 3.5 m in depth (McGonigal and Barrette 2017). Pipelines exporting fluids from offshore platforms are most susceptible to ice gouging, as they often cover long distances to bring oil and gas to shore (Barrette 2011). Historic stress-based design of pipelines is unlikely to be sufficient for the internal pressures experienced by pipelines in the Arctic. Stress-based designs focus on limiting stress, a measure of external forces acting over an area of the pipeline, to below the pipeline material's minimum yield stress in all three dimensions. Instead, strain-based principles are considered for Arctic pipelines, as a supplement to stress-based design because they consider the pipeline strain, a measure of a material deformation when a force is exerted upon it, and account for a certain amount of permanent deformation up to the material's strain limits (Paulin and Caines 2016). Plans for the Liberty pipeline in the North Slope included 100-year and 1,000-year gouge depth predictions to hedge the threats of ice gouging (Hilcorp Alaska, LLC 2015). In the Arctic, where high strain occurs more often than in the GOM from pipeline deformation due to ground movement, unsupported spanning, and seismic loading, a certain amount of permanent strain must be accounted for in the pipeline's design (Gao et al. 2010).

A strategy for mitigating the threats of ice gouging is burying pipelines beneath the seabed. This strategy reduces the likelihood of ice features directly impacting the pipelines and causing an oil spill, but it does not remove the causal factor entirely. In **Figure 3**, the ice keel created a gouge in the seabed above the pipeline and displaced soil. Gouges may be as deep as five meters and many kilometers long, but the impacts of some ice keels have been documented at depths of fifteen meters (Arndt et al. 2014). Burying pipelines under the seabed is a legitimate option but may be costly. While buried pipelines may reduce the likelihood of ice gouging damage, they are unlikely to eliminate the risks associated with ice gouging.

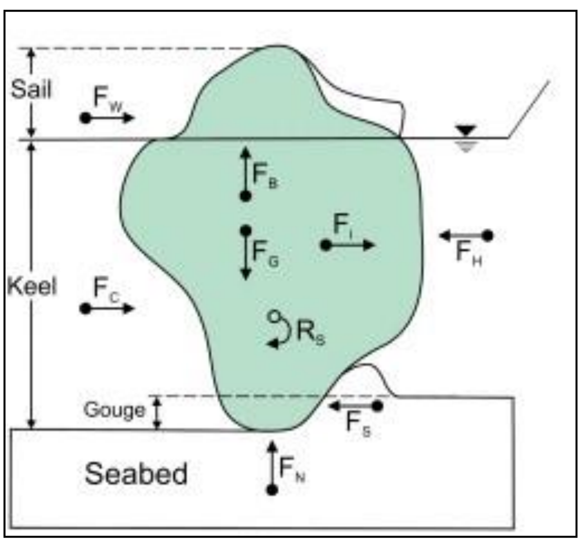

Figure 3. Ice gouging poses risks to pipelines through direct contact or soil displacement as the seabed is changed (Barrette 2011)

Without appropriate design standards or burial depths for pipelines, ice gouging may be a strong causal factor of oil spills in the Arctic. Other mitigation options have been the subject of research efforts, but standards and requirements do not yet reflect the need for additional, specific pipeline protections (Barrette 2011). Sea ice movement cannot easily be controlled or well predicted at this time, as Arctic ice features or floes can weigh between an estimated 85,000 and 292,000 tons (Bruneau et al. 1977). Towing and other efforts to move sea ice are realistic mitigation strategies for ice gouging, but the practice of ice towing is not yet widespread in the US Arctic OCS. This is an active research topic, however, indicating that offshore operations are likely to pursue ice towing as an offshore development strategy in the Arctic (Yulmetov and Loset 2017). Ice towing can also be applied as a mitigation strategy for platform or vessel collisions that may cause oil spills.

3.5 Strudel Scouring

Strudels are vertical holes in sea ice through which above-ice flood water drains, often in jet-like or whirlpool forms. In the case of relatively shallow sea beds, this downward stream or whirlpool can cause depressions in the seabed below, a phenomenon called scouring (USACE 1998). Strudel scouring most commonly occurs in the spring when river floodwater drains through landfast sea ice (Hilcorp Alaska, LLC 2015).

Strudel scouring poses a threat to submarine pipelines as seabed erosion from water movement removes support from the pipeline (Barrette 2011). Loss of sediment can undermine a pipeline's stability and lead to pipeline oscillation, lateral buckling, or general overstress causing heightened vulnerability to other impacts. As ice becomes newer, the vulnerability to strudel scouring increases as ice layers are thinner and more susceptible to cracking under the pressure of flowing water. Deep strudel scouring may even expose the pipelines entirely, leaving them vulnerable to natural or operational forces, though this is unlikely in the Arctic (Hilcorp Alaska, LLC 2015). As shown in **Figure 4**, the proportion of new and young sea ice is historically high for winter.

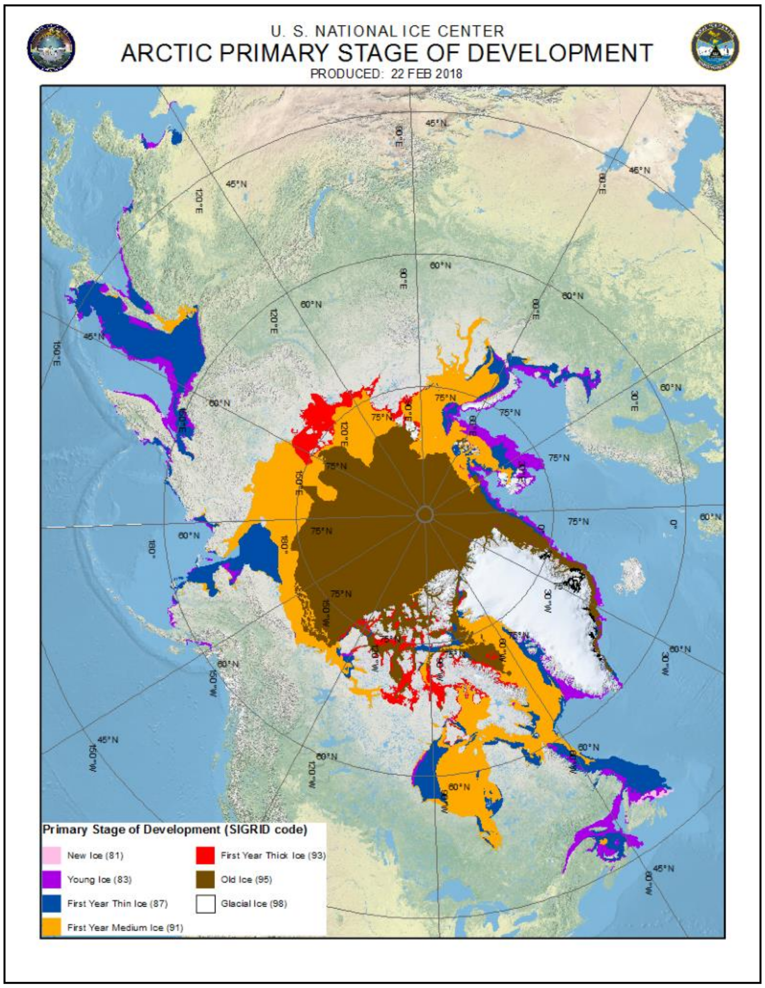

Figure 4. Sea ice extent and distribution according to the stage of development of the ice (NSIDC 2018)

As research on pipeline structure and dynamics continues, scouring will be considered more heavily or as a more critical issue when designing and installing offshore pipelines. Extensive research has been conducted on scouring in existing offshore areas, like the GOM, but the translation to the Arctic environment and strudel scouring is not exact. Scouring may be caused by a variety of sources in the GOM or PAC, including sediment movement from extreme waves during hurricanes (Teague et al. 2006). In one study that considers the scour depth beneath pipelines experiencing vibration, equilibrium is calculated based on the sandy seafloor in the GOM without consideration of ice or low temperatures (Luan et al. 2015) as would be necessary to understand the dynamics of scouring in the Arctic OCS. Planning for the Liberty project pipeline identified strudel scouring as a considerable risk and thus included extensive research on the likelihood in the nearby bays and deltas (Hilcorp Alaska, LLC 2015). Further studies are necessary across all parts of the US Arctic OCS to understand the Arctic environment's equilibrium and necessary design requirements of pipelines to avoid oil spills (Carpenter 2017).

3.6 Upheaval Buckling

When pipelines are laid and buried in the OCS, they are subject to forces from the ocean around them, the seabed beneath and above them, and the fluids within them. Maintaining a balance across all variables requires precision and caution, and when that balance is lost, pipelines may be subject to upheaval buckling. While these forces and their impacts on pipelines are not uniquely present in the Arctic, they are of greater consideration in the Arctic than other regions due to the variability in seabed, exposed temperatures, and construction materials. Pipelines often operate at high temperatures and pressures to encourage high flow rates, and the resulting axial expansion can cause substantial axial compressive loads in the pipe wall (Maltby 1993). Upheaval buckling is the upward bending of a pipeline away from the seabed to accommodate the pressure from the fluids inside the pipeline. **Figure 5** illustrates three possible scenarios of upheaval buckling that may occur depending on the location of bend and the shape of the seabed (Karampour et al. 2013). Lateral buckling, or the outward bending of a pipeline, is another possible result of increased pressure within pipelines, but upheaval buckling is more likely to trigger failure in pipelines and thus oil spills (Karampour et al. 2013).

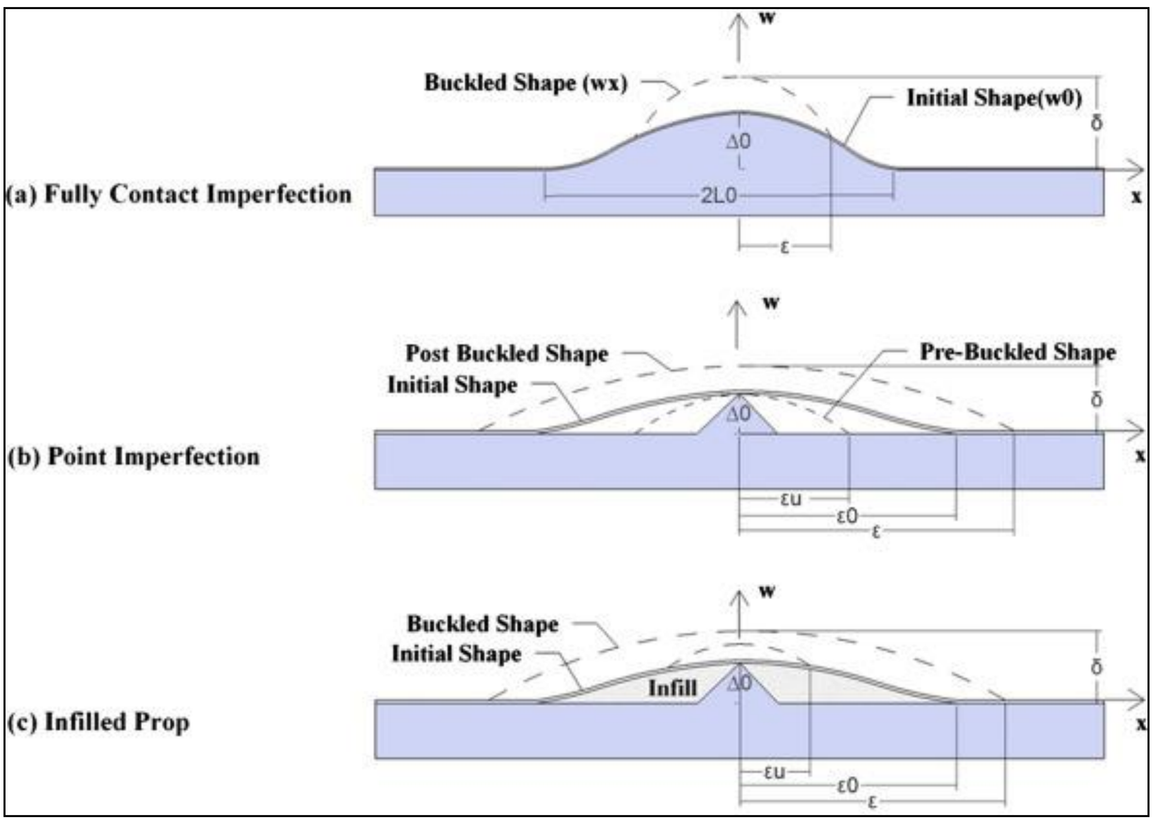

Figure 5. Three possible upheaval buckling situations: fully contact imperfection, point imperfection, and infilled prop (Karampour et al. 2013)

Upheaval buckling can occur in pipelines that are laid straight or with initial imperfections. These imperfections may be the result of laying the pipeline over an irregular portion of the seabed and may increase the risk of buckling (Adebanjo and Simms 2016). Irregularities in the seabed can be caused by landslides, lateral spreading, or seismic settlement (O'Rourke and Liu 2012). The oil and gas industry in Japan is incorporating seismic activity into pipeline design guidelines after extensive upheaval buckling during a major 2007 earthquake (Shinkai et al. 2012). While active faults and historic seismic activity are generally present in the Beaufort Sea region, particularly concentrated near Camden Bay, seismic activity in the Arctic in general is extensively lower in comparison to other regions associated with oil and gas operations (MMS & NOAA 2007).

3.7 Thaw Settlement

Thaw settlement occurs most often when permafrost or other frozen formations melt because of the heat generated by pipelines. The melted permafrost removes support from the pipeline and leaves the pipeline subject to collapse or other damage (Pullman et al. 2007). This factor is primarily a threat to terrestrial ice features, but damage to any part of a pipeline could cause complications and thus oil spills elsewhere.

The thawing of permafrost from warming seas and air may also introduce changes to the ocean and arctic environments through methane releases. The impacts of permafrost thawing differ for ancient ice and new ice because the methane molecules' carbon may be different isotypes (Sparrow et al. 2018). In a study of the continental shelf offshore the US Beaufort Sea, ancient carbon could be found in permafrost, terrestrial peat, and permafrost soils. The methane tested in the atmosphere in the study area showed a statistically significant presence of both ancient and modern sources of carbon. Though the presence of ancient methane does not inherently pose a threat to offshore oil and gas development activities, it does solidify thaw settlement as a legitimate causal factor to consider in site planning for future Arctic activities (Sparrow et al. 2018). Consideration of permafrost ought to be included in the design, construction, and operations of pipelines in the Arctic (Oswell 2011). Proper routing of pipelines and thorough seabed stability assessments may greatly reduce the likelihood of thaw settlement acting as a causal factor for oil spills.

Permafrost thawing can also occur on the sea floor, underneath layers of historic ice and water. Releases of methane on the sea bed may cause uplifts in the sea floor or chasms where frozen gases were previously stored. The heat from the methane can further exacerbate the thawing and contribute to additional pressures on pipelines and platforms on the Arctic OCS. On the Yamal Peninsula, the permafrost extends to the ocean floor, meaning the risks of thaw settlement are not unique to land or coastal pipelines and structures (Sojtaric 2014). Furthermore, there is also the presence of offshore permafrost in the Beaufort Sea region, as recent research surveys have concluded that most of the subsea permafrost lies close to the shoreline and in water less than 20 m deep (Ruppel et al. 2017). In contrast, the presence of offshore permafrost in the Chukchi Sea region is not heavily studied, as it is predicted to be relatively low, particularly due to the rate of shoreline retreat in the affected coast line region (Harper 1978).

4 Comparing the Gulf of Mexico, Pacific, and Arctic Outer Continental Shelf Regions

4.1 Regional Comparison

Though the causal factors of oil spills of 50 bbls or more in the GOM and PAC OCS are discussed together and categorized by their general source, distinctions between the GOM and PAC environments should be considered for detailed analysis. Environmental factors such as those identified in **Table 3** may influence the potential likelihood and consequence of the previously discussed causal factors of oil spills. The temperature range of the Arctic is narrower than the ranges of the GOM and PAC, and the practical salinity scale (PSS) measurements at the surface of Arctic waters are also lower than in the GOM or PAC.

The differences across the regions are less dramatic in deeper water. The similarity of the GOM and PAC OCS regions supports the grouped comparisons between the causal factors of oil spills to the Arctic.

Table 3. Comparison of ecological and climate attributes in the OCS[1]

Attribute	GOM	PAC	Arctic
Annual Water Temperature Range at Surface (degrees Celsius)	25 – 30	15 – 25	-2 – 2
Annual Water Temperature Range at 3,000 meters (degrees Celsius)	4 – 5	0 – 1	-1 – 0
Sea Bed / Bottom	Soft sediments	Sandy, some soft sediments	Sand and gravel sediments
Salinity Range at Surface (PSS)	34 – 37	33 – 35	27 – 33
Salinity Range at 3,000 meters (PSS)	35	34	34-35

[1] (National Center for Environmental Information 2017).

4.2 Causal Factors Comparison

This section discusses the influence of Arctic conditions on GOM and PAC OCS causal factors of oil spills of 50 bbls or more. The relationship between Arctic conditions and events to the GOM and PAC causal factors is discussed through the influence of the Arctic conditions on the likelihood of the GOM and PAC causal factors.

4.2.1 Weather and Natural Hazards

Natural hazards are generally less likely to act as a causal factor of oil spills in the Arctic as in other OCS regions due to a lower likelihood of occurrence. Severe storms such as polar lows are moderately less likely to be a causal factor in the Arctic due to their predicted low frequency compared to hurricanes in the GOM OCS (Smirnova et al. 2015). Other natural hazards, like mudslides, are not likely in the Arctic OCS due to the flat seabed. The low seabed gradients through much of the Chukchi Sea OCS and on the Beaufort Sea shelf reduce the risk of mudslides, though it is possible that OCS activities could extend beyond the shelf break to steeper areas (Horowitz 2002). The adverse weather, however, is more likely to act as a causal factor of oil spills in the Arctic due to the harsh conditions compared to the GOM and PAC. The low temperatures of the Arctic climate and the cold and windy weather creates an unstable and potentially dangerous working environment that may lead to human error (Balindres et al. 2016).

4.2.2 Corrosion

The Arctic's cold-water environment presents new microorganisms and stresses that may present distinct corrosion risks absent from GOM and PAC environments (Duncan et al. 2017). However, the low temperatures of the Arctic are likely to slow down biological and chemical processes that cause corrosion in offshore environments including the GOM and PAC OCS. Recent technological advances are also expected to reduce spill rates in the Arctic compared to historical GOM data. "Smart" pigs, which use magnetic and acoustic imaging to detect internal surface pitting and corrosion, are expected to reduce spill rates from pipelines. Higher pipeline inspection frequencies are also expected to be mandated in the Arctic due to harsher conditions (IMO 2015). Together, technological advances and increased inspection frequency are expected to moderately decrease corrosion's role as a causal factor of oil spills in the Arctic.

4.2.3 Third-party Impacts and Collisions

Third-party impacts from fishing trawls and nets are less likely to cause oil spills in the Arctic OCS due to the closure of all Federal waters to commercial fishing in accordance with the Fishery Management Plan for Fish Resources of the Arctic Management Area (Arctic FMP) enacted in 2009 (MacLean 2018).

Collisions of vessels with platforms or pipelines are moderately less likely to cause an oil spill in the Arctic due to lower traffic. As ship technology improves and Arctic maritime transportation routes open, however, collisions may become a more influential causal factor as the volume of vessels increases. To account for the variety of changes in the Arctic, a full assessment of the factors is necessary (Nevalainen et al. 2017). However, tankers are uncommon in the US Arctic OCS, removing an additional threat of collision. The lack of permanent infrastructure means more vessels or other moving structures will be part of the operations, leading to a greater likelihood of collision without proper precautions (Khan et al. 2018).

4.2.4 Operational Impacts

As technology continues to advance, icebreakers and other Arctic vessels are likely to become more common in the Arctic OCS. Due to the lack of existing infrastructure, vessels must be sent out to perform activities that would be accomplished by more permanent structures in the GOM or PAC OCS. Shell's oil rig sent out to explore the Chukchi Sea in 2015 was accompanied by a 25-vessel fleet to hold supplies, prepare for oil spill response, and observe marine mammals (Garnick and Bernton 2015). While explorations in the Arctic OCS consist of more vessels than those in the GOM, Arctic exploratory activity levels are likely to remain below those of the GOM in the future. In addition, the increased burial depth of Arctic pipelines to avoid ice gouging and strudel scouring will also help minimize operational impacts to pipelines due to rig and work boat anchoring. The high proportion of vessels to other offshore structures in the Arctic, offset by lower activity and deeper pipeline burial depths, are expected to make operational pipeline impacts slightly less likely to cause oil spills in the Arctic as in the GOM.

Within the Arctic, the likelihood of operational pipeline impacts is less in Beaufort Sea than in the Chukchi Sea. The Beaufort Sea has docking facilities already installed, while the Chukchi Sea does not. Refueling and resupplying in the Beaufort Sea will likely take place in the Prudhoe Bay area, while all refueling, and resupplying of the Chukchi may occur at sea. The increased boat traffic involved with at-sea refueling and resupplying is estimated to make spills from operational impacts to unburied pipelines moderately more likely in the Chukchi Sea than the Beaufort Sea (MMS & NOAA 2007).

4.2.5 Equipment and Mechanical Failure

Equipment and mechanical failures aboard platforms are highly more likely to be causal factors of oil spills in the US Arctic OCS. The low temperatures, sea ice presence, and thaw settlement may all cause equipment or mechanical failures. In particular, low temperatures may substantially influence the operability of key features of offshore operations including metals, gaskets, seals, and lubricants (Wood Group Kenny 2016). An event similar to the 2009 Transocean *Discoverer Spirit* pollution event in the GOM described in Section 2**Error! Reference source not found.**, which was attributed to a leak in the k ill line, is highly more likely to occur in the Arctic due to ice formation and expansion inside exposed kill lines (MMS 2010). Other platform equipment failures that are more likely under Arctic conditions include the telescopic joint packer, where the control hoses and lubricating fluid are vulnerable to freezing.

4.2.6 Scouring and Gouging

Though scouring and gouging are not considered as independent causal factors in this report for the GOM and PAC OCS, they may have an influence on the likelihood of oil spills of 50 bbls or more in the Arctic OCS. In addition to causing damage directly, scours and gouges may be the source of other causal factors identified, such as operational impacts or equipment failure, by relocating or reducing the structural integrity of pipelines and platforms. In the GOM and PAC OCS, pipelines may be displaced due to seabed changes from hurricanes (Teague et al. 2006). However, seabed gouging in the GOM from a hurricane would be considered a side effect of the hurricane damage as discussed in Section 2. Scouring and gouging are likely to be more influential in the Arctic as ice features move and seismic activity cause changes to the seabed (Horowitz 2002). Scours or other changes to the seabed may increase the likelihood of upheaval buckling in pipelines in the Arctic as well (Adebanjo and Simms 2016).

4.2.7 Human Error

The influence of human error on frequency of oil spills in the Arctic is likely to be considerably higher than in the GOM or PAC OCS. A spill similar to that in 2001 aboard ENSCO 29, which is described in Section 2, is more likely to occur in the Arctic. This spill was attributed to human error when an employee inadvertently opened the overboard drain line to the mud pit reserve storage tank (MMS 2001). Low Arctic temperatures require bulkier clothing, can reduce cognitive performance, and are likely to physically strain employees and increase HEPs (Balindres et al. 2016), considerably increasing the likelihood of a spill caused by human error. Though the quantification of this influence may be difficult, the impact of the Arctic environment is a definitive factor in how offshore operations must be conducted compared to other regions with more temperate climates (Solberg et al. 2017). The International Maritime Organization (IMO) attempted to address the additional risks humans face when working or living in Arctic conditions, as evidenced by the Polar Code requiring particular training, testing, and protective measures for operations in polar waters (IMO 2015).

4.3 Other Factors to Consider

In addition to the causal factors identified for the US Arctic, GOM, and PAC OCS regions, more abstract factors may influence the likelihood and impacts of oil spills.

4.3.1 Data Availability

In addition to the causal factors discussed, the impact of the timescale of the data should also be mentioned as, over time, the Arctic itself has changed and continues to change. Positive temperature anomalies were seen everywhere across the central Arctic for the first decade in the 21st century (2001-2011) relative to a 1971-2000 baseline period at the end of the 20th Century (Overland et al. 2011). As these changes in the Arctic environment occur, human behaviors related to the Arctic also change. The IMO Polar Code serves as one such example of how regulatory requirements have changed over time as the Arctic and its various hazards are better understood. Within the Polar Code, there is a requirement for a Polar Water Operations Manual (PWOM). This Manual is designed to provide the owner, operator, and crew with information on a ship's capabilities in polar conditions (IMO 2015). However, this manual will only be as informative as the data supporting it. As polar conditions and the data behind it continue to change, a ship's PWOM will undoubtedly need to change as well. Ultimately, as the Arctic environment changes over time, related regulations and standards will also change.

4.3.2 Combined and Compounding Factors

The combination of causal factors as they influence the frequency of oil spills of 50 bbls or more should be considered for a thorough analysis of the Arctic operating environment (Landucci et al. 2017). Though the causal factors identified in this report may be discussed individually as influential to oil spills, the permutations of these factors require a different consideration. For example, the ice gouging events in the Arctic OCS may contribute to operational or third-party impacts as the seabed changes. An event such as this may be classified differently depending on the available data. Ice gouging may indeed act directly as a causal factor for oil spills, but its influence is more expansive on offshore operations in the Arctic.

5 Conclusion

As demand for petroleum continues to grow, pressure to pursue and expand oil and gas activity in the Arctic OCS will increase. Understanding the possibilities and causal factors of oil spills is necessary to prevent, mitigate, and respond to offshore incidents. The Arctic OCS poses unique challenges that have yet to be faced on a large scale by the oil and gas industry, and proper precautions must be taken.

Low temperatures and weather patterns are the Arctic conditions most likely to influence the existing causal factors of oil spills present in the GOM and PAC OCS. Low temperatures and Arctic weather are likely to increase incidents of human error, equipment failure, and mechanical failure. These factors are known to be the causes of small and medium oil spills in the GOM and PAC, so an increased likelihood of these events may lead to a greater number or size of oil spills in the Arctic.

The most likely unique causal factors of oil spills in the Arctic OCS are inherent to the Arctic climate, including ice gouging, strudel scouring, and thaw settlement. These three factors are most likely to impact pipelines rather than platforms. Arctic pipelines are more susceptible than pipelines in other regions of the OCS due to local environmental factors, including the presence of ice and permafrost. Though scouring and gouging may occur in the GOM and PAC due to hurricanes, the rates and impacts are unlikely to impact pipelines in a serious enough way to cause oil spills. The likelihood of ice gouging, however, is relatively high, particularly as sea ice continues to move and the distribution of ice features change. **Table 4** outlines the causal factors with their estimated probabilities in the Arctic, GOM, and PAC OCS regions.

Table 4. Estimated probabilities of oil-spill causal factors in the OCS

Oil Spill (≥50) Causal Factors	Outer Continental Shelf Region		
	Arctic	GOM	PAC
Hurricanes	Almost Certainly Not	Almost Certain	Almost Certainly Not
Equipment Failure	Almost Certain	Probable	Probable
Human Error	Almost Certain	Chances About Even	Chances About Even
Collisions	Probable	Chances About Even	Chances About Even
Weather and Natural Hazards	Probable	Chances About Even	Chances About Even
Ice Forces	Probable	Impossible	Almost Certainly Not

Oil Spill (≥50) Causal Factors	Outer Continental Shelf Region		
	Arctic	GOM	PAC
Third-party Impacts	Probably Not	Probable	Chances About Even
Corrosion	Probably Not	Probable	Chances About Even
Operational Impacts	Probable	Chances About Even	Chances About Even
Mechanical Failure	Chances About Even	Chances About Even	Chances About Even
Ice Gouging	Probable	Impossible	Impossible
Strudel Scouring	Probable	Impossible	Impossible
Upheaval Buckling	Chances About Even	Probably Not	Probably Not
Thaw Settlement	Probable	Impossible	Impossible

Though oil spill causal factors may be identified and analyzed for the Arctic OCS, granular understanding of causal factors will benefit future fault tree analyses of oil spills. Differences in the natural environment, operating conditions, structural design, and regulatory environment must be considered when comparing oil spills in the GOM and PAC to the Arctic OCS.

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