OCS Study
BOEM 2022-013

# Oil-Spill Occurrence Estimators: Storm and Vessel Traffic Adjustment Factor Analyses


**U.S. Department of the Interior**
**Bureau of Ocean Energy Management**
**Alaska OCS Region, Anchorage, AK**

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# Oil-Spill Occurrence Estimators: Storm and Vessel Traffic Adjustment Factor Analyses

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BOEM
Bureau of Ocean Energy Management

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Study concept, oversight, and funding were provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, DC, under Contract Number M17PC00015, Task Order 140M0121F0028. This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of BOEM, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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## CITATION

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## ABOUT THE COVER

Cover graphic of offshore platform under aurora borealis: V. Belov/Shutterstock.com.

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# List of Abbreviations and Acronyms

| | |
|---|---|
| AIS | Automatic Identification System |
| Arctic OCS | U.S. Beaufort Sea and Chukchi Sea |
| bbl | Barrel or barrels |
| BOEM | Bureau of Ocean Energy Management |
| BSEE | Bureau of Safety and Environmental Enforcement |
| CBHAR | Chukchi-Beaufort High-Resolution Atmospheric Reanalysis |
| CI | Confidence Interval |
| GOM | U.S. Gulf of Mexico |
| O&G | Oil & Gas |
| OCS | Outer Continental Shelf |
| OPD | Official Protraction Diagram |
| IBTrACS | International Best Track Archive for Climate Stewardship |
| MMS | Minerals Management Service |
| NEPA | National Environmental Policy Act of 1969 |
| NOAA | National Oceanic and Atmospheric Administration |
| NDBC | National Data Buoy Center |

# 1 Introduction

The purpose of this study is to estimate the Outer Continental Shelf (OCS) oil spill hazard level due to storms and maritime vessel traffic in the U.S. Beaufort and Chukchi Seas relative to the U.S. Gulf of Mexico (GOM). The U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM) contracted ABSG Consulting, Inc. in an Indefinite Delivery/Indefinite Quantity contract, Oil-Spill Occurrence Estimators for the Outer Continental Shelf in the Arctic (M17PC00015) in 2017. This work is performed under task order 140M0121F0028 of this contract.

The National Environmental Policy Act of 1969 (NEPA) (42 U.S.C. 4321–4347) requires that all federal agencies use a systematic, interdisciplinary approach that will ensure the integrated use of the natural and social sciences in any planning and decision-making that may influence the human environment. Typically, BOEM NEPA analyses use historical OCS oil spill occurrence rates to estimate potential oil spills in order to evaluate environmental impacts from proposed oil and gas lease sales. Historical rates are calculated as the number of historical oil spills per unit of historical exposure. Exposure may be measured in terms of volume of production, number of wells drilled, number of facilities in operation, or any other unit relevant to the types of oil spills being evaluated. These spill rates can also be split into component spill rates which quantify the proportion of oil spills related to factors that have historically contributed to oil spills, such as weather, human error, and third-party impacts to Oil & Gas (O&G) assets. We refer to these causal factors as either spill hazards or subfactors.

In the U.S. Beaufort Sea and Chukchi Sea Planning Areas, historical spill data are not available in sufficient quantity to conduct a robust statistical analysis. To support an alternative estimation of future spill rates, this study aims to quantify the degree to which spill hazards/subfactors vary between the GOM and the Arctic. As stated, it specifically focuses on storms and maritime vessel traffic hazards and their associated subfactors related to oil spills. This study develops adjustment factors based on the regional variation in these hazards between the GOM and Arctic regions. These adjustment factors could support future adaptation of historical GOM oil spill occurrence rates to the unique conditions in the Arctic.

## 1.1 Scope

This report examines the relative frequency of oil spill hazards between the GOM OCS and the Beaufort Sea and Chukchi Sea Planning Areas. We refer to the Beaufort Sea and Chukchi Sea Planning Areas as the “Arctic OCS” for the remainder of the report.

The analysis focuses on the relative hazard levels, not oil spill occurrence rates. However, to understand the importance of the hazards, we examined oil spills with subfactors associated with those hazards. Table 1 summarizes the scope of the oil spills, hazards, and geographies that we considered. Sections 1.1.1–1.1.3 further clarify and contextualize the study scope related to historical spill data, the study area, and spill hazards/subfactors.

**Table 1. Analysis scope boundaries**

| Scope Boundary | Included | Excluded |
|---|---|---|
| **Spill Volume** | ≥50 barrels (bbl) | <50 bbl |
| **Spill Substances** | Oil: crude, condensate, hydrocarbon fuels | Natural gas, lubricants, hydraulic fluid, drilling fluid (mud) |
| **Spill Source** | Platforms/rigs, pipelines | Shuttle tankers, unknown sources |
| **Spill Activities** | Offshore O&G exploration, development | Petroleum shipping (besides pipeline) |
| **Spill Occurrence Geography (Historical)** | GOM OCS | Pacific OCS, State Waters |
| **Study Geography** | Beaufort Sea and Chukchi Sea | State Waters |
| **Hazard/Subfactors** | Storms, Maritime Vessel Traffic | Arctic factors (snow, ice, low temperatures), O&G workboat incidents (if not storm-related) |

Besides the factors listed in Table 1, it is important to realize that O&G operations and infrastructure in the Arctic OCS may differ substantially from GOM operations and infrastructure. It is beyond the scope of this project to estimate the impact that storms and vessel traffic may have on installations or operational configurations and schedules adapted specifically to this region.

### 1.1.1 Historical Offshore Oil Spills (GOM OCS)

We collected oil spills from the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement's (BSEE) spill reports (BSEE 2012). We used GOM OCS historical spill data from 1973 to 2019 as the basic context of this analysis. The study team reviewed 189 historical oil spills (these oil spills are listed in Appendix A) to understand the underlying hazards associated with storms and maritime vessel traffic in the GOM OCS. We focused on the subset of oil spills that fell within the scope described in Table 1.

We reviewed oil spills greater than or equal to 50 bbl. Although oil spills less than 50 bbl occur more frequently, they generate less than 1% of the total volume of oil spilled (ABSG 2016, Table 42), individually have a lower environmental impact, and tend to be less well documented (Stalfort et al. 2021, p. 3). Focusing on the 50 bbl threshold is consistent with prior studies (ABSG 2016, Anderson et al. 2012, Bercha 2002).

Regular GOM OCS spill records begin as early as 1964. However, spill reporting became more detailed after the passage of the Federal Water Pollution Control Act Amendments of 1972. For this reason, we excluded spill data from before 1973 in our analysis. This period is consistent with prior spill analysis reports (Bercha 2002, Anderson et al. 2012, ABSG 2016). In some cases, we further focused on oil spills after 2002 since these records often included more context for the incident, especially for details related to hurricane oil spills[1].

We also categorically excluded historical oil spills associated with operations that now use environmentally friendly alternative fluids. For example, the O&G industry has replaced oil-based drilling fluid and lubricating oils with environmentally friendly alternatives. Natural gas releases into the atmosphere are not included but releases containing natural gas that formed condensates are included. O&G industry hydrocarbon fuels include diesel, gasoline, fuel oil, jet fuel, and kerosene. Hydrocarbon fuel spills are included. Crude oil spills are included and are the primary focus.

The dataset incorporates details about the facility such as location and type. We included platforms, pipelines and drilling rig facilities. Oil spills from tankers are excluded from this project scope in accordance with the statement of work provided by BOEM.

### 1.1.2 Arctic OCS Planning Areas

The U.S. Beaufort and Chukchi Seas are the northernmost planning areas within the Alaska OCS as shown in Figure 1. The planning areas are largely unleased today, but BOEM has issued leases historically (see Appendix A). BOEM estimates that 45% of U.S. OCS undiscovered technically recoverable resources are in the Alaska OCS (BOEM 2021a). The Chukchi Sea and Beaufort Sea Planning Areas account for 82% of the undiscovered technically recoverable resources in the Alaska region. Potential focus areas for future O&G development may include the shallow areas of the OCS along the coast of the Beaufort Sea Planning Area and in the central to southern portion of the Chukchi Sea Planning Area. BOEM has permitted geophysical surveys (an early step in the O&G exploration and development process) in these areas (BOEM 2021b).

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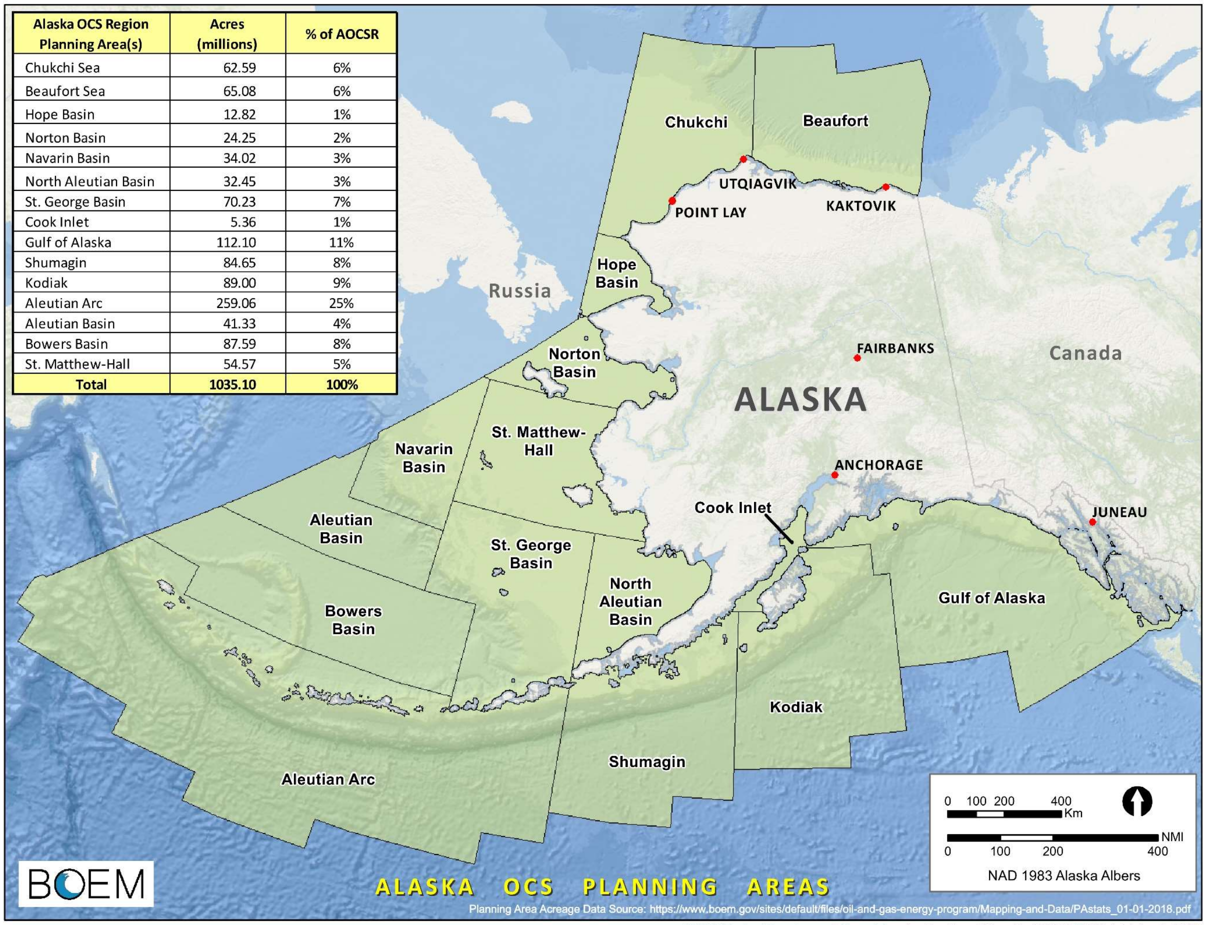
[1] In 2002, MMS identified petroleum losses from tanks on platforms and rigs destroyed by Hurricane Lili and counted those as oil spills even though no evidence of a release was observed, and no response was required. Hurricane Ivan (2004) was the first hurricane for which unrecovered petroleum amounts on destroyed, heavily damaged, and/or missing structures (platforms, rigs, and pipelines) were inventoried and reported as oil spills in a comprehensive manner. This collection of 'unseen' and relatively 'passive' oil spills was performed for Hurricanes Katrina, Rita, Gustav, Ike and all hurricanes since that time.



BOEM Alaska | Leasing and Plans | Leasing Section | Map ID: AKR2020078v1 | May 4, 2020

**Figure 1. Map of Alaska OCS Planning Areas**

Source: BOEM 2020

When performing geospatial analysis, this research used the "BOEM 2019-2024 Draft Proposed Program Area – Alaska Region" shapefiles provided by BOEM to delimit the 199,628 square miles of the Beaufort and Chukchi Seas (BOEM 2021c). When evaluating statistics for comparison from the GOM, this research used the shapefiles provided by BOEM which describe the 148,479 square miles of the Western GOM and Central GOM Planning Areas (BOEM 2013).

### 1.1.3 Spill Hazards

This report focuses on storm and vessel traffic hazard levels associated with the GOM and Arctic OCS. Although there are many other spill hazards, including spill hazards that are specific to the Arctic region, this project only considers the relative intensity of storm and vessel traffic hazards between the GOM and the Arctic OCS.

# 2 Literature Review

We performed literature review to identify estimates used in prior analyses to quantitatively compare the Arctic hazard levels to hazard levels in other areas. This review provided a basis for comparing and evaluating our study results. In addition, we performed literature review to understand the presence, geographic distribution and intensity of specific hazards and their related subfactors in the Arctic. The results of this more detailed review are found within the discussion of our analysis of each individual subfactor.

This research builds off of prior assessments of Arctic spill hazards for oil and gas leasing and one development and production plan. In 2008, The Bercha Group reported oil spill occurrence estimators for the U.S. Chukchi and Beaufort Seas (Bercha 2008a, 2008b). These reports assimilate historical OCS spill data and account for several causal factors, including anchor impacts, trawl/fishing net snags, landslides, and storms. Bercha incorporates these causal factors by assessing the difference between the Arctic OCS and the GOM and Pacific OCS for each causal factor. These results are presented in Table 2. They presented a reduction range assessed for different water depths or shelf locations. Bercha determined these values from their assessment that low vessel traffic density, limited fishing activity, low seafloor gradient, and fewer storms would occur in the Arctic OCS where oil and gas leasing or development and production was proposed to occur. This assessment does not provide further justification of the quantities selected. Similar oil spill occurrence rates have been estimated since 2008 and each has used similar adjustment factors (Lakhani et al.  2018, Bercha 2016). Bercha (2016) covers a specific development and production location with site specific information, which may explain the differences in assessed reduction.

**Table 2. Historical Spill Hazard Adjustment Factor Assumptions**

| Causal Factor | Adjustment Factor (Bercha 2008a, 2008b) | Adjustment Factor (Bercha 2016) | Adjustment Factor (ABSG 2018) |
|---|---|---|---|
| **Anchor Impacts** | 0.5 | 0.50 | 0.5 |
| **Trawl/Fishing Net Snags** | 0.5 to 0.7 | 0.40 | 0.5 to 0.7 |
| **Landslides** | 0.4 to 0.6 | 0.80 | 0.4 to 0.6 |
| **Severe Storms** | 0.7 to 0.8 | 0.85 | 0.7 to 0.8 |

There are several causal factors for spills present in the Arctic OCS that are not observed in the GOM OCS. These are typically associated with the unique conditions present in the Arctic. These conditions include: intense and limited sunlight; extreme low temperatures and large temperature fluctuations; thaw settlement; sea ice effects such as ice gouging, strudel scouring and upheaval buckling; and polar mesocyclones and the more intense storms called polar lows (Lakhani 2018). There may also be unique corrosion risks in the Arctic environment as well (Myers 2018).

Of the above factors, only polar mesocyclones and polar lows fall within the scope of this report. Polar lows are the more severe type of storm, occurring as short-lived Arctic low pressure weather systems similar to a hurricane. They are typically smaller than GOM hurricanes but can feature high winds reaching category 1 hurricane wind speeds (Safir 1973). However, polar lows are relatively uncommon in the U.S. Beaufort and Chukchi Seas as seen in Figure 2. One occurrence of a polar low in the Chukchi Sea was noted by the research vessel Mirai in October of 2009 (Inoue 2010).

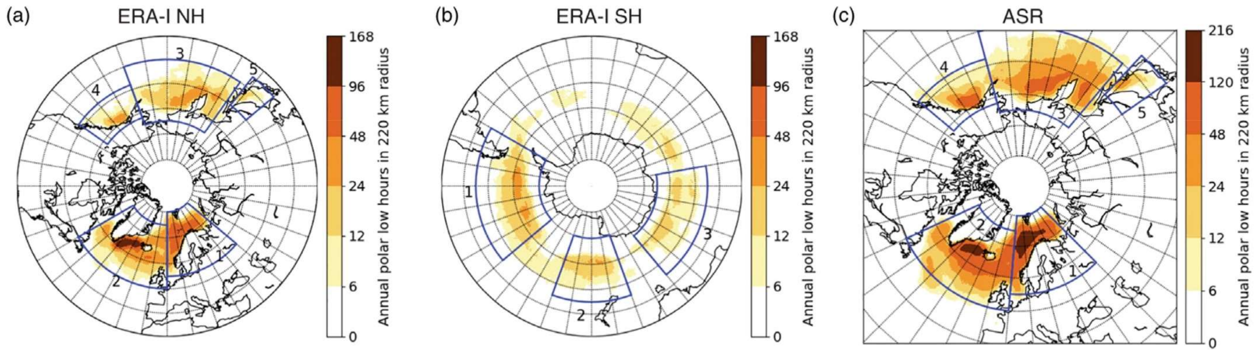



**Figure 2. Map of Polar Low Storm Distributions**
Source: Stoll et al. 2018

# 3 Methodology

As stated in the introduction, this report examines the relative intensity of oil spill hazards for storms and vessels between the Arctic and GOM OCS regions. We define this "relative" metric as the ratio of the Arctic OCS hazard intensity to the GOM OCS hazard intensity. This ratio could then be used as an adjustment factor for scaling the expected frequency of spills to reflect Arctic, rather than GOM, conditions. We calculate hazard intensities differently, depending on the available data for the particular hazard type. The methodology below describes the broad steps used across each of the hazards and subfactors. Specific details for individual hazards/subfactors — such as the exact datasets used — are described in Sections 4 and 5.

The first step in quantifying the hazard intensities was reviewing historical oil spills in the GOM OCS related to storms and vessel traffic. This review aimed to understand the physical mechanisms involved with these hazards to establish a basis for consistent quantitative comparison. For example, spills resulting from storms could involve high winds, large waves, or heavy precipitation. While the definition of storm may vary substantially by region or dataset, the frequency of wind speeds above a set threshold (one potential indicator of storms) provides a consistent definition for comparison across geographic regions. The initial review also included a literature review to understand the types of storms and vessel traffic that exist in the Arctic OCS and how they may vary from the GOM OCS.

Next, we gathered a variety of datasets to support individual comparative analysis of each subfactor. Ideal datasets included many years of reliable data to inform seasonality effects and distinguish potential sub-geographies within the OCS assessment areas. Some storm and vessel hazard subfactors were found to have substantial seasonal and geographic variations in the Arctic OCS because of environmental factors such as sea ice coverage. These data were then conditioned to provide an equivalent basis for comparison between the GOM and Arctic OCS regions before they were used to calculate relative hazard intensity values for each of the specific subfactors.

We combined these subfactor results into blended adjustment factors representing the difference in vessel traffic and storms, generally, in the Arctic OCS versus the GOM OCS. This blending process used the proportion of historical spill events due to each subfactor as weights for averaging the subfactor adjustment factors. The equation below describes this calculation.

$$\begin{aligned}&Blended\ Adjustment\ Factor\\ &= \frac{\sum_{subfactors}\left(Adjustment\ Factor_{Subfactor} \cdot Count\ of Relevant\ Spill\ Events_{Subfactor}\right)}{\sum_{subfactors}\left(Count\ of Relevant\ Spill\ Events_{Subfactor}\right)}\end{aligned}$$

Finally, we created 95% confidence intervals[2] (CI) for each of the relative intensity measures. The analysis team used bootstrapped[3] distributions using 20,000 simulations to develop confidence intervals without requiring assumptions about the statistical distribution of computed values.

# 4 Storm Analysis

Calculation of the relative intensity of storms in the Arctic OCS relative to the GOM OCS began with an assessment of subfactors associated with the storm hazard type. We performed a line-by-line review of weather-related oil spills reported to the BSEE. We found that although BSEE spill occurrence data do not specifically categorize spills as storm-related, the weather-related flags within those data usually indicate the presence of a storm. Table 3 summarizes the distribution by subfactor of the 109 storm-related spills from 1973 to 2019 that fell within the scope of this research shown previously in Table 1.

**Table 3. Distribution of Storm-Related Spills ≥ 50 bbl in the GOM OCS by Subfactor**

| Storm-Related Subfactor | Spill Events | Percent of Total |
|---|---|---|
| Hurricane | 94 | 86.2% |
| Rough Seas | 8 | 7.4% |
| Submarine Landslide | 6 | 5.5% |
| High Wind (non-hurricane) | 1 | 0.9% |
| **Total** | **109** | **100%** |

[2] A CI is a range of values that contains the true population value with a given degree of certainty. For example, a 95% CI indicates that the true value will fall within the CI's range for 95% of the theoretical resamples.

[3] Bootstrapping, as used in this analysis, is a process of resampling observations from a dataset with replacement to create a large number of hypothetical datasets from which the statistic of interest can be calculated to develop a confidence interval. We can also construct and test hypothesis intervals using bootstrapping techniques.

Table 4 below provides examples of typical oil spill descriptions associated with the 107 weather-related spills:

**Table 4. Examples of Storm-Related Spill Incident Descriptions**

| Storm-Related Subfactor | Example Spill Description |
|---|---|
| **Hurricane**[4] | Platform fully submerged after Hurricane Ike. 150.17 bbl crude oil, 2.14 bbl diesel, 42.86 bbl aviation fuel, 6.55 bbl engine oil, etc. |
| **Rough Seas** | Rough seas while taking on fuel from the M/V "Imco Pat", the diesel transfer hose broke about 20' feet from the boat and landed in the water. |
| **Submarine Landslide** | A submerged oil pipeline was pulled apart by a mud slide approximately 500' from "A" platform. Bad weather with high winds and rough seas preceded the mud slide. |

These findings draw attention to the importance of high winds (as used in BSEE incident descriptions) as a major subfactor associated with storm spills. Hurricanes are defined according to the Saffir-Simpson Scale as tropical cyclones achieving sustained surface wind speeds greater than or equal to 64 knots. The Saffir-Simpson scale uses 34 knots as the minimum wind speed of a tropical storm (Saffir 1973). Since storms in the study area were not observed to achieve hurricane wind speeds, this study defines high winds relevant to the Arctic as winds greater than or equal to 34 knots and less than 64 knots. A thorough review of the hurricane spills within this assessment scope did not reveal other sub-factors besides high wind (such as heavy precipitation). We combine the analysis of hurricane and high winds in section 4.1.

Besides high winds, we noted storm-related spills associated with rough seas. While rough seas are correlated with high winds and hurricanes, this correlation is impacted by sea ice coverage in the Arctic throughout the year. For this reason, this analysis treats the rough seas subfactor separately from high winds in section 4.2.

Finally, submarine landslides can be triggered by a variety of external forces. The submarine landslide spills that have been observed in the GOM have been documented as related to rough seas that accompany hurricanes. Section 4.3 describes our analysis of submarine landslides in more detail.

Section 4.4 combines the analysis results from these sections into an overall adjustment factor for storm hazards in the Arctic OCS relative to the GOM OCS.

## 4.1 High Wind

This section describes the steps taken to gather and analyze historical wind intensity, one of the subfactors for comparing storms between the GOM OCS and Arctic OCS. It is assumed that oil spills related to

[4] Note that hurricane oil spills are not always observed. See footnote 1 above.

hurricanes and high wind come from the wind itself, such as damages caused by overblown or displaced process equipment.

### 4.1.1 Data Sources

We used two data sources to quantify the intensity of high winds in the GOM OCS and Arctic OCS, respectively. Wind data for the GOM OCS was derived from the historical hurricane tracking data found on the National Oceanic and Atmospheric Administration (NOAA) sponsored National Centers for Environmental Information's International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp 2010). The IBTrACS information is provided as a series of latitude and longitude points representing the position of the hurricane at 3-hour intervals. Wind speed is captured by the IBTrACS data as the radial extent of both 34 knot and 64 knot winds for each time point. Using the IBTrACS dataset to understand high-wind events in the GOM implicitly assumes that high wind events are always associated with tropical storms, or 34 to 64-knot winds. While this may not always be the case, we accepted this as a conservative, simplifying assumption (i.e., the results will, if anything, overstate relative Arctic wind hazard).

Wind data for the Arctic OCS was derived from the Chukchi-Beaufort High-Resolution Atmospheric Reanalysis (CBHAR), an adaptation of the Weather Forecasting and Research model (Zhang et al. 2013). The output from the CBHAR was accessible from the Alaska Ocean Observing System as hourly modelled estimates of sustained (average over 10 minutes) surface wind speeds. Zhang et al. (2013) describes this project further. This resource is particularly appropriate as it was created with oil spill modeling in mind.

CBHAR has advantages in that it assimilates the inconsistent surface wind data that is available for the study region. Using modeling, CBHAR combines observations from onshore sites and offshore buoy data. Such a modeling approach to data does have the potential to underestimate extreme low or high values. However, Zhang et al. (2013) suggests that the modelled results are highly accurate, with fewer than 2% of data quality checks against observed validation data exceeding acceptable thresholds. We used historical information from two meteorological buoys from the U.S. Chukchi Sea to independently confirm the modeled data. Stations 48214 and 48216 each offered sporadic data every 3 to 6 minutes that spanned July to October in 2012, 2013, 2014, and/or 2015. This time period coincides to the open water season. In all of this observed data, no wind speeds were recorded over 31 knots.

Table 5 summarizes some of the strengths and weaknesses of the two data sources.

**Table 5. Hurricane and High Wind Data Sources**

| Data Source | Region | Strengths | Weaknesses |
|---|---|---|---|
| **IBTrACS** | GOM OCS | • Captures precise geographical extent of high winds | • Does not include high, non-hurricane wind events |
| **CBHAR** | Arctic OCS | • High temporal resolution time series<br>• Includes high winds from all causes | • Wind speeds are modeled rather than measured directly<br>• Is difficult to extract and process at high geospatial resolution |

### 4.1.2 Calculations and Assumptions: IBTrACS

The first step in conditioning the IBTrACS data for use in this study was to convert the radial extent of the 5 hurricane observations in Table 6 into a geospatial area. Each observation was converted into a geographic information system polygon representing a circular shape using the coordinates of the observation as the center and the maximum diameter implied by the radial extents as the diameter. We applied this calculation to both the 34- and the 64-knot wind extents at each hurricane location observed every three hours. As an example, the Figure 3 shows high wind extents for hurricane Katrina.

**Table 6. Hurricane Oil Spills**

| Hurricane Name | Spill Counts |
|---|---|
| Lili | 3 |
| Ivan | 10 |
| Katrina | 21 |
| Rita | 19 |
| Ike | 22 |
| **Total** | **75** |

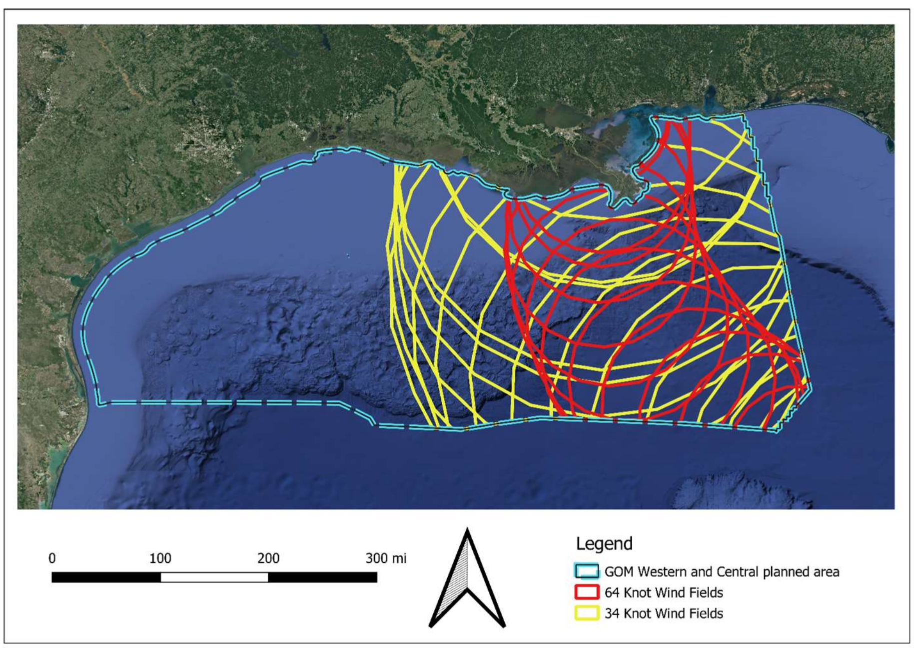



**Figure 3. Example GOM OCS Hurricane Wind Extents: Katrina**

The next step in the data conditioning was to translate the derived polygons of hurricane wind areas into the percentage of the Western and Central GOM Planning Areas and time affected by high winds on average throughout the year. This calculation tallies up the area affected by high wind speeds at each 3-hour interval and compares this affected area to the area of the entire region multiplied by the number of

3-hour intervals included in the historical period. The equation below describes the Affected Area Tally calculation:

$$Affected\ Area\ Tally\ in\ square\ miles = \sum_{Observed\ 3\ hour\ periods} Affected\ Area\ \ in\ square\ miles$$

We used the last 19 years of IBTrACS data from the GOM, from January 2002 until December 2020. This corresponds to 6,940 days of historical data and 55,520 3-hour periods for each polygon. This analysis was constrained to Western GOM and Central GOM Planning Areas, as defined by BOEM, since the Eastern GOM Planning Area has been excluded from O&G development (BOEM 2013). Table 7 presents these results:

**Table 7. High Wind Intensity Distribution: GOM OCS**

| Wind Speed Observation | Number of 3-hour Periods Observed | Average Affected Area per Period[1] (square miles) | Affected Area Tally (square miles) | % of Total Affected Area Tally |
|---|---|---|---|---|
| **Total (≥ 0 knots)** | **55,520** | **148,479** | **8,243,554,080** | **100.00%** |
| ≥ 0 to < 34 knots | 55,520 | 148,154 | 8,225,500,262 | 99.79% |
| **≥ 34 knots[2]** | **753** | **23,976** | **18,053,818** | **0.21%** |
| ≥ 34 to < 64 knots | 753 | 22,497 | 16,940,484 | 0.19% |
| ≥ 64 knots | 134 | 7,229 | 1,113,334 | 0.01% |

[1] The average affected area is found by dividing the affected area tally by the number of periods.

[2]≥ 34 knots indicates the high wind category

### 4.1.3 Calculations and Assumptions: CBHAR

The CBHAR dataset was also conditioned and analyzed to create a comparable dataset to the IBTrACS data. We extracted the sustained 10-m CBHAR wind data at the centroids of each of the 55 largest Official Protraction Diagram (OPD) areas in the Arctic OCS. The smallest OPD areas were evaluated along with their nearest adjacent OPD area. Rather than identifying the areas impacted by specific storms, this approach assumed that the whole OPD area experienced high winds any time high winds were identified at the centroid of the OPD area. As before, this enabled the analysis to tally the percentage of Arctic OCS area affected by high winds on average, at any time throughout the year. As an example, Figure 4 shows an instance of 3 of the 55 OPDs experiencing high winds.

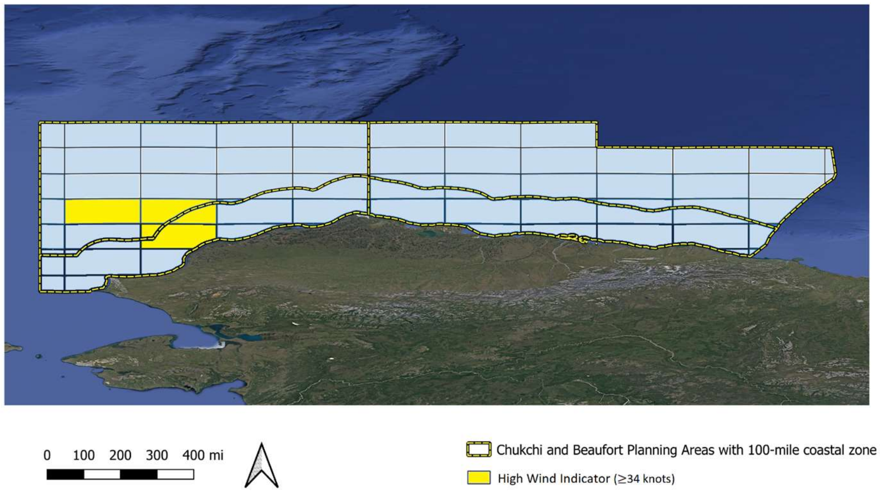



**Figure 4. Example Arctic OCS High Wind Event**

We used the last 31 years of data from the CBHAR dataset, from January 1979 to December 2009. This corresponds to 11,323 days of historical data and 271,752 1-hour periods. This analysis included the 657,661 square miles within the Arctic OCS, as defined by BOEM (BOEM 2021c). Table below presents these results.

**Table 8 High Wind Intensity Distribution: Arctic OCS**

| Wind Speed Observation | Number of 1-hour Periods Observed | Average Affected Area per Period (square miles) | Affected Area Tally[1] (square miles) | % of Total Affected Area Tally |
|---|---|---|---|---|
| **Total (≥ 0 knots)** | **271,752** | **657,661** | **178,720,700,000** | **100.00%** |
| ≥ 0 to < 34 knots | 271,752 | 656,849 | 178,500,020,400 | 99.88% |
| ≥ 34 knots[2] | 7,961 | 27,720 | 220,679,600 | 0.12% |
| ≥ 34 to < 64 knots | 7,961 | 27,720 | 220,679,600 | 0.12% |
| ≥ 64 knots[3] | 0 | NA | NA | NA |

[1] The affected area tally is found by multiplying the number of periods by the average affected area. These values are large because each square mile in the relevant area is added up for every 1-hour period observed.

[2]≥ 34 knots indicates the high wind category

[3]54 knots was the highest wind speed calculated in the Arctic OCS in the CBHAR dataset

### 4.1.4 Subregions

The Arctic OCS experiences persistently stronger winds along the coast than further out at sea (Zhang et al. 2013). This is also observable in the CBHAR data as seen in Figure 5, which shows the percentage of the full data period that the OPD areas experience high winds as defined as sustained surface (10-m) winds greater than or equal to 34 knots.

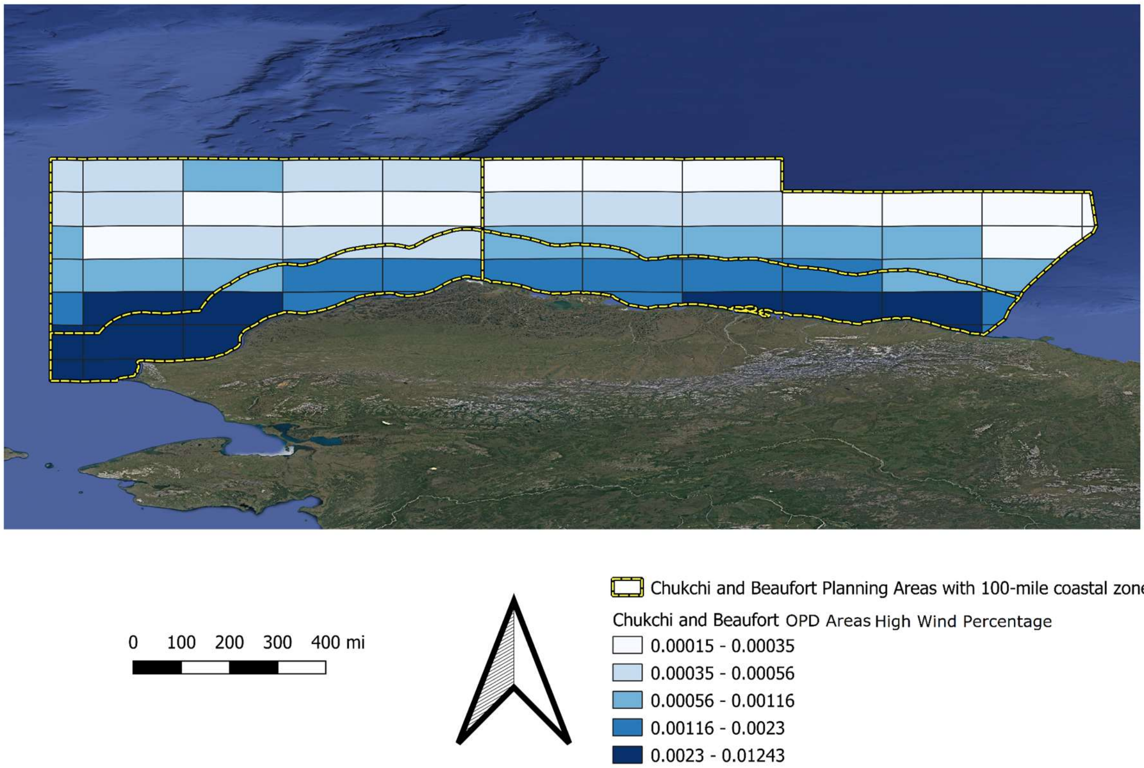



**Figure 5. Coastal High Winds in Arctic OCS**

To account for this, we created a 100-mile[5] buffer around the southern boundary of the Arctic OCS. The analysis then segmented the 55 selected OPD areas so that the wind speeds observed in each OPD area could be spatially apportioned to the subregions formed by the 100-mile buffer. Table 9 presents the wind hazard intensity results, split into coastal and non-coastal subregions.

[5] statue, not nautical miles

**Table 9 High Wind Intensity Distribution by Subregion: Arctic OCS**

| Wind Speed Observation | Number of 3-hour Periods Observed | Average Affected Area per Period (square miles) | Affected Area Tally (square miles) | % of Total Affected Area Tally |
|---|---|---|---|---|
| **Coastal Total (≥ 0 knots)** | **271,752** | **206,362** | **56,079,000,000** | **100.00%** |
| ≥ 0 to < 34 knots | 271,752 | 205,819 | 55,931,000,000 | 99.74% |
| ≥ 34 knots | 7,655 | 19,290 | 147,668,719 | 0.26% |
| ≥ 34 to < 64 knots | 7,655 | 19,290 | 147,668,719 | 0.26% |
| ≥ 64 knots[3] | 0 | NA | NA | NA |
| **Non-Coastal Total (≥ 0 knots)** | **271,752** | **451,299** | **122,641,000,000** | **100.00%** |
| ≥ 0 to < 34 knots | 271,752 | 451,030 | 122,568,000,000 | 99.94% |
| ≥ 34 knots | 3,882 | 18,808 | 73,010,881 | 0.06% |
| ≥ 34 to < 64 knots | 3,882 | 18,808 | 73,010,881 | 0.06% |
| ≥ 64 knots[3] | 0 | NA | NA | NA |

Recall from Section 4.1.2 that the GOM OCS saw winds greater than or equal to 34 knots but less than 64 knots in 0.19% of the area over time. Given the considerable difference in the relative intensity of high winds in the coastal versus non-coastal areas, splitting the Arctic OCS into coastal and noncoastal subregions is appropriate. The statistical significance of this distinction is formally tested in Section 4.1.6.

### 4.1.5 Seasonality

High wind events are also seasonal in the Arctic OCS (Zhang et al. 2013). Pressure increases in the summer months make wind and storm systems less prevalent. We see this seasonal pattern emerge in our data as well. Figure 6 shows the average high wind (greater than 34 knots) percentages for the coastal and non-coastal regions by month in the Arctic OCS.

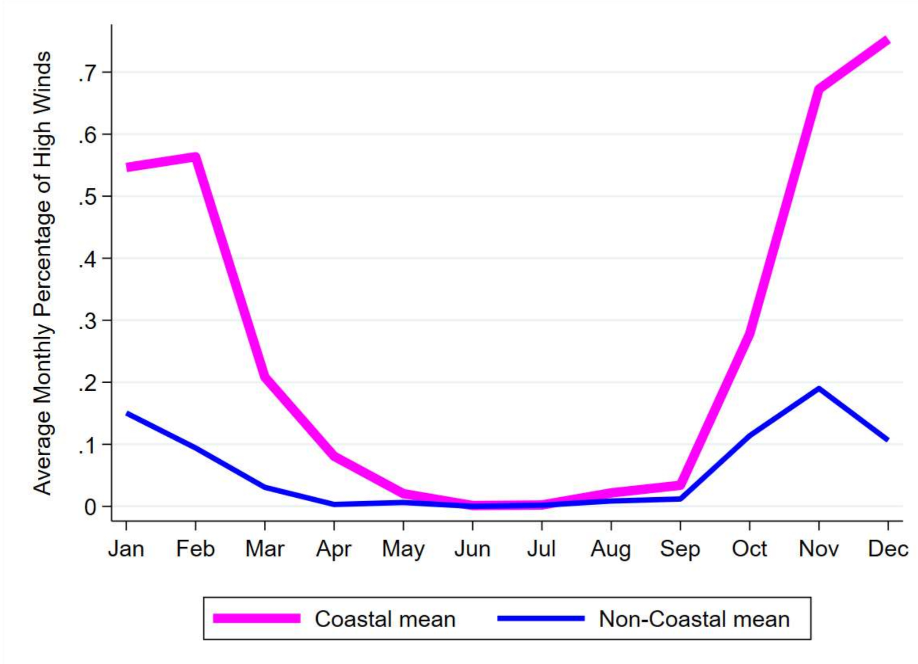



**Figure 6. High Wind Intensity Distribution by Month and Subregion: Arctic OCS**

The months from May to September rarely experience 34-knot winds or greater while from November to February the coastal areas experience four times the average annual high-wind intensity for the Arctic OCS.

### 4.1.6 High Wind Adjustment Factors

The preceding sections compute hazard intensities as the percent of the total affected area tally affected by the high wind subfactor of the storm hazard. Table 10 shows Arctic OCS hazard intensity metrics and the GOM intensity metric. The ratio of the Arctic to GOM metrics were used to calculate adjustment factors.

**Table 10. High Wind Adjustment Factors**

| Region | Hazard Intensity | Adjustment Factor | CI Low[1] | CI High[1] |
|---|---|---|---|---|
| GOM OCS | 0.19% | | | |
| Arctic OCS | 0.12% | 0.68 | 0.38 | 1.06 |
| Coastal Areas | 0.26% | 1.44 | 0.88 | 2.40 |
| Non-coastal areas | 0.06% | 0.33 | 0.18 | 0.57 |

[1] 95% confidence intervals generated by bootstrap resampling individual years from the historical GOM OCS and Arctic OCS wind data with replacement to create 20,000 simulated historical periods.

The confidence intervals suggest the non-coastal region has a statistically significant (p-value <0.001) difference in relative wind hazard intensity when compared to the GOM. The Arctic OCS coastal region does not have a statistically significant difference from the GOM OCS (p-value = 0.353) but does have a statistically significant difference from the non-coastal region (p-value = 0.001).

## 4.2 Rough Seas

This section describes the steps taken to gather and analyze the historical intensity of rough seas, one of the subfactors for comparing severe storms between the GOM and Arctic OCS. In BSEE spill incident records, most oil spills caused by rough seas involve an O&G vessel colliding with or separating from offshore facilities, leading to hydrocarbon fuel leaks or parted transfer hoses, respectively. Despite the involvement of maritime vessels, this research does not include these oil spills in the vessel traffic risk assessment because they are associated with O&G operations, rather than third party vessel traffic.

### 4.2.1 Data Sources

Rough seas can be measured by assessing wave height. NOAA's National Data Buoy Center (NDBC) measures seas using *significant wave height*. Significant wave height is the average wave height of the highest one-third of waves during a specified time interval.

This analysis uses significant wave height buoy data from the GOM OCS and Arctic OCS to estimate the relative intensity of rough seas between the two regions. For the GOM OCS, a 10-year data period for the NDBC buoy number 42001, from 2011 to 2020 was used. This data was selected for several reasons: it is one of the few buoys that is managed directly by the NDBC, it is located within the GOM OCS, and it has many years of recorded wave information.

The NDBC does not currently maintain a similar buoy in the Arctic OCS, presumably because of the area's remoteness and frequent sea ice coverage. Instead, this assessment used a small wave height dataset from two drifting-type wave buoys deployed off Utqiaġvik (formerly Barrow), Alaska and published by Waseda and Nose (2018)[6]. This dataset covers two months from September 10, 2016, to November 2, 2016, and provides insight into wave action in the central part of the Arctic OCS. Besides these wave observations, this analysis also leverages seasonal ice coverage data to identify the parts of the year when wave action would be suppressed by ice coverage.

### 4.2.2 Calculations and Assumptions

The buoy information from the Arctic OCS and GOM OCS had to be conditioned before they could be compared. The Arctic OCS records have wave heights every three hours while the GOM OCS records have wave heights every hour. Also, both datasets occasionally have missing observations. To overcome these issues, we summarize the wave information to a daily maximum significant wave height for both

[6] The NDBC has some historical data in the U.S. Arctic OCS, but it is less up-to-date and less consistent. The data from Waseda and Nose (2018) provided a better-documented and more conservative data source for comparison to the GOM.

the Arctic OCS and GOM OCS. The Arctic OCS dataset included two buoys associated with the research study, so each time interval has two observations. The two buoys were typically located close to each other, so the two values were averaged into a single observation for each 3-hour period.

The final conditioning step was to convert the daily significant wave height information into a daily "rough seas" indicator. We adopted the World Meteorological Organization's published guidelines for sea wave terminology and interpreted "rough seas" as being those whose significant wave height is at least 2.5 meters (Part II, Section 4.2.2.13.5) (WMO 2014).

The GOM OCS experienced "rough seas" in 9.8% of days (see Table 11). The Arctic OCS experienced "rough seas" in 31.5% of the days covered in the dataset, which represents the open-water period (see Table 12).

**Table 11. Rough Seas Intensity: GOM OCS**

| Significant Wave Height Observation | Number of Observations | % of Total |
|---|---|---|
| **Total (≥ 0 meters)** | 2,609 | 100% |
| ≥ 0 to < 2.5 meters | 2,353 | 90.2% |
| ≥ 2.5 meters | 256 | 9.8% |

**Table 12. Rough Seas Intensity: Arctic OCS[7]**

| Significant Wave Height Observation | Number of Observations | % of Total |
|---|---|---|
| **Total (≥ 0 meters)** | 54 | 100% |
| ≥ 0 to < 2.5 meters | 37 | 68.5% |
| ≥ 2.5 meters | 17 | 31.5% |

### 4.2.3 Seasonality

The spill hazard associated with rough seas is primarily associated with support vessel traffic in the GOM OCS. Because most vessels do not operate in the dense sea ice of Arctic winters, this "open water" hazard may not be relevant year-round. Appendix C describes the calculations used to estimate that the Arctic OCS has open waters for support vessels for 27.4% of the year as measured from January 2015 to December 2019.

[7] For comparison, the historical NDBC data across four years and two buoys shows a significant wave height greater than or equal to 2.5 meters in 7.3% of observations.

### 4.2.4 Rough Seas Adjustment Factors

The preceding sections computed the hazard intensities as a percent of observations affected by the rough seas subfactor of the storm hazard. Table 13 calculates the adjustment factor as the ratio of Arctic intensity metrics and the GOM intensity metrics.

**Table 13. Rough Seas Adjustment Factors**

| Region | Hazard Intensity | Adjustment Factor | CI low[1] | CI high[1] |
|---|---|---|---|---|
| **GOM OCS** | 9.8% | | | |
| **Arctic OCS** | 31.5% | 3.21 | 1.98 | 4.64 |
| **Arctic OCS (Sea Ice Adjusted)** | 8.6% | 0.88 | 0.54 | 1.27 |

[1] 95% confidence intervals generated by bootstrap resampling observations from the historical GOM OCS and Arctic OCS wave data with replacement to create 20,000 simulated historical periods.

These values imply that during the months in which Waseda and Nose (2018) recorded wave heights, they were about 3.2 times as likely as the GOM to have a significant wave height greater than 2.5 meters. However, sea ice adjusted values account for the fact that O&G vessels would be likely to operate only during the percentage of the year that has open water (i.e., 27.4%). By multiplying the base values by 27.4%, we can see that the number of days with rough seas in the Arctic OCS, during the few months when O&G vessels could operate, would be similar to the entire year of days with rough seas in the GOM OCS.

The unadjusted confidence interval suggests that the Arctic OCS has a statistically significant (p-value = 0.001) difference in relative rough seas hazard intensity when compared to the GOM OCS. The sea ice-adjusted value is less compelling (p-value = 0.51).

## 4.3 Submarine Landslides

This section examines submarine landslides, one of the subfactors associated with storms in the GOM. It provides a qualitative examination of the relative intensity of Arctic and GOM OCS submarine landslides in association with storms.

This analysis proved to be particularly challenging because not all submarine landslides are triggered by weather phenomena. The Minerals Management Service (MMS) created a database of known submarine landslides (Hance 2003). This database includes 534 landslides and provides information on the causal details when available. The top five triggering events are, in order: earthquakes, rapid sedimentation, gas hydrate disassociation, erosion processes, and salt diapirism. Figure 7 depicts each of the submarine landslides in this database. Ocean storm waves accounted for 5% of the landslides in the dataset.

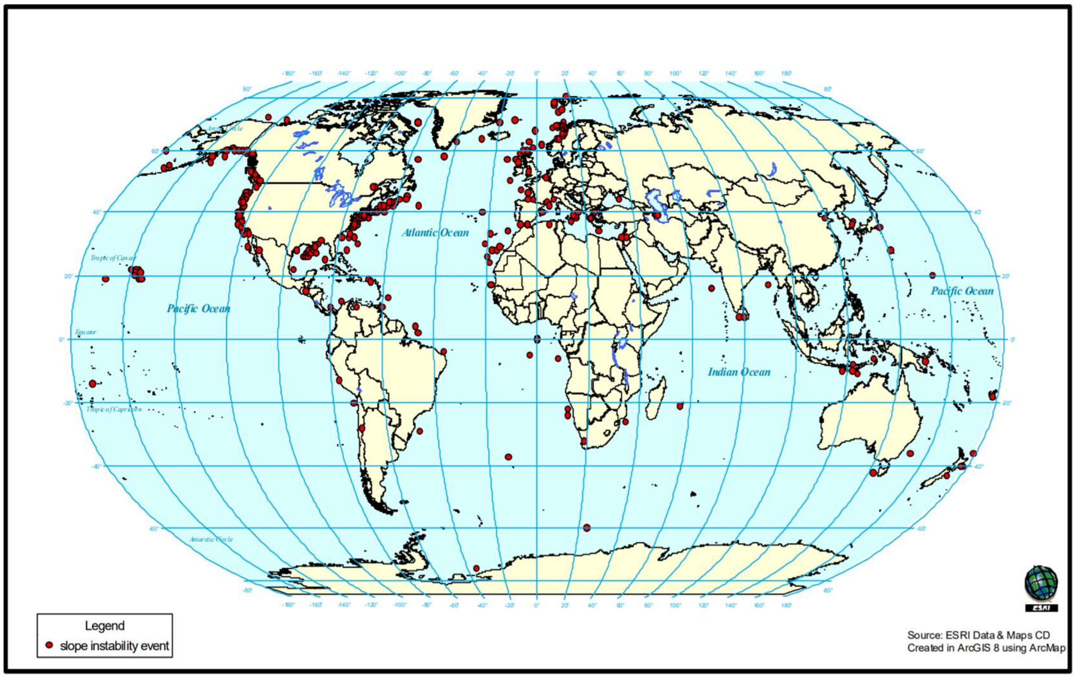



**Figure 7. Map of Submarine Landslides Worldwide (Hance 2003)**
Source: Hance 2003

### 4.3.1 GOM OCS Submarine Landslides

Submarine landslides have caused six oil spills greater that 50 bbl as recorded in the spill data in the GOM OCS. In each case, these landslide-caused oil spills were reported as coinciding with a storm. The Taylor Energy spill is one such example; a landslide triggered by hurricane Ivan toppled the Taylor Energy platform and damaged its wells, causing a long-running oil spill. However, submarine landslides in the GOM are not only caused by hurricanes. Fan et al. (2020) identified 85 previously unknown GOM submarine landslides and determined that 75 of them had been triggered by seismic activity. Furthermore, it was suggested that some of these landslides were triggered by seismic disruptions at the San Andreas fault, rather than by local activity. These findings suggest that understanding of submarine landslides and their hazards to O&G operations is still evolving.

### 4.3.2 Arctic OCS Submarine Landslides

The MMS study identified one submarine landslide in the Arctic OCS, triggered by natural gas disassociation. Research on submarine landslides in the Arctic OCS, particularly in the U.S. Beaufort Sea, indicates that they have occurred recently. Kayen and Lee (1993) provided an analysis of this region and confirmed that landslides occur at the region’s steeper slopes, which begin at depths around 200 meters and descend to 2,000 meters (Kayen and Lee 1993) and appear to have been triggered by gas hydrate disassociation. Kayen and Lee delineated a zone of instability in the Beaufort Sea Planning Area but did not research the Chukchi Sea Planning Area. We merged this zone of slope instability onto a recent bathymetric map shown in Figure 8.

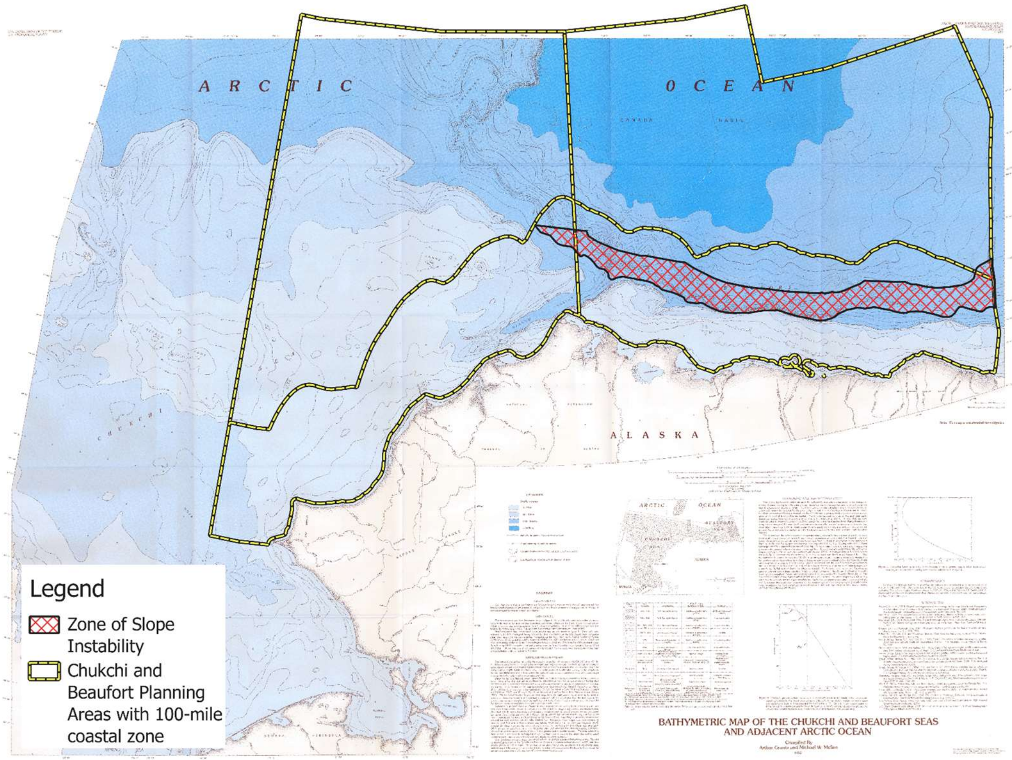



**Figure 8. Map of Beaufort Sea Submarine Landslide Zone of Instability**
Source: Grant and Mullen, 1992; Kayen and Lee, 1993

Gas hydrate disassociation is not the only trigger event in this area. Cameron and King (2019), on behalf of the Geological Survey of Canada, performed a thorough analysis of the Canadian side of the Beaufort Sea, which is outside of the Arctic OCS boundary. They concluded that earthquakes have caused landslides in the past. This is corroborated by other research (Paull et al. 2021).

None of the literature review for this report identified storms as a major cause of submarine landslides on the Arctic OCS. Also note that the relatively flat shelf terrain throughout much of the Arctic OCS may limit the potential for submarine landslides.

## 4.4 Storm Adjustment Factors

Sections 4.1 through 4.3 evaluated the separate effects of multiple storm subfactors: High winds, rough seas, and storm-triggered submarine landslides. Our research led us to identify two kinds of adjustments that could be made while developing oil spill occurrence rates for the Arctic OCS. First, there are a few types of storm related oil spills which may not be relevant to the Arctic OCS. Specifically, we found that storm-triggered submarine landslides and greater than Category 1 hurricane winds (≥64 knots) are unlikely to be substantial hazards in the Arctic OCS. Omitting GOM oil spills caused by landslides and hurricanes reduces the relevant historical spill count from 109 to 25.

Second, there are quantitative adjustments based on the relative hazard intensity based on the analysis of storm hazard data. Table 14 compiles the adjustment factors calculated in the subfactor analyses and includes an average Storm adjustment factor weighted by the number of relevant oil spills by subfactor.

**Table 14. Storm Adjustment Factors**

| Storm Subfactor | GOM OCS Spill Occurrences | Spills Relevant to the Arctic OCS | Adjustment Factor | Adjusted Spill Count |
|---|---|---|---|---|
| Hurricane & High Wind | 95 | 17[1] | 0.68 | 11.5 |
| Rough Seas | 8 | 8 | 0.88 | 7.0 |
| Submarine Landslide | 6 | 0 | NA | 0 |
| **Storm Total** | **109** | **25** | **0.74** | **18.5** |

[1] Appendix C includes calculations estimating that 83% of hurricane oil spills are caused by greater than category 1 hurricane winds (≥64 knots). Subtracting 83% of 94 hurricane oil spills leaves approximately 16 relevant oil spills. Adding back the 1 non-hurricane wind spill leads to 17 relevant hurricane and high wind oil spills.

Section 4.1.4 found that high winds were more pronounced in coastal areas. Using the same weighted average approach as above, Table 15 presents storm adjustment factors by subregion, along with confidence intervals.

**Table 15. Storm Adjustment Factors by Subregion**

| Subregion | Adjustment Factor | CI Low[1] | CI High[1] |
|---|---|---|---|
| **Storm Total** | **0.74** | 0.46 | 0.79 |
| Coastal | 1.26 | 0.78 | 1.45 |
| Non-coastal | 0.51 | 0.32 | 0.55 |

[1] The 95% CIs are estimated by assuming the underlying subfactor confidence intervals follow a triangular distribution and sampling 20,000 times to calculate the rolled-up storm adjustment factor.

***It is critically important to realize that these adjustment factors apply only to the categories of storm oil spills which we have identified above as relevant to the Arctic OCS. Section 6 describes the interpretation of these findings when comparing the Arctic and GOM OCS at large, and when comparing them to similar assumptions used in prior studies.***

# 5 Vessel Traffic Analysis

Calculation of the intensity of vessel traffic in the Arctic OCS relative to the GOM OCS began with an assessment of subfactors associated with the vessel traffic hazard type. As stated in Section 1.1, this assessment's comparison of vessel traffic hazards does not include O&G vessel traffic. Instead, it is focused on fishing, personal, shipping, government, and other commercial vessel traffic. Oil spills associated with O&G operations are assumed to correlate with O&G activity, rather than vessel traffic in general.

We performed a line-by-line review of vessel-traffic-related oil spills reported to the BSEE. Table 16 summarizes the distribution by subfactor of 15 vessel-traffic-related oil spills which fell within the scope of this research.

**Table 16. Distribution of Vessel-Related Oil Spills by Subfactor**

| Vessel-Related Subfactor | Spill Occurrences | Percent of Total |
|---|---|---|
| Anchor Impact | 10 | 66.7% |
| Fishing/Trawling Impact | 5 | 33.3% |
| **Total** | **15** | **100%** |

These vessel traffic-related oil spills have caused impacts to pipelines rather than O&G platforms and rigs. While it is not impossible for third party vessels to collide with O&G platforms, this has been rare, according to historical BSEE data. Table 4 provides examples of typical spill descriptions associated with these vessel traffic-related oil spills:

**Table 17. Examples of Vessel-Related Spill Incident Descriptions**

| Vessel-Related Subfactor | Example Spill Description |
|---|---|
| **Anchor Impact** | A break in the Bonita Pipeline was discovered, most probably caused by an anchor dragging across the submerged oil pipeline. |
| **Fishing/Trawling Impact** | A 1" valve protruding from a threadolet on an 8-5/8" spool piece on Exxon's submarine tie-in on oil pipeline to Texaco's 20" EIPS was apparently pulled from the threadolet by a trawl net. |

Ten anchor impact incidents in the BSEE spill data indicate that the anchor belonged to an O&G vessel. In these cases, the spill incident was excluded from analysis. In other cases, this research conservatively assumes that anchors are associated with non-O&G activities.

The following sections detail the data conditioning and analysis for evaluating the relative intensity of vessel traffic from the anchor and fishing/trawling impact subfactors.

## 5.1 Anchor Impacts

This section describes the steps taken to gather and analyze the historical intensity of anchor impacts, one of the subfactors for comparing vessel traffic between the GOM and Arctic OCS. This analysis assumes that anchor drops correlate with maritime vessel traffic in general.

### 5.1.1 Data Sources

This analysis leveraged vessel traffic data collected for the Automatic Identification System (AIS). AIS is used by maritime vessels for collision avoidance and navigation. AIS data is generally collected via land-based receivers. For the Arctic OCS, the small amount of vessel traffic and the remoteness of the region limit the availability of land-based data. To supplement these data, BOEM provided the research team with proprietary satellite-based AIS data (Crowley HA, personal communication, 2021). This data covered the Arctic OCS and spanned the time period from May 1, 2018, through December 31, 2020.

For the GOM OCS, the research team downloaded terrestrial-based AIS data hosted by the Marine Cadastre (BOEM and NOAA 2021). Because the AIS dataset was so large for the GOM OCS, we sampled the data, including the 1st, 15th, and last day of each month for 2018, 2019, and 2020.

### 5.1.2 Calculations and Assumptions

Upon initial review of the data, the team determined that the terrestrial-monitored AIS data from the GOM OCS differed from the satellite-monitored AIS data from the Arctic OCS in the frequency of records captured per vessel per hour. While the GOM vessel locations were documented approximately every 3 minutes, Arctic vessel locations might be recorded only a few times per day. The research team agreed to count the number of unique vessels per day to reduce the data size and to avoid bias from missing data in the Arctic OCS. Dividing this daily vessel count by the area of the region produces a hazard intensity, as shown in Table 18.

These unique counts included only vessels which transmit their locations within the western and central leasing areas of the GOM OCS and the Beaufort and Chukchi Seas in the Arctic OCS.

**Table 18. Anchor Impact Intensity by Region**

| Region | Area (square miles) | Average Daily Vessel Count | Hazard Intensity (Daily Vessels per Square Mile) |
|---|---|---|---|
| **GOM OCS** | 148,479 | 710 | 0.004782 |
| **Arctic OCS** | 199,628 | 3.88 | 0.000019 |

### 5.1.3 Subregions

Figure 9 shows a spatial plot of the AIS location data within the Arctic OCS, revealing subregions that may be relevant to planning and estimating relative hazard intensities. This plot includes all AIS location records within the Arctic OCS, not the daily vessel count.

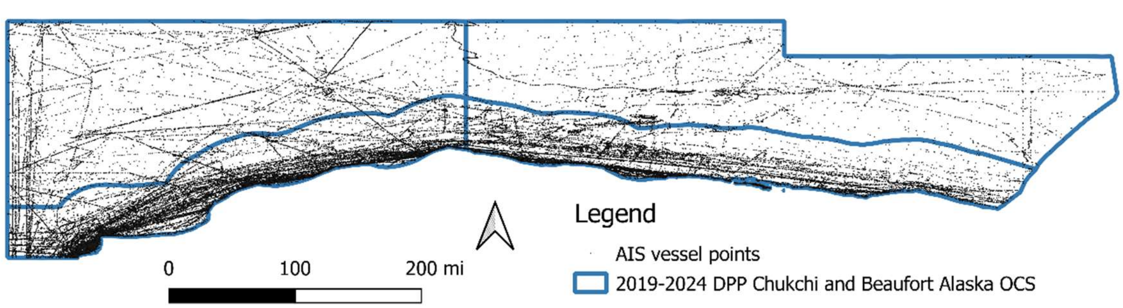



**Figure 9. Map of Arctic OCS Vessel Traffic**

This plot reveals two trends for consideration. First, vessel traffic is densest in the coastal areas (using the same 100-mile buffer area as identified in Section 4.1.4). Second, vessel traffic seems to dwindle east of the city of Utqiaġvik, Alaska, located near the dividing line of the Chukchi Sea and Beaufort Sea Planning Areas.

Table 19 shows that the Chukchi coastal area has the highest concentration of vessel traffic for the region, in agreement with the trends above.

**Table 19. Anchor Impact Intensity by Subregion: Arctic OCS**

| Region | Area (square miles) | Average Daily Vessel Count | Hazard Intensity (Daily Vessels per Square Mile) |
|---|---|---|---|
| **Total Coastal** | **67,830** | **2.3** | **0.000034** |
| Coastal Chukchi | 32,188 | 1.27 | 0.000039 |
| Coastal Beaufort | 35,642 | 1.06 | 0.000030 |
| **Total Off Coast** | **131,798** | **1.58** | **0.000012** |
| Off Coast Chukchi | 65,685 | 0.85 | 0.000013 |
| Off Coast Beaufort | 66,113 | 0.74 | 0.000011 |

### 5.1.4 Seasonality

The absence of open water for much of the year, as described in Appendix B, results in a strong seasonal distribution of vessel traffic in the Arctic OCS. Figure 10 illustrates the average monthly variation in vessel traffic (measured as daily unique vessel counts), split by each of the subregions described above. This figure suggests that the peak months of August and September experience the most vessel traffic.

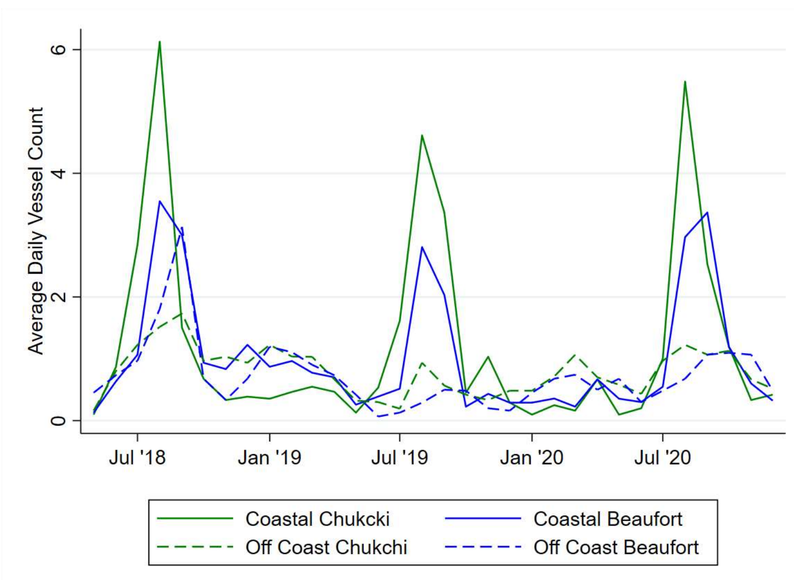



**Figure 10. Anchor Impact Intensity (Vessel Traffic) by Month: Arctic OCS**

Table 20 summarizes the seasonal variation in vessel anchor hazard intensity across regions. Although these seasonal variations are substantial, they are not anticipated to impact the average annual intensity of anchor impacts as a hazard to O&G operations, especially pipelines.

**Table 20. Anchor Impact Intensity by Season: Arctic OCS**

| Season | Area (square miles) | Average Daily Vessel Count | Hazard Intensity (Daily Vessels per Square Mile) |
|---|---|---|---|
| **Peak: August to September** | 199,628 | 9.75 | 0.000049 |
| **Off-Peak: October to July** | 199,628 | 2.53 | 0.000013 |

### 5.1.5 Relative Intensities

The preceding sections describe the intensity of vessel traffic anchor impacts as a subfactor of the vessel traffic hazard. Relative intensities by season were not included since they do not affect average annual hazard intensity. However, the dramatic variation in vessel traffic (i.e., anchor collision risk) between the coastal and non-coastal regions suggested that these regions should be considered separately. Table 21 calculates adjustment factors as the ratio of these intensity metrics and the GOM OCS intensity measure.

**Table 21. Anchor Impact Adjustment Factors**

| Region | Hazard Intensity | Relative (to GOM) Intensity | CI Low[1] | CI High[1] |
|---|---|---|---|---|
| **GOM OCS** | 0.004782 | | | |
| **Arctic OCS Total** | 0.000019 | 0.0039 | 0.0028 | 0.0050 |
| Coastal | 0.000034 | 0.0071 | 0.0046 | 0.0099 |
| Non-coastal | 0.000012 | 0.0025 | 0.0020 | 0.0030 |

[1] 95% confidence intervals generated by bootstrap resampling daily vessel counts from the historical GOM OCS and Arctic OCS vessel traffic data with replacement to create 20,000 simulated historical periods.

These results imply that the GOM OCS experiences 141 times more times as much anchor impact risk per square mile than the coastal Arctic OCS and 399 times more risk than the non-coastal Arctic OCS.

These confidence intervals suggests that the Arctic OCS has a statistically significant (p-value = <0.001) different anchor risk when compared to the GOM OCS. In addition, the coastal and non-coastal hazard intensities are statistically different from each other (p-value=0.001).

## 5.2 Fishing/Trawling Impact

The GOM OCS is frequented by commercial fishing vessels, with about 75% of the shrimp harvested in the United States coming from the GOM (NOAA 2020). This is not true of the Arctic OCS. In 2009, the National Marine Fisheries Service, implemented a new fishery management plan for the Arctic

Management Area (FMP 2009), closing the entire Arctic OCS to commercial fishing. The plan does not restrict subsistence or recreational fishing.

For the GOM OCS, the AIS data identified 195 unique fishing vessels per day on average, as shown in Figure 11. This number excludes smaller fishing vessels which are not required to transmit AIS information. In the Arctic OCS, no fishing vessels were observed. This research concludes that the fishing/trawling hazards in the Arctic OCS are negligible and should not be included until such time the Arctic Management Area plan changes.

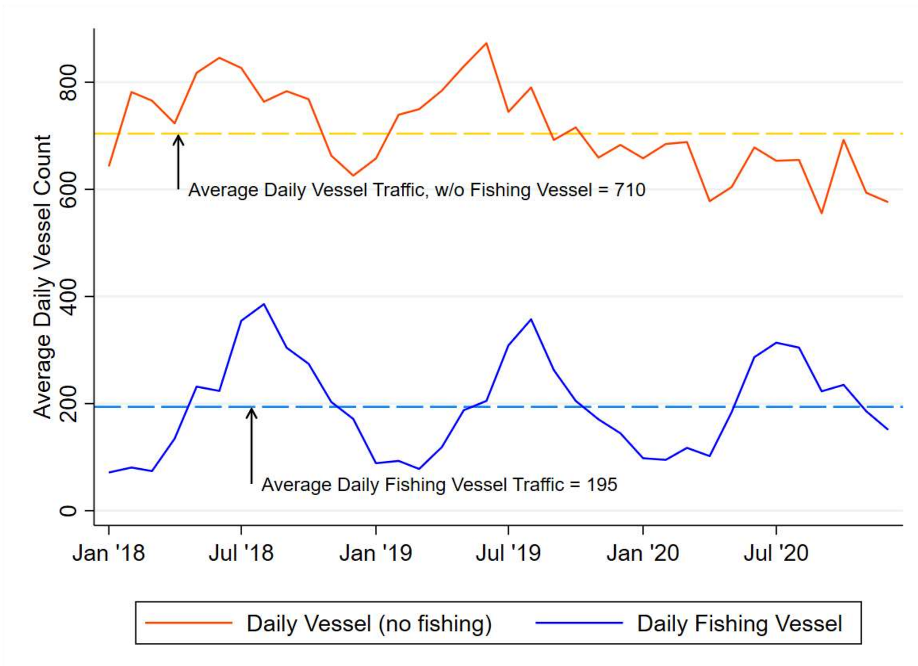



**Figure 11. Fishing/Trawling Vessel Traffic by Month: GOM OCS (BOEM and NOAA 2021)**

## 5.3 Vessel Traffic Adjustment Factors

Sections 5.1 and 5.2 evaluate the separate effects of anchor impacts and fishing/trawling impacts as vessel traffic subfactors. Our research identified two adjustments to the vessel traffic subfactors. First, the Arctic OCS experiences no commercial fishing or trawling. Therefore, 5 out of the 15 oil spills due to commercial fishing or trawling factors in the GOM OCS historical record should not be considered for developing oil spill occurrence rates for the Arctic OCS.

Second, because the U.S. Beaufort and Chukchi Seas have relatively infrequent open water throughout the year, there is dramatically less vessel traffic in the Arctic OCS than in the GOM OCS. Since fishing/trawling oil spills are not relevant to the Arctic OCS, the anchor impact adjustment factors are the only factors to incorporate into the general vessel traffic adjustment factors; no weighted average is required. Table 22 summarizes these results.

**Table 22. Vessel Traffic Adjustment Factors**

| Vessel Traffic Subfactor | GOM OCS Oil Spill Occurrences | Oil Spills Relevant to the Arctic OCS | Adjustment Factor | Adjusted Oil Spill Count |
|---|---|---|---|---|
| Anchor Impact | 10 | 10 | 0.0041 | 0.04 |
| Fishing/Trawling Impact | 5 | 0 | NA | 0 |
| **Vessel Traffic Total** | **15** | **10** | **0.0041** | **0.04** |

[1] 95% confidence intervals generated by resampling daily vessel counts from the historical GOM OCS and Arctic OCS vessel traffic data with replacement to create 20,000 simulated historical periods.

Section 5.1.3 found that vessel traffic was substantially higher in Arctic OCS coastal areas. Table 15 presents vessel traffic adjustment factors by region, along with confidence intervals.

**Table 23. Vessel Traffic Adjustment Factors by Region**

| Region | Adjustment Factor | CI Low[1] | CI High[1] |
|---|---|---|---|
| Arctic OCS Total | 0.0039 | 0.0028 | 0.0050 |
| Coastal | 0.0071 | 0.0046 | 0.0099 |
| Non-coastal | 0.0025 | 0.0020 | 0.0030 |

***It is critically important to realize that these adjustment factors apply only to the categories of vessel traffic oil spills which we have identified above as relevant to the Arctic OCS. Section 7 describes the interpretation of these findings when comparing the Arctic and GOM OCS at large, and when comparing them to such assumptions used in prior studies.***

# 6 Climate Change and Future Conditions

The analysis and findings in this assessment are based on current conditions as of 2021. This section lays out the potential impacts as these conditions change with global climate. The Arctic is experiencing among the fastest warming of any place on earth with average temperatures climbing twice as fast as the global average (Thoman et al. 2020) as seen in Figure 12. For example, this warming could dramatically reduce Arctic sea ice coverage, directly affecting assumptions that this report uses to estimate the hazard intensity of subfactors such as rough seas and anchor impacts from vessel traffic.

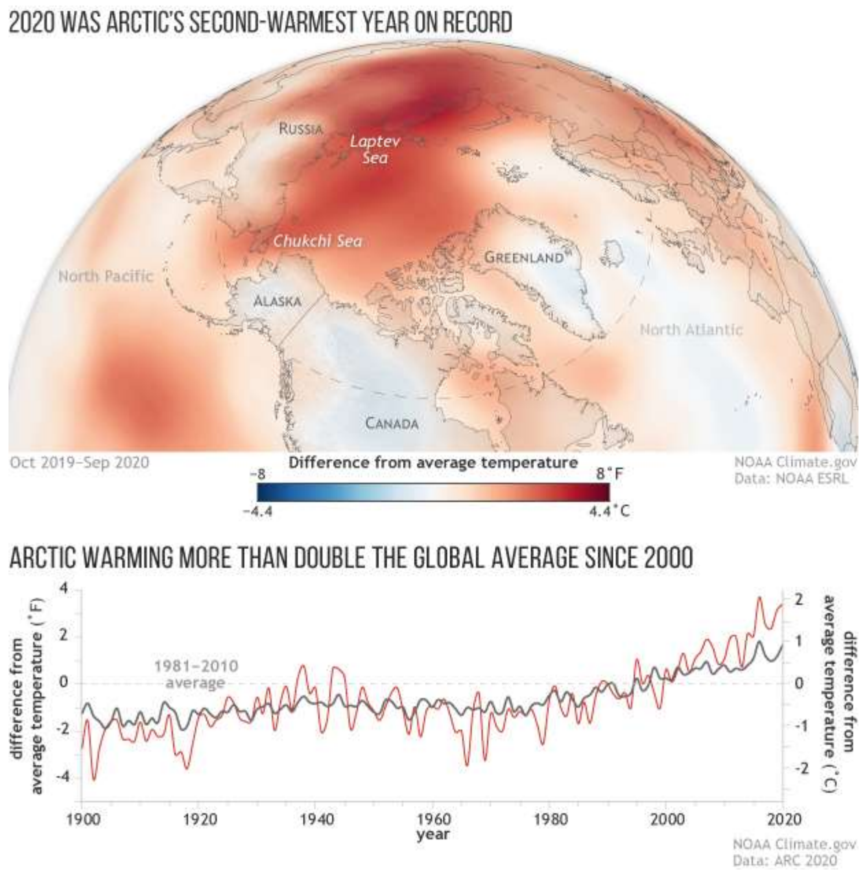



**Figure 12. Arctic Climate Change Trends**

Source: Thoman, Richter-Menge, and Druckenmiller, 2020

## 6.1 Rough Seas

This report assumes that the hazards associated with rough seas will be reduced by the presence of sea ice in the Arctic OCS. Sea ice could prevent O&G service vessels from accessing offshore facilities. This would reduce the exposure to oil spills from O&G service vessels operating in rough seas. In addition, sea ice dampens waves (Sutherland and Balmforth 2019), reducing the threat of rough seas in the first place.

## 6.2 Vessel Traffic

The effect that climate change could have on vessel traffic is even more pronounced. Current vessel traffic through the Arctic OCS is limited, following two main routes: the Northwest Passage and the Northern Sea Route as shown in Figure 13 (Boylan and Elsberry 2019). These routes are currently used but are only available for a short window of the year because of sea ice coverage (see Appendix B) and harsh weather. Because of this, most of the current vessel traffic in the Arctic is shipping to the Arctic as a destination rather than passing through to connect the Atlantic and Pacific oceans. The U.S. Arctic AIS data supports this.

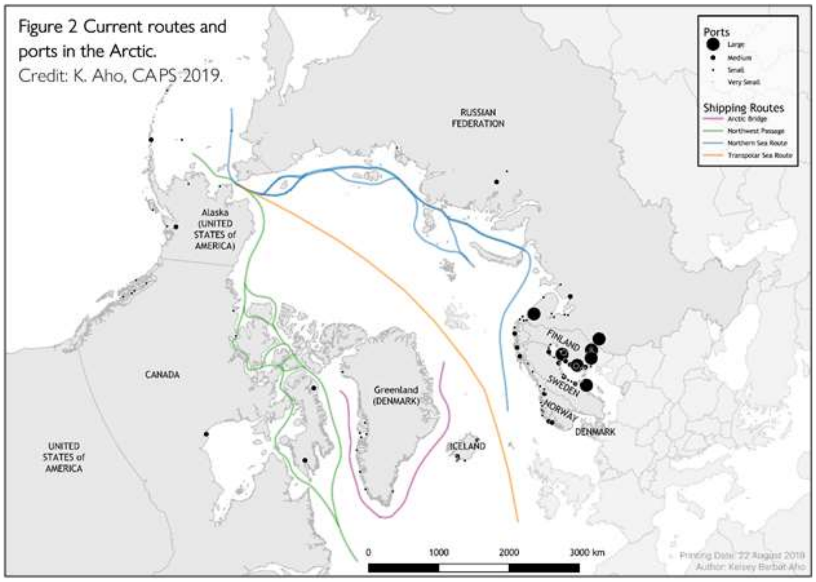



**Figure 13. Arctic Shipping Routes (Boylan and Elsberry 2019)**

Source: Boylan and Elsberry 2019

Climate modeling has predicted that September will experience a nearly ice-free Arctic Ocean for at least 5 consecutive years by 2050 (Collins et al. 2013). This change will substantially expand the use of these shipping routes. In fact, the ice retreating effect is already underway as shown in Figure 14 (Thoman et al. 2020).

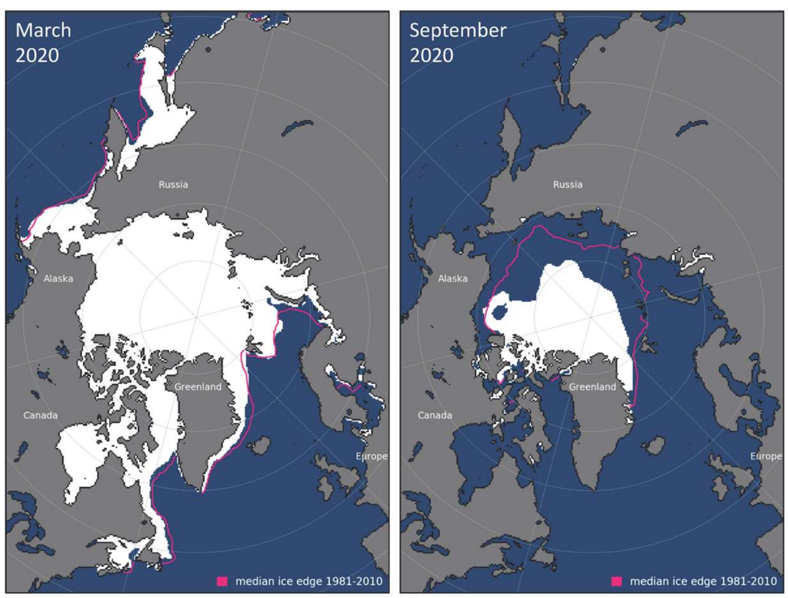



**Figure 14. Arctic Sea Ice Coverage in 2020**

Source: Thoman et al. 2020

An open route through the Arctic from Europe and the U.S. East Coast to Asia would be thousands of miles shorter and weeks faster than existing shipping routes through the Panama or Suez canals (Lee and

Song 2014). In 2019 the Panama Canal accounted for 12,281 transits carrying 259 million Tons of cargo (PCA 2020) and the Suez Canal accounted for 18,880 transits carrying 1,031 million tons of cargo (SCA 2019). Corbett et al. (2010) estimated 2% of global shipping might use an Arctic route by 2030 and 5% by 2050. If this estimate holds true, this will translate to 554 million tons in today's global shipping economy. This would equate to between 10,141 ship transits of Suez Canal size or up to 26,221 ship transits of the smaller Panama Canal size.

As one potential Arctic route, the Northwest Passage directly transits the U.S. Arctic OCS and could result in dramatically increased vessel traffic hazards for future O&G operations.

# 7 Discussion and Conclusions

This report documents the methodology, assumptions, and results of our investigation of the intensity of storm and vessel traffic hazards leading to oil spills during O&G operations in the Arctic OCS relative to the GOM OCS. The purpose of this exercise was to develop adjustment factors to enable conversion of historical oil spill occurrence rates from the GOM OCS into estimated spill rates for the Arctic OCS. In the process, we found that it was meaningful to consider performing this conversion in two steps:

1) Selection of relevant GOM OCS spill occurrences for the purpose of developing Arctic OCS spill rates; and
2) Applying adjustment factors to the selected oil spills based on the relative intensity of associated hazards.

As described in Sections 4.4 and 5.3, we found that oil spills associated with winds higher than 64 knots, storm-driven submarine landslides, and fishing/trawling impacts were not comparable to the storm and vessel traffic hazards in the Arctic OCS. These oil spills accounted for 89 out of the 126 oil spills that we identified related to storms and vessel traffic.

After removing the oil spills associated with the above three subfactors from a spill occurrence rate-making dataset, our research suggests that a moderate adjustment could be made to further adjust the storm spill rate by a factor of 0.74. Most importantly, the potential hazard to O&G operations from vessel traffic in the Arctic OCS appears to be extremely small, with an adjustment factor of 0.004.

Table 24 consolidates these findings for comparison to common assumptions that have been used in prior Arctic oil spill occurrence studies. For this table, our findings have been presented using the hazard categories commonly used in prior research. All of the factors show dramatic reductions from what was assumed in prior research. Landslides are shown as "NA" because this hazard is present in the Arctic OCS, but not likely related to the storms or vessel traffic scope of our analysis.

**Table 24. Historical Spill Hazard Mode Reduction Assumptions**

| | Prior Research | Proposed Adjustments (%) | | |
|---|---|---|---|---|
| **Causal Factor** | **Adjustment Factor (Bercha 2006, 2008; ABSG 2018)** | Adjustment to Relevant Spill Count | Hazard Adjustment Factors | **Total Combined Adjustment** |
| **Anchor Impacts** | **0.5** | 1 | 0.004 | **0.004** |
| **Trawl/Fishing Net Snags** | **0.5 to 0.7** | 0 | NA | **0** |
| **Landslides** | **0.4 to 0.6** | NA | NA | **NA** |
| **Severe Storms** | **0.7 to 0.8** | 0.23 | 0.74 | **0.17** |

Finally, we caution users of these results to carefully consider how these assumptions may be affected by future conditions. Climate change and geopolitical factors are likely to dramatically diminish the accuracy of these findings in coming decades.

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## Appendix A: Spill Records

Table 25 presents spill records using in this report for oil spills that originated from platforms. Table 26 details oil spills from pipelines. Note that in summary tables throughout the report, oil spills with multiple storm or vessel traffic subfactors listed below are counted multiple times, once for each subfactor listed.

**Table 25. Platform spill records**

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth | Storm | Vessel Traffic | Volume (bbl) | Crude/ Condensate | Refined Oil (bbl) | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 1973 | 61 | Rough Seas | | 7000 | 7000 | 0 | 525 |
| 2 | 3 | 1973 | 300 | Rough Seas | | 239 | 0 | 239 | 615 |
| 3 | 4 | 1973 | 103 | Rough Seas | | 95 | 0 | 95 | 693 |
| 4 | 5 | 1974 | 60 | | | 130 | 130 | 0 | 746 |
| 5 | 6 | 1974 | 29 | High Wind | | 75 | 75 | 0 | 757 |
| 6 | 7 | 1974 | 27 | | | 50 | 50 | 0 | 767 |
| 7 | 8 | 1974 | 140 | | | 120 | 120 | 0 | 783 |
| 8 | 9 | 1974 | 30 | High Wind | | 200 | 200 | 0 | 787 |
| 9 | 10 | 1975 | 200 | High Wind/ Rough Seas | | 100 | 0 | 100 | 874 |
| 10 | 11 | 1976 | 127 | | | 300 | 0 | 300 | 963 |
| 11 | 13 | 1978 | 105 | | | 104 | 104 | 0 | 1102 |
| 12 | 14 | 1979 | 311 | | | 321 | 0 | 321 | 1171 |
| 13 | 15 | 1979 | 210 | | | 60 | 60 | 0 | 1197 |
| 14 | 16 | 1979 | 280 | Rough Seas | | 1,500 | 0 | 1,500 | 1278 |
| 15 | 17 | 1980 | 156 | | | 286 | 0 | 286 | 1291 |
| 16 | 19 | 1980 | 220 | Rough Seas | | 80 | 0 | 80 | 1322 |
| 17 | 20 | 1980 | 187 | | | 83 | 0 | 83 | 1339 |
| 18 | 21 | 1980 | 60 | High Wind | | 1,456 | 14,56 | 0 | 1344 |
| 19 | 22 | 1980 | 99 | | | 118 | 0 | 118 | 1349 |
| 20 | 23 | 1981 | 54 | | | 58 | 58 | 0 | 1363 |

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth | Storm | Vessel Traffic | Volume (bbl) | Crude/ Condensate | Refined Oil (bbl) | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 21 | 24 | 1981 | 49 | | | 210 | 0 | 210 | 1368 |
| 22 | 25 | 1981 | 350 | | | 50 | 0 | 50 | 1395 |
| 23 | 26 | 1981 | 340 | | | 64 | 64 | 0 | 1422 |
| 24 | 27 | 1982 | 180 | | | 400 | 0 | 400 | 1434 |
| 25 | 28 | 1982 | 394 | | | 228 | 0 | 228 | 1447 |
| 26 | 29 | 1982 | 60 | Rough Seas | | 214 | 0 | 214 | 1474 |
| 27 | 32 | 1983 | 50 | | | 320 | 0 | 320 | 1533 |
| 28 | 33 | 1983 | 65 | | | 200 | 0 | 200 | 1536 |
| 29 | 35 | 1983 | 105 | | | 119 | 0 | 119 | 1581 |
| 30 | 36 | 1984 | 94 | | | 50 | 50 | 0 | 1650 |
| 31 | 37 | 1984 | 307 | | | 100 | 0 | 100 | 1653 |
| 32 | 38 | 1985 | 130 | | | 107 | 0 | 107 | 1683 |
| 33 | 39 | 1985 | 50 | | | 60 | 0 | 60 | 1684 |
| 34 | 40 | 1985 | 196 | | | 50 | 50 | 0 | 1689 |
| 35 | 41 | 1985 | 3,115 | | | 643 | 0 | 643 | 1711 |
| 36 | 42 | 1985 | 200 | | | 50 | 0 | 50 | 1723 |
| 37 | 43 | 1985 | 55 | High Wind | | 66 | 66 | 0 | 1734 |
| 38 | 44 | 1985 | 103 | | | 58 | 0 | 58 | 1739 |
| 39 | 46 | 1987 | 126 | | | 60 | 60 | 0 | 1828 |
| 40 | 47 | 1988 | 172 | | | 50 | 50 | 0 | 1871 |
| 41 | 49 | 1988 | 140 | | | 55 | 55 | 0 | 1897 |
| 42 | 50 | 1989 | 112 | | | 400 | 400 | 0 | 1903 |
| 43 | 51 | 1989 | 206 | | | 55 | 55 | 0 | 3351 |
| 44 | 53 | 1991 | 50 | | | 280 | 280 | 0 | 2010 |
| 45 | 54 | 1992 | 187 | | | 100 | 100 | 0 | 2053 |
| 46 | 55 | 1993 | 8 | | | 250 | 250 | 0 | 3360 |
| 47 | 56 | 1994 | 150 | | | 50 | 50 | 0 | 2111 |
| 48 | 57 | 1995 | 50 | | | 600 | 600 | 0 | 2114 |

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth | Storm | Vessel Traffic | Volume (bbl) | Crude/ Condensate | Refined Oil (bbl) | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 49 | 58 | 1995 | 116 | | | 75 | 75 | 0 | 2133 |
| 50 | 59 | 1995 | 56 | | | 435 | 435 | 0 | 2149 |
| 51 | NA | 1995 | - | | | 63 | 63 | 0 | NA |
| 52 | 61 | 1997 | 40 | | | 170 | 170 | 0 | 2245 |
| 53 | 62 | 1998 | 700 | Rough Seas | | 100 | 0 | 100 | 2259 |
| 54 | 63 | 1999 | 463 | | | 125 | 125 | 0 | 2361 |
| 55 | 65 | 2000 | 2,223 | | | 200 | 200 | 0 | 2389 |
| 56 | 66 | 2000 | 172 | | | 60 | 60 | 0 | 2407 |
| 57 | 67 | 2001 | 243 | | | 127 | 127 | 0 | 2446 |
| 58 | 70 | 2002 | 50 | High Wind | | 350 | 350 | 0 | 2555 |
| 59 | 71 | 2002 | 37 | High Wind | | 445 | 0 | 445 | 2557 |
| 60 | 72 | 2002 | 94 | High Wind | | 741 | 0 | 741 | 2556 |
| 61 | 73 | 2002 | - | High Wind | | 230 | 0 | 230 | NA |
| 62 | 74 | 2004 | 277 | High Wind | | 52 | 0 | 52 | 2707 |
| 63 | 76 | 2004 | 305 | High Wind | | 257 | 126 | 131 | 2695 |
| 64 | 77 | 2004 | 244 | High Wind | | 106 | 77 | 29 | 2697 |
| 65 | 79 | 2004 | 479 | High Wind/ Submarine Landslide | | 50,100 | 50,000 | 100 | 2703 |
| 66 | 80 | 2005 | 86 | High Wind | | 141 | 141 | 0 | 2771 |
| 67 | 81 | 2005 | 83 | High Wind | | 242 | 242 | 0 | 2770 |
| 68 | 82 | 2005 | 91 | High Wind | | 204 | 204 | 0 | 2772 |
| 69 | 83 | 2005 | 88 | High Wind | | 195 | 195 | 0 | 2773 |
| 70 | 84 | 2005 | 1,023 | High Wind | | 325 | 325 | 0 | 2775 |
| 71 | 85 | 2005 | 140 | High Wind | | 380 | 0 | 380 | 2781 |
| 72 | 87 | 2005 | 322 | High Wind | | 110 | 85 | 25 | 2793 |
| 73 | 88 | 2005 | 340 | High Wind | | 369 | 180 | 9 | 2788 |
| 74 | 89 | 2005 | 153 | High Wind | | 307 | 307 | 0 | 2819 |
| 75 | 90 | 2005 | 223 | High Wind | | 57 | 50 | 7 | 2821 |
| 76 | 91 | 2005 | 228 | High Wind | | 140 | 130 | 10 | 2830 |

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth | Storm | Vessel Traffic | Volume (bbl) | Crude/ Condensate | Refined Oil (bbl) | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 77 | 92 | 2005 | 285 | High Wind | | 117 | 109 | 8 | 2832 |
| 78 | 94 | 2005 | 137 | High Wind | | 99 | 48 | 51 | 2808 |
| 79 | 97 | 2005 | 117 | High Wind | | 50 | 50 | 0 | 2813 |
| 80 | 98 | 2005 | 140 | High Wind | | 96 | 95 | 1 | 2816 |
| 81 | 100 | 2005 | 182 | High Wind | | 1,566 | 0 | 1,566 | 2881 |
| 82 | 101 | 2005 | 204 | High Wind | | 56 | 44 | 12 | 2853 |
| 83 | 102 | 2005 | 230 | High Wind | | 2,000 | 2,000 | 0 | 2855 |
| 84 | 103 | 2005 | 254 | High Wind | | 150 | 150 | 0 | 2856 |
| 85 | 104 | 2005 | 231 | High Wind | | 162 | 150 | 12 | 2858 |
| 86 | 105 | 2005 | 472 | High Wind | | 101 | 101 | 0 | 2860 |
| 87 | 106 | 2005 | 238 | High Wind | | 1,494 | 0 | 1,494 | 2870 |
| 88 | 107 | 2005 | 182 | High Wind | | 67 | 0 | 67 | 2842 |
| 89 | 108 | 2005 | 230 | High Wind | | 659 | 582 | 77 | 2838 |
| 90 | 109 | 2005 | 230 | High Wind | | 166 | 166 | 0 | 3059 |
| 91 | 110 | 2005 | 230 | High Wind | | 53 | 53 | 0 | 3009 |
| 92 | 111 | 2005 | - | High Wind | | 119 | 119 | 0 | NA |
| 93 | NA | 2005 | 255 | High Wind | | 124 | 106 | 12 | 2783 |
| 94 | 114 | 2006 | 240 | High Wind | | 528 | 528 | 0 | 3062 |
| 95 | 116 | 2006 | 240 | High Wind | | 133 | 133 | 0 | 2995 |
| 96 | 118 | 2006 | 240 | High Wind | | 120 | 120 | 0 | 2933 |
| 97 | 119 | 2007 | - | | | 71 | 71 | 0 | NA |
| 98 | 122 | 2008 | 187 | High Wind | | 685 | 685 | 0 | 3219 |
| 99 | 123 | 2008 | 210 | High Wind | | 101 | 20 | 81 | 3251 |
| 100 | 124 | 2008 | 262 | High Wind | | 61.5 | 55 | 6.5 | 3226 |
| 101 | 125 | 2008 | 415 | High Wind | | 159 | 150 | 9 | 3249 |
| 102 | 126 | 2008 | 414 | High Wind | | 52 | 52 | 0 | 3227 |
| 103 | 127 | 2008 | 472 | High Wind | | 513 | 513 | 0 | 3250 |
| 104 | 128 | 2008 | 541 | High Wind | | 200 | 200 | 0 | 3209 |

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth | Storm | Vessel Traffic | Volume (bbl) | Crude/ Condensate | Refined Oil (bbl) | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 105 | 129 | 2008 | 235 | High Wind | | 490 | 0 | 490 | 3252 |
| 106 | 130 | 2008 | 175 | High Wind | | 140 | 140 | 0 | 3270 |
| 107 | 131 | 2008 | 76 | High Wind | | 50 | 48 | 2 | 3266 |
| 108 | 132 | 2008 | 169 | High Wind | | 126 | 126 | 0 | 3271 |
| 109 | 134 | 2008 | 186 | High Wind | | 194 | 112 | 82 | 3225 |
| 110 | 135 | 2008 | 220 | High Wind | | 170 | 170 | 0 | 3275 |
| 111 | 136 | 2008 | 324 | High Wind | | 194 | 31 | 163 | 3238 |
| 112 | 138 | 2008 | 472 | High Wind | | 58 | 58 | 0 | 3331 |
| 113 | 140 | 2009 | 4,420 | | | 50 | 50 | 0 | 3454 |
| 114 | 141 | 2009 | 6,050 | | | 62 | 62 | 0 | 3435 |
| 115 | 142 | 2009 | 254 | High Wind | | 70 | 70 | 0 | 3319 |
| 116 | 143 | 2009 | 340 | | | 186 | 186 | 0 | 3409 |
| 117 | 144 | 2009 | - | High Wind | | 100 | 100 | 0 | NA |
| 118 | 145 | 2010 | 4,992 | | | 4,916,896 | 4,916,896 | 0 | 3496 |
| 119 | 147 | 2011 | - | | | 67 | 67 | 0 | NA |
| 120 | 148 | 2012 | - | High Wind | | 480 | 480 | 0 | NA |
| 121 | 149 | 2015 | - | High Wind | | 250 | 0 | 250 | NA |

**Table 26. Pipeline spill records**

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth (ft) | Pipe Diameter (in) | Storm | Vessel Traffic | Volume (bbl) | Material | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 1974 | 240 | 14 | | Anchor | 19,833 | Crude | 729 |
| 2 | 4 | 1974 | 246 | 12 | | | 65 | Crude | 737 |
| 3 | 5 | 1974 | 141 | 8 | High Wind | | 3,500 | Crude | 760 |
| 4 | 6 | 1976 | 160 | 18 | | Anchor | 414 | Crude | 916 |
| 5 | 7 | 1976 | 210 | 10 | | Fishing/Trawling | 4,000 | Crude | 979 |
| 6 | 8 | 1977 | 105 | 12 | Submarine Landslide | | 250 | Crude | 1005 |
| 7 | 9 | 1977 | 247 | 8 | | | 50 | Crude | 1014 |
| 8 | 10 | 1977 | 210 | 8 | | Anchor | 300 | Crude | 1053 |
| 10 | 11 | 1978 | 177 | 6 | | | 135 | Crude | 1094 |
| 9 | 12 | 1978 | 103 | 9 | | Anchor | 900 | Crude | 1128 |
| 11 | 13 | 1979 | 300 | 8 | | | 50 | Crude | 1228 |
| 12 | 14 | 1980 | 137 | 8 | | Fishing/Trawling | 100 | Condensate | 1295 |
| 13 | 15 | 1981 | 54 | 4 | | | 80 | Crude | 1393 |
| 14 | 16 | 1981 | 190 | 8 | | | 5,100 | Crude | 1427 |
| 15 | 17 | 1983 | 184 | 8 | Submarine Landslide | | 80 | Crude | 1515 |
| 16 | 18 | 1985 | 162 | 12 | | | 323 | Crude | 1688 |
| 17 | 19 | 1985 | 17 | 12 | | | 200 | Crude | 1755 |
| 18 | 20 | 1986 | 27 | 6 | | | 119 | Crude | 1773 |
| 19 | 21 | 1986 | 300 | 8 | | Anchor | 210 | Crude | 1819 |
| 20 | 22 | 1988 | 75 | 14 | High Wind | Anchor | 15,576 | Crude | 1868 |
| 21 | 23 | 1990 | 197 | 4 | | Fishing/Trawling | 14,423 | Condensate | 1934 |
| 22 | 24 | 1990 | 230 | 8 | | Fishing/Trawling | 4,569 | Crude | 1950 |
| 23 | 25 | 1990 | - | - | | | 100 | Crude | NA |
| 24 | 26 | 1991 | 90 | 10 | | | 50 | Crude | 1989 |
| 25 | 27 | 1992 | 90 | 12 | | | 190 | Crude | 2022 |
| 26 | 28 | 1992 | 30 | 20 | High Wind | | 2,000 | Crude | 2046 |
| 27 | 29 | 1993 | 116 | 4 | | | 50 | Crude | 2059 |
| 28 | 30 | 1994 | 197 | 4 | | Fishing/Trawling | 4,533 | Condensate | 2105 |

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth (ft) | Pipe Diameter (in) | Storm | Vessel Traffic | Volume (bbl) | Material | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 29 | 31 | 1996 | 1,075 | - | | | 150 | Crude | 2160 |
| 30 | 32 | 1998 | 150 | 14 | | Anchor | 800 | Crude | 2253 |
| 31 | 33 | 1998 | 264 | 16 | | | 1,211 | Condensate | 2255 |
| 32 | 34 | 1998 | 108 | 10 | High Wind/ Submarine Landslide | | 8,212 | Crude | 2300 |
| 33 | 35 | 1998 | 170 | 8 | | Anchor | 738 | Crude | 2252 |
| 34 | 36 | 1999 | 133 | 12 | | | 3,200 | Crude | 2346 |
| 35 | 37 | 2000 | 435 | 24 | | | 2,240 | Crude | 2379 |
| 36 | 38 | 2004 | 479 | 6 | Submarine Landslide | | 1,720 | Crude | 2704 |
| 37 | 39 | 2004 | 200 | 18 | High Wind | | 671 | Crude | 2667 |
| 38 | 40 | 2004 | 305 | 6 | | | 126 | Crude | 2696 |
| 39 | 41 | 2004 | 244 | 8 | High Wind | | 200 | Crude | 2698 |
| 40 | 42 | 2004 | 255 | 6 | High Wind | | 250 | Crude | 2701 |
| 41 | 43 | 2004 | 255 | 8 | High Wind | | 260 | Crude | 2700 |
| 42 | 44 | 2004 | 185 | 8 | High Wind | | 95 | Crude | 2709 |
| 43 | 45 | 2004 | 300 | 10 | High Wind/ Submarine Landslide | | 123 | Crude | 2710 |
| 44 | 46 | 2005 | 1,100 | 8 | High Wind | | 960 | Crude | 2835 |
| 45 | 48 | 2005 | 240 | 10 | High Wind | | 55 | Crude | 2794 |
| 46 | 49 | 2005 | 216 | 10 | High Wind | | 132 | Crude | 2787 |
| 47 | NA | 2005 | 340 | 8 | High Wind | | 50 | Crude | 2789 |
| 48 | 50 | 2005 | 48 | 8 | High Wind | | 50 | Condensate | 2802 |
| 49 | 51 | 2005 | 180 | 4 | High Wind | | 75 | Crude | 2880 |
| 50 | 52 | 2005 | 17 | 14 | High Wind | | 100 | Condensate | 2845 |
| 51 | 53 | 2005 | 141 | 8 | High Wind | | 862 | Crude | 2894 |
| 52 | 54 | 2005 | 152 | 12 | High Wind | | 67 | Crude | 2897 |
| 53 | 55 | 2005 | 210 | 6 | High Wind | | 108 | Crude | 2900 |
| 54 | 56 | 2005 | - | - | High Wind | | 100 | Crude | NA |
| 55 | 57 | 2006 | 126 | 14 | | Anchor | 870 | Crude | 2976 |
| 56 | 58 | 2007 | 420 | 4 | | | 188 | Crude | 3034 |
| 57 | 59 | 2008 | 46 | 8 | High Wind | | 69 | Crude | 3231 |

| Spill ID | Spill ID (from ABSG 2018) | Year | Depth (ft) | Pipe Diameter (in) | Storm | Vessel Traffic | Volume (bbl) | Material | BSEE ID |
|---|---|---|---|---|---|---|---|---|---|
| 58 | 60 | 2008 | 50 | 6 | High Wind | | 108 | Condensate | 3232 |
| 59 | 61 | 2008 | 105 | 6 | High Wind | | 56 | Crude | 3260 |
| 60 | 62 | 2008 | 150 | 42 | High Wind | Anchor | 1,316 | Condensate | 3255 |
| 61 | 63 | 2008 | 324 | 4 | High Wind | | 209 | Crude | 3237 |
| 62 | 64 | 2008 | 324 | 8 | High Wind | | 268 | Condensate | 3236 |
| 63 | 65 | 2009 | 60 | 20 | | | 1,500 | Crude | 3387 |
| 64 | 66 | 2011 | - | - | High Wind | | 400 | Fuel | NA |
| 65 | 67 | 2013 | - | - | High Wind | | 113 | Crude | NA |
| 66 | 68 | 2013 | - | - | High Wind | | 102 | Crude | NA |
| 67 | 69 | 2016 | - | - | High Wind | | 2,100 | Crude | NA |
| 68 | 70 | 2017 | - | - | High Wind | | 16,152 | Crude | NA |

## Appendix B: Beaufort and Chukchi Sea O&G Profile

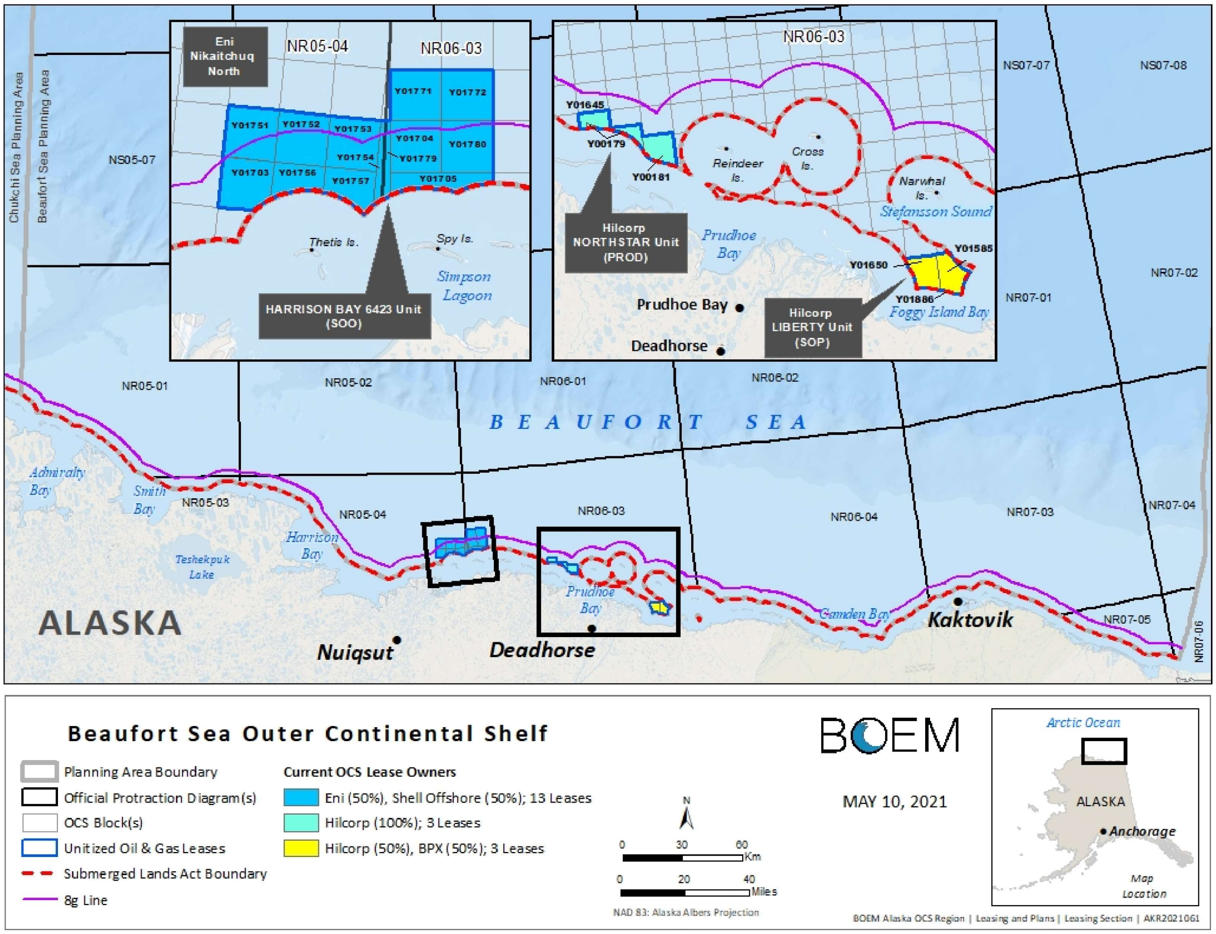


**Figure 15. Arctic OCS Active Leases**

Source: BOEM 2021c

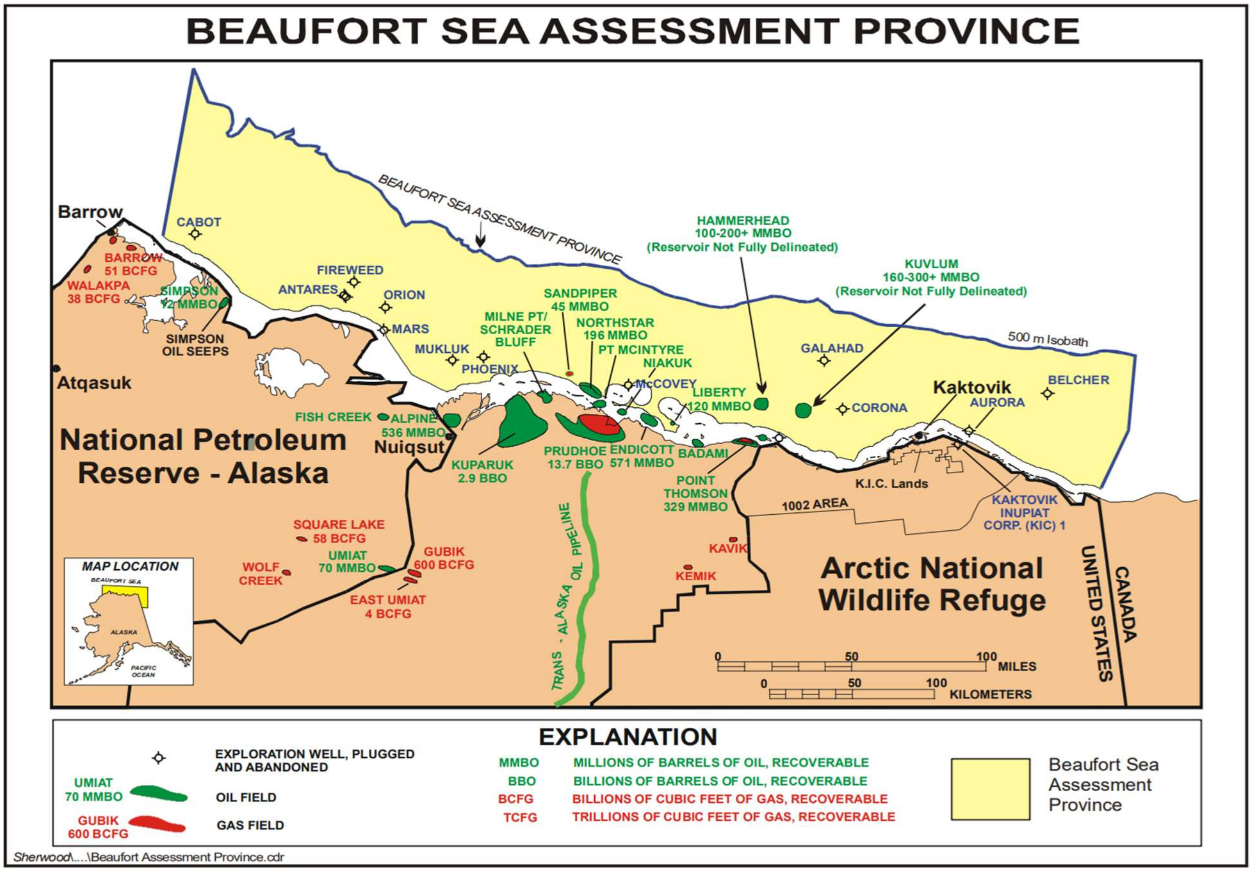


**Figure 16. Beaufort Sea O&G Reserves**

Note. Figure taken from “Beaufort Sea Province Summary”, by BOEM 2006.

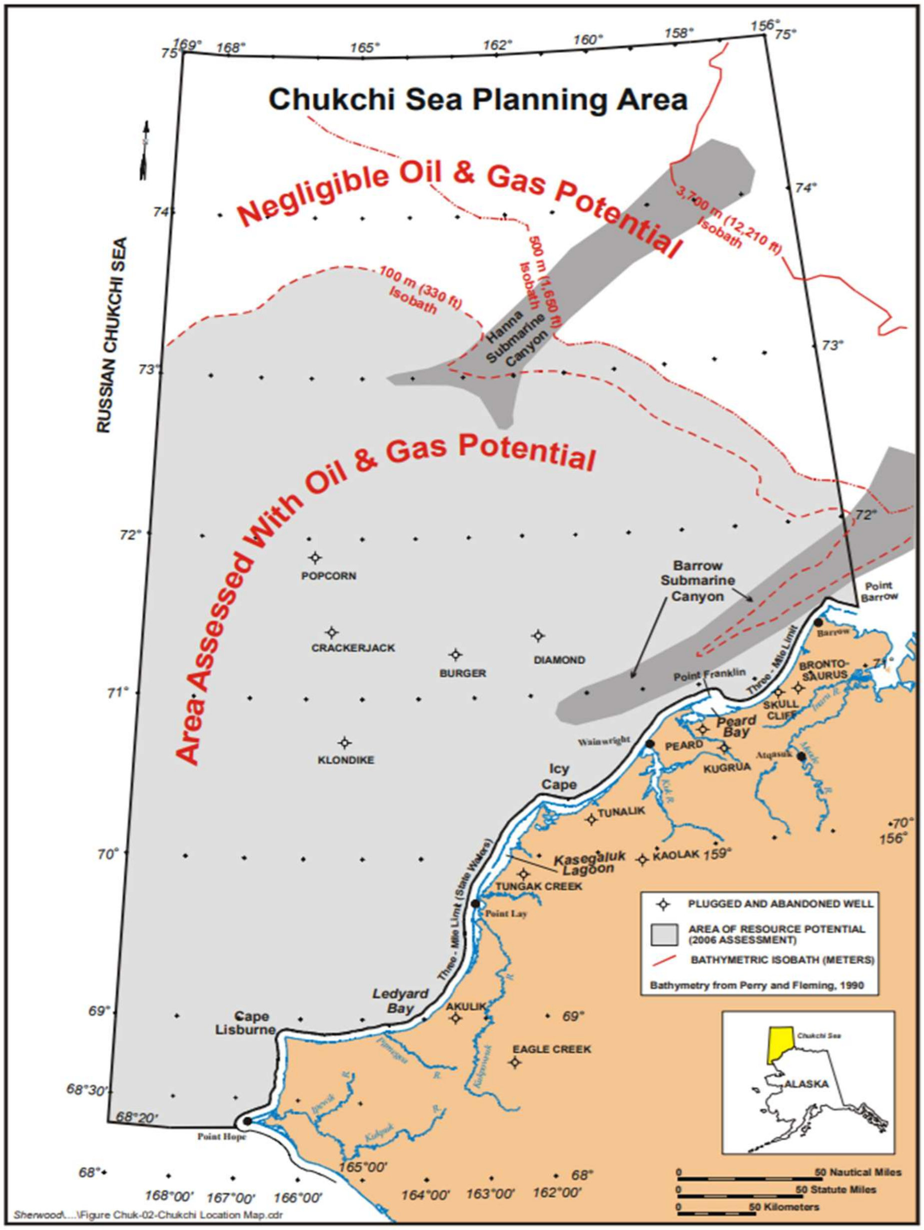


**Figure 17. Chukchi Sea O&G Potential**

Note. Figure taken from "Chukchi Sea Province Summary", by BOEM 2006b.

## Appendix C: Sea Ice Seasonality

Sea ice coverage drives hazard exposure for several vessel or storm subfactors in our research. It affects the frequency of rough seas and the level of vessel traffic, including O&G support vessels. The National Snow and Ice Data Center defines open water as having floes (floating ice sheets) in concentrations under 10% (NSIDC 2021). Figure 18 shows the percentage of the Chukchi and Beaufort OCS OPD areas that are passable by ordinary vessels for 2015 through the end of 2019, split by the coastal and non-coastal subregions. In addition, the months where the average total ice coverage were less than 10% are flagged.

Months with high amounts of open water correspond directly to months with high vessel traffic (see Figure 10 on page 24).

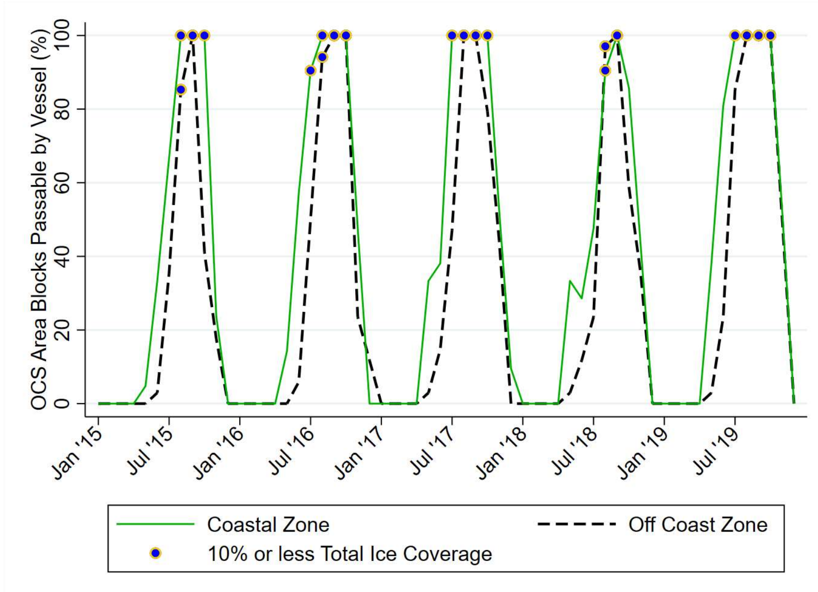


**Figure 18. Open Water Seasonality**

The 55 OPD areas that we analyzed do not all freeze over simultaneously. Figure 19 shows the distribution of ice coverage for the month of June 2018. Using the same methodology as for aggregating the intensity of high winds (see Section 4.1.3), we aggregated ice coverage data to find the average presence of more than 10% ice coverage at the centroid of the OPD across the Arctic OCS area and across seasons. We found that the Arctic OCS has open water across the area and across seasons 27.4% of the time.

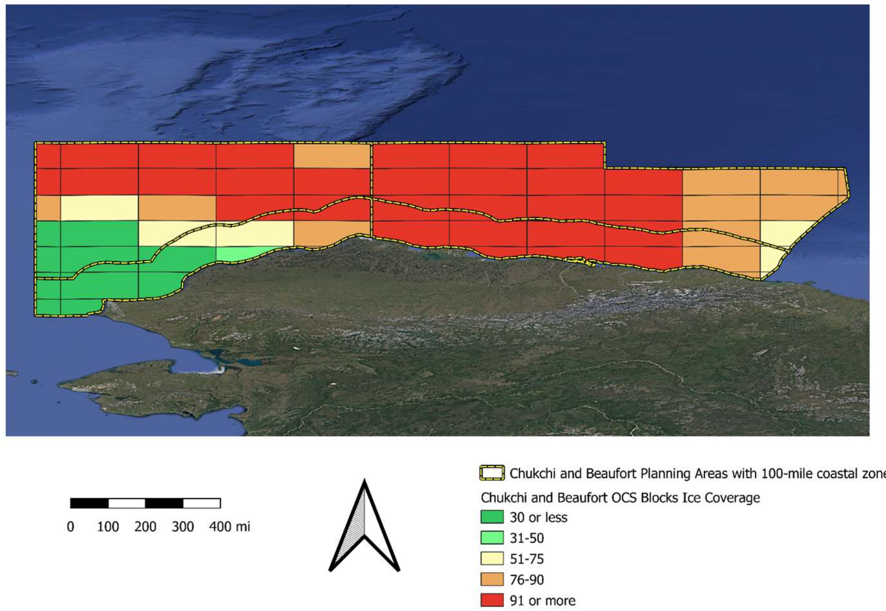


**Figure 19. Ice Coverage by OPD Area**

## Appendix D: GOM Hurricane Oil Spills by Wind Speed

Out of the 94 hurricane-related oil spills that we analyzed, we identified 76 incident records with enough information to estimate the maximum wind speeds experienced by the platforms where a spill occurred. These 75 incidents occurred between 2002 and 2016 and were associated with five named hurricanes (Lili, Ivan, Katrina, Rita, and Ike), shown in Figure 20. This figure clearly suggests a relationship between hurricane-caused oil spills and the 64-knot wind field. Of the 76 oil spills, 63 (83%) occurred at facilities that fell within the 64-knot wind field at some point during the storm.

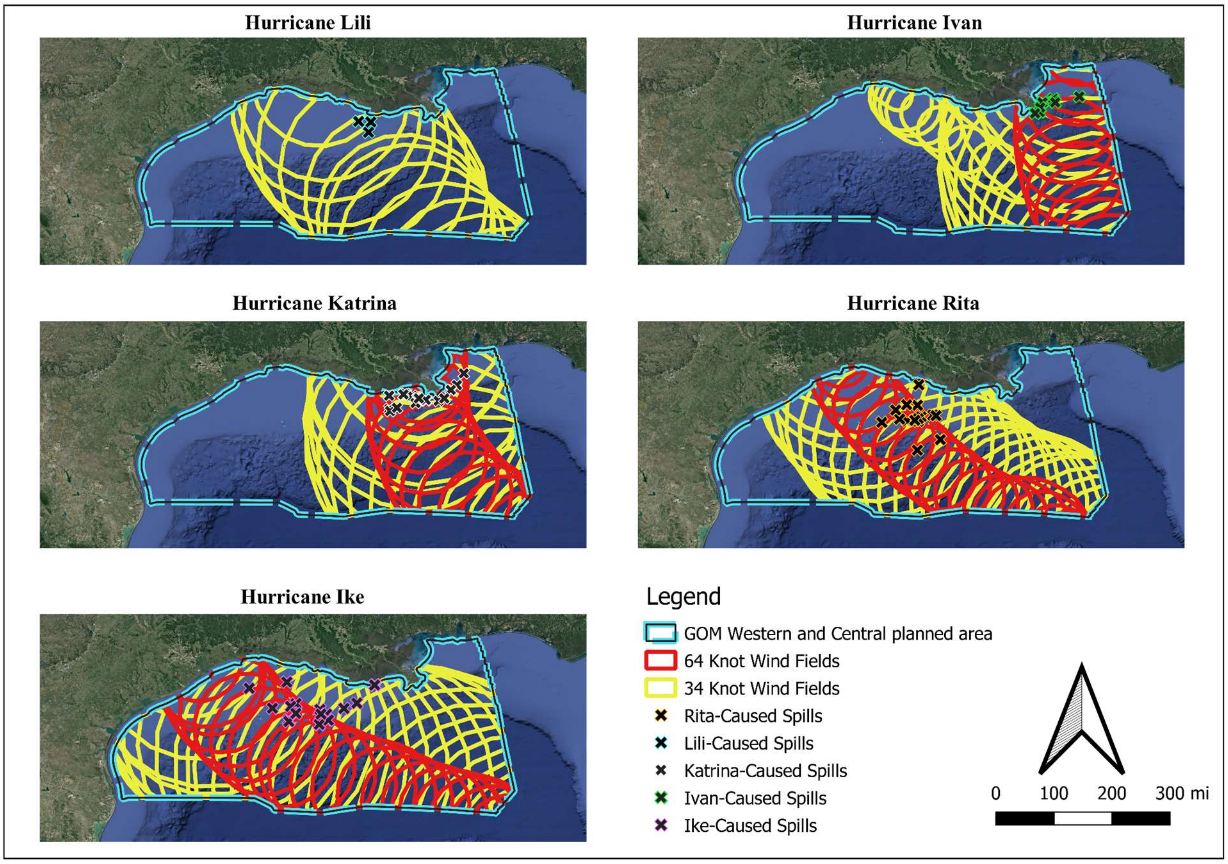


**Figure 20. Map of Hurricane Oil Spills by GOM Hurricane Event**

The calculated wind field areas are approximate, based on the IBTrACS radial extents, and may be biased to the west since they are centered on the eye of the storm while hurricanes in the northern hemisphere tend to have higher wind speeds on the right-hand side (the east, when moving north). This potential bias may explain some of the oil spills which occurred to the east of our estimated 64-knot wind field during hurricane Ike, for example. We expect that this potential bias makes our estimate of "83% of oil spills occurring within the 64-knot wind field" conservative.

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