Estimating an Oil Spill Response Gap for the U.S. Arctic Ocean (Revised)

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Nuka Research and Planning Group, LLC

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Executive Summary

As sea ice retreat increases the potential for vessel traffic and oil and gas activities in the Arctic Ocean (Arctic Council, 2009), it is valuable for oversight agencies, operating companies, and oil spill response planners and responders to understand the limitations that Arctic conditions may pose to oil spill response in the Arctic marine environment. The Bureau of Safety and Environmental Enforcement (BSEE) contracted Nuka Research and Planning Group to perform an oil spill response gap analysis (also known as a response viability analysis) for two locations in the U.S. Beaufort and Chukchi Seas. This analysis quantified the frequency with which environmental conditions may be favorable, marginal, or not favorable for the deployment of specific oil spill response tactics. Wind, sea state, temperature, ice coverage, and visibility were examined. Response tactics evaluated included mechanical recovery, dispersants applied from aircraft and vessels, and in-situ burning ignited from aircraft and vessels.

The study focuses on two offshore locations, one in the Chukchi Sea and one in the Beaufort Sea. Environmental data are drawn from onshore sources, except for sea ice. Oil spill response tactics common to the study area are selected. For each tactic, limits are then defined for each environmental factor. Limits are categorized as green, yellow, and red. The use of three categories acknowledges, in a simple way, the fact that response does not suddenly change with a set wind speed or wave height, but transitions gradually. The categories are:

- ***Favorable:*** Green refers to generally favorable conditions in which the tactic could be expected to be deployed safely and operate as intended.
- ***Marginal:*** Yellow refers to conditions that are marginal where the tactic could be deployed but operations may be compromised or challenged in some way.
- ***Not favorable:*** Red refers to unfavorable conditions in which the tactic would not typically be used due to the impact of environmental conditions on safety or equipment function.

Results are similar for the two locations studied, within just a few percentage points in all cases. Not surprisingly, conditions are more likely favorable for all tactics studied in the ice-free months (here considered summer) as compared to the ice-infested winter months. In summer, the application of dispersants by vessel is most likely to be favorable. In winter, either of the in-situ burning tactics is most likely to be favorable, with a slight preference towards ignition from a vessel. The results are summarized in Figure ES-1, below.

Consecutive hours of green, or green and yellow, conditions are calculated to analyze the time window that may be available for each tactic. The percentage of time during which a response would be favorable or marginal drops significantly when considering not just one hour but consecutive hours. In-situ burning from a vessel is the most likely to be viable as it is the most likely to have one-hour green or yellow conditions (64% of the year, when combined); when considering 6-hour time increments, however, the combined green and yellow conditions drop to 44% of the time.

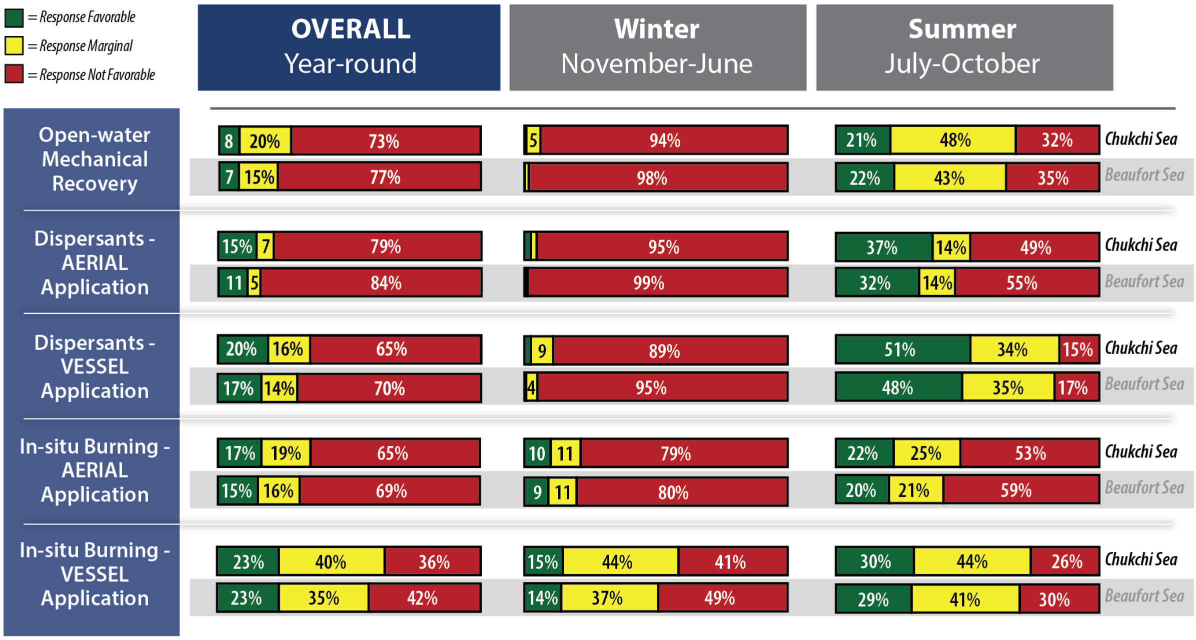

Figure ES-1. Summary of results at Chukchi and Beaufort Sea locations studied, where green is the percentage of time a particular tactic if favorable, yellow is marginal, and red is not favorable based on the conditions studied.

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1. Introduction

As sea ice retreat increases the potential for vessel traffic and oil and gas activities in the Arctic Ocean (Arctic Council, 2009), it is valuable for oversight agencies, operating companies, and oil spill response planners and responders to understand the limitations that Arctic conditions may pose to oil spill response in the Arctic marine environment. The Bureau of Safety and Environmental Enforcement (BSEE) contracted Nuka Research and Planning Group to perform an oil spill response gap analysis (also known as a response viability analysis) for two locations in the U.S. Beaufort and Chukchi Seas. This analysis quantified the frequency with which specific oil spill response tactics may or may not be recommended due to environmental conditions. Conditions examined included wind, sea state, temperature, ice coverage, and visibility. Response options evaluated included mechanical recovery, dispersants, and in-situ burning.

The initial project was conducted in 2013-2014. BSEE then commissioned a peer review of the final report, and requested that Nuka Research revise the analysis and report based on the comments received that fell within the original project scope. The primary change made in this revised report is in the way the results are presented. This change aligns the approach with a new project being implemented by the Emergency Prevention, Preparedness and Response Workgroup of the Arctic Council (DNV GL and Nuka Research, 2015). Nuka Research also added a discussion of the time window available for a response. Other changes enhanced the clarity of the methodology and results.

This report provides an overview of the response gap analysis method and limitations (Section 2), describes the environmental data sources used (Section 3), characterizes the compiled environmental dataset (Section 4), and presents the key inputs and results of the analysis for each tactic in Section 5-7. Section 8 summarizes the results. Section 9 discusses the results, with a brief conclusion in Section 10. Supplementary information is provided in in Appendices A-E.

2. Methodology

Nuka Research developed the methodology and implemented the first response gap analysis for Prince William Sound, Alaska, in a series of studies conducted from 2006-2008 (Nuka Research, 2006; 2007a; 2008). Subsequent studies have examined the north and south coasts of British Columbia (Nuka Research, 2012; Terhune, 2011), Canadian Beaufort Sea and Davis Strait (SL Ross, 2011), Aleutian Islands (Nuka Research, 2014), Barents Sea (DNV GL, 2014). The methodology used for this analysis build on this previous work.

2.1 Scope of this Analysis

This response gap analysis considers the following spill response tactics and environmental factors:

Spill Response Tactics

- Open-water mechanical recovery
- Dispersant application by aircraft
- Dispersant application by vessel
- In-situ burning ignited from aircraft
- In-situ burning ignited from vessel

Environmental Factors

- Wind speed
- Wave height and steepness[1]
- Wind chill
- Temperature/icing
- Visibility
- Ice coverage

In order to establish limits, a specific tactic must be chosen with at least some basic assumptions about the vessels or aircraft and other equipment that comprise it. This project focuses on tactics designed to respond to a marine oil spill on the surface of the water; different tactics may be used for a subsea release or a spill to the surface of sea ice. Tactics and limits were selected with input from BSEE, the U.S. Coast Guard, and the Alaska Department of Environmental Conservation. Tactics are based on common, established tactics used in the area. Other tactics may also be used, with different results. The results may also be different if emerging technology is incorporated or tactics are otherwise modified so that the limits change. The number of tactics studied was limited by project scope and budget.

2.2 Methodology

This analysis quantifies the frequency with which environmental conditions may be favorable, marginal, or not favorable throughout the year in two locations. Historic environmental conditions are compared to a set of response limits, or metrics above (or below) which a particular response tactic would not be recommended. The results are presented as a percentage of time that conditions would likely be favorable, marginal, or not favorable for a particular response tactic. This section describes the methodology applied, based on the following steps:

1. Compile historic environmental data for relevant environmental conditions. Historic weather data is compiled or interpolated in hourly time intervals. This study uses

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[1] Wave height is modeled due to data gaps.

data from three airports, offshore ice observations, and offshore buoys (data are available for only a few months).

2. Establish operational limits for each environmental factor based on published literature and best professional judgment. The approach used to develop the limits is summarized in Section 2.3. The actual limits used in this study are described with each response tactic in Sections 5-7.

Oil spill response tactics common to the study area are selected. For each tactic, limits are then defined for each environmental factor. Limits are categorized as green, yellow, and red, where:

- Green refers to generally favorable conditions in which the tactic could be expected to be deployed safely and operate as intended,
- Yellow refers to conditions that are marginal where the tactic could be deployed but operations may be compromised or challenged in some way, and
- Red refers to unfavorable conditions in which the tactic would not typically be used due to the impact of environmental conditions on safety or equipment function.

The values used to define the limits are inherently subjective, without consistent metrics used to define "favorable," "marginal," or "not favorable" and extensive field trials to collect data on system performance in different conditions. The three categories are used to acknowledge the fact that response does not suddenly change with a set wind speed or wave height, but will transition gradually.

3. Determine whether each hourly time interval is green, yellow, or red. Each hourly time interval is identified as green, yellow, or red based on the concurrent conditions recorded for that hour. The overall percentage of time during the year or season for which conditions are green, yellow, and red is then calculated.

A simple rule is applied to each hourly time interval (as shown in Table 1), such that: if any condition is red, that hour is red; if all conditions are green, that hour is green; and all other combinations (all yellow, or a mix of yellow and green) are yellow.

Table 1. Establishing green, yellow, and red hourly time intervals.

IF…	THEN THE HOUR IS…
…*any* single environmental factor is ruled RED	RED (not favorable)
…*all* environmental factors are ruled GREEN	GREEN (favorable)
…at least one factor is YELLOW and all others are GREEN or YELLOW (or, all other options)	YELLOW (marginal)

A custom program is used to establish whether each hourly time interval is green, yellow, or red based on the rule described in Table 1. This is further complicated by the fact that some hourly intervals do not have data for all environmental factors. A single red factor is enough to make the whole hour red, regardless of what is known about the rest of the factors, but including these hours when estimating the proportion of time where conditions are red could bias the results towards red since a single green or single yellow condition is not enough to establish that hour as green or yellow (this would require either that all factors are green, or that all are a green or yellow). To address this issue, we first *estimate* the percentage of green, yellow, or red hours for each based on hours with complete data only. This estimate is then checked against the minimum possible percentage of hours of each color, and the maximum possible percentage of hours of each color to determine the best result.

This step was changed based on input from the peer review.[2] Previously, an hour that had all green readings except one yellow would be ruled as green. Any two or more yellow conditions in an hour would establish that hour as red. All hours were thus established as either red or green based on this approach. The rule was changed to that shown in Table 1.

4. Calculate the proportion of hourly time intervals that are green, yellow, or red and present this overall and for each season. The same custom program calculates the proportion of the season or year that is comprised of hourly intervals of each color, which are then presented as the results.

For this study, we use July – October as the "summer" and November – June as "winter." This seasonal breakdown was chosen to reflect the general ice and ice-free seasons and proves more meaningful than the common calendar delineations of the season.

Previously, the rule now replaced by Table 1 meant that the results yielded only red and green hours (though the nuances were shown in annual cycle graphics which depicted the extent of green, yellow, or red readings). The results of the analysis are now presented to show the percentage of time that hourly conditions are green, yellow, or red.

5. Analyze time window sensitivity. The analysis uses hourly time increments for the hindcast of environmental conditions. This provides some granularity regarding the environmental conditions, but a single hour is not enough time for most response activities. Since this is not a scenario-based analysis, we do not have a hypothetical spill "start time" to consider, and so instead calculate the percentage of time that the data contain consecutive hours that are ruled (in Step 3, above) green or yellow for each tactic. This calculation is made up to 24 hours and presented in the results. Where the data are incomplete for an hour, again a process of developing an estimate and comparing it to a maximum or minimum possible result is used.

6. QA/QC outputs. Program operation and data inputs are checked through a quality assurance process. A second analyst verifies that algorithms, limit sets, and other inputs

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[2] As noted, the revised approach also aligns with the EPPR's pending Circumpolar Oil Spill Response Viability Analysis.

used in the program operate correctly. This includes replicating results from the program with a separate analysis conducted for a smaller, randomly generated set of data using a spreadsheet. This was implemented for the original study and re-checked for the revised study.

7. Present results. The results are presented in both graphical and tabular format. For each tactic, an annual cycle graphic is used to combine the five years of data into a single annual cycle from January – December. These figures show the extent to which hourly recordings are yellow or red. (All green hours have only green conditions.) They are provided for individual factors as well to show the relative contribution of red (or yellow, or green) hours based on that factor to the overall results. The time window sensitivity analysis results are presented separately, along with additional summaries.

2.3 Development of Limits

Different response tactics are subjected to different types of impacts from environmental conditions. Tactics appropriate to the geographic area studied must be selected before response limits can be determined for the response gap analysis.

The environmental limits used in this study are based on previous response gap analyses conducted by Nuka Research for Prince William Sound (2006-2008)[3] and the Aleutian Islands (2014).[4] As these previous analyses have *not* included limits based on the presence of sea ice, we developed ice limits based on a review of the relevant literature. Subject matter experts from BSEE, the Alaska Department of Environmental Conservation and U.S. Coast Guard reviewed and commented on the limits before they were finalized.

Within a broader literature search, the following key documents were reviewed to identify ice limits and verify limits for other factors:

1. Technical manuals from Alaska-based oil spill recovery organizations: Alaska Clean Seas (ACS, 2012), Cook Inlet Spill Prevention and Response, Inc. (CISPRI, 2013), and Alyeska's Ship/Escort and Response Vessel System (APSC, 2013)

2. Spill Tactics for Alaska Responders (STAR) Manual (ADEC, 2014)

3. Spill Response Gap Study for the Canadian Beaufort Sea and Canadian Davis Strait (SL Ross, 2011)

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[3] These limits were vetted with the Prince William Sound Regional Citizens' Advisory Council, Prince William Sound shippers, and the U.S. Coast Guard, and are largely based on the realistic maximum response operating limits put forward by the industry operating tank vessels engaged in Trans-Alaska Pipeline System trade. They were used for a 2012 response gap analysis for northern British Columbia as well (Nuka Research, 2012).

[4] These limits were vetted with a group of expert consultants to the project, including Pearson Consulting, LLC; Moran Environmental Recovery; Moran Towing; and The Glosten Associates, Inc. (Nuka Research, 2014).

4. Arctic Council's Emergency Prevention, Preparedness, and Response (EPPR) Field Guide (Owens et al., 1998) and Guide to Oil Spill Response in Snow and Ice Conditions in the Arctic (EPPR, 2015)

5. Other publications as cited, including studies from the Arctic Oil Spill Response Joint Industry Program (JIP)

Quantifying response limits is inherently subjective. Limits are rarely, if ever, documented in field trials or actual spill response, and may vary widely depending on other factors such as operator proficiency. This study focuses on the impact of environmental conditions on the ability to safely deploy a response tactic and have it operate as intended. The limits are not based on oil weathering, which is also influenced by environmental conditions and can have a significant impact on the effectiveness of a response tactic. These and other limitations of the approach are acknowledged and discussed further in Section 2.4.

2.4 Limitations of the Approach

A response gap analysis provides a useful tool for oil spill response planning and advancement, but it does not seek to incorporate all aspects of an oil spill response and has some inherent limits, including:

- **Focuses only on impacts of environmental factors.** A response gap analysis does not guarantee that a response will be deployed and be successful, even when conditions are deemed "favorable" for a given time period in the analysis. This analysis does *not* consider the overall operational picture, including whether or not the necessary equipment is available, the ability to transport that equipment to the site, how long it could be deployed (consecutive hours or days), whether there are sufficient personnel who are qualified to deploy the equipment, whether those personnel have the organization and logistical support they need to launch and sustain operations, or numerous other factors that impact oil spill response operations. The response gap also does not estimate the extent to which a response tactic would be effective, such as on-water recovery rate or in-situ burn efficiency. Some of these additional factors relate to weather conditions and could be examined using the same dataset used in this study; most, however, would require different, though complementary, analyses.

- **Quality and availability of environmental data.** A response gap analysis relies on having environmental data available to build a historic dataset of the relevant environmental conditions at the sites considered. Such data are not always available, necessitating the use of proxy data or assumptions. In some cases, reliable measurement of environmental conditions may not exist at all for a given location. For example, this analysis relies on onshore data as the best indication of some of the offshore conditions when in fact offshore conditions may be different from onshore conditions (see Appendix A).

- **Relies on past environmental data to inform future decisions.** This response gap analysis is based on environmental observations for the prior five years of conditions. Although much longer records are available, five years was selected due to the observed rapid changes in the arctic climate. As observed by Thomson et al. (2013), conditions in the Arctic Ocean and associated seas are changing rapidly. Without citing the diverse organizations and research entities that are investigating arctic climate change, we acknowledge the expectation that arctic warming will continue, with associated changes in sea ice and weather regimes. Among other entities, the U.S. Navy is anticipating this trend in their future plans for the region (U.S. Navy, 2014).

- **Uneven documentation of response limits.** While some response limits are well documented or widely accepted for specific equipment, such as the wave heights used to characterize different types of containment boom (ASTM, 2000), other response system *limits* are not as well studied, even if aspects or components of the system maybe. The response gap analysis approach – and pragmatic spill response planning in general – will benefit from further documentation of environmental limits based on field trials, exercises, or actual responses.

- **Simplified incorporation of response degradation.** The degradation of response does not occur at a single point, nor is it necessarily linear in nature. The use of three tiers of response limits is intended to acknowledge and partially overcome this challenge. More tiers could be used to represent a more nuanced degradation, but pinpointing the values for even three tiers is often difficult as noted in the above discussion on uneven documentation of response limits.

- **Use of one-hour increments.** The response gap analysis incorporates environmental data into hourly increments (data are either reported directly, as from an airport weather station, or, for ice, interpolated based on weekly data). Generally, more than one hour will be needed to implement a response tactic. We consider the time windows for response viability based on consecutive hourly increments of green and yellow. This was added following the peer review.

- **Analysis does not consider oil weathering**. This analysis focuses on the ability to safely deploy response tactics in different conditions in which they could be expected to function generally as intended. It does not consider the effectiveness of the response, which will be impacted by oil weathering among other factors. The weathering of oil in the marine environment will vary depending on the oil, temperature and salinity of the water, and wind and wave conditions, and will have a significant effect on the utility of various response and their effectiveness (Allen, 1988). While we note its importance, including oil weathering in this analysis would require a scenario-based approach that considers both a specific type of oil (as different oils will weather differently) and a "start" time since oil weathering depends on the duration of exposure to, for example, wind and waves in addition to knowing what the wind speed and wave height may be.

3. Environmental Data Sources

This section presents a characterization of environmental data that were used for this analysis. Shore station and offshore buoy wind speed data are characterized independently in this section, and compared in Appendix A.

3.1 Data Considerations

The response gap analysis involves estimating whether a response would be favorable, marginal, or not favorable for each hour of the study period, based on historic environmental data. The best possible data source would be actual observations taken from the location studied at hourly intervals, with no missing observations, and cover the entire time period studied. Unfortunately this is seldom the case, so data from multiple sources, often with missing observations, must be combined to compile a data set. The data sources must be carefully rectified to align the time, location, resolution, and precision.

Aircraft pilots or vessel captains may have recorded their observations regarding conditions on – or above – the water, but these observations typically do not come from a single location nor are they sustained or necessarily consistent. Anecdotal data taken from observers in the offshore environment that specifically aligned with consistent, onshore readings could be very valuable, but we are not aware of such an existing data source and collecting this kind of field data is outside the scope of this project.

At lower latitudes, weather buoys have met many of these criteria for wind, sea state, and air and water temperature readings (though not visibility-related parameters). These buoys often have gaps in their recorded data, but this can be addressed by using multiple years of data and ensuring that the gaps do not always fall at the same time of year. Airports typically provide excellent sources of continuous data, including horizontal visibility and cloud ceiling, but as they are on land, they do not provide sea state or water temperature data, nor do they record data from an actual marine study location.

For this study, we use a combination of airport data, weekly satellite data (for sea ice), and limited buoy data. The lack of continuous sea state data poses the greatest challenge, and this is discussed further in Section 4.2.

3.2 Summary of Data Sources

The data sources used in this study are listed below and shown by their associated location in Figure 2.

- Recorded observations from coastal airports related to wind, air temperature, and visibility (National Weather Service compiled by, and purchased from Weatherspark[5]).

- Offshore buoys in the Chukchi Sea for a few months each in 2010 and 2011, with data sourced via the National Oceanographic Data Center (NODC). [6]

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[5] weatherspark.com

- Sea ice coverage from the National Ice Center,[7] based on weekly interpretations of satellite imagery. Sea ice data were taken for two locations, shown in Figure 2. Locations were chosen with input from BSEE and based on offshore lease activity at the time.

- Daylight/darkness (civil twilight) tables from the U.S. Naval Observatory for the same two locations as the sea ice data.

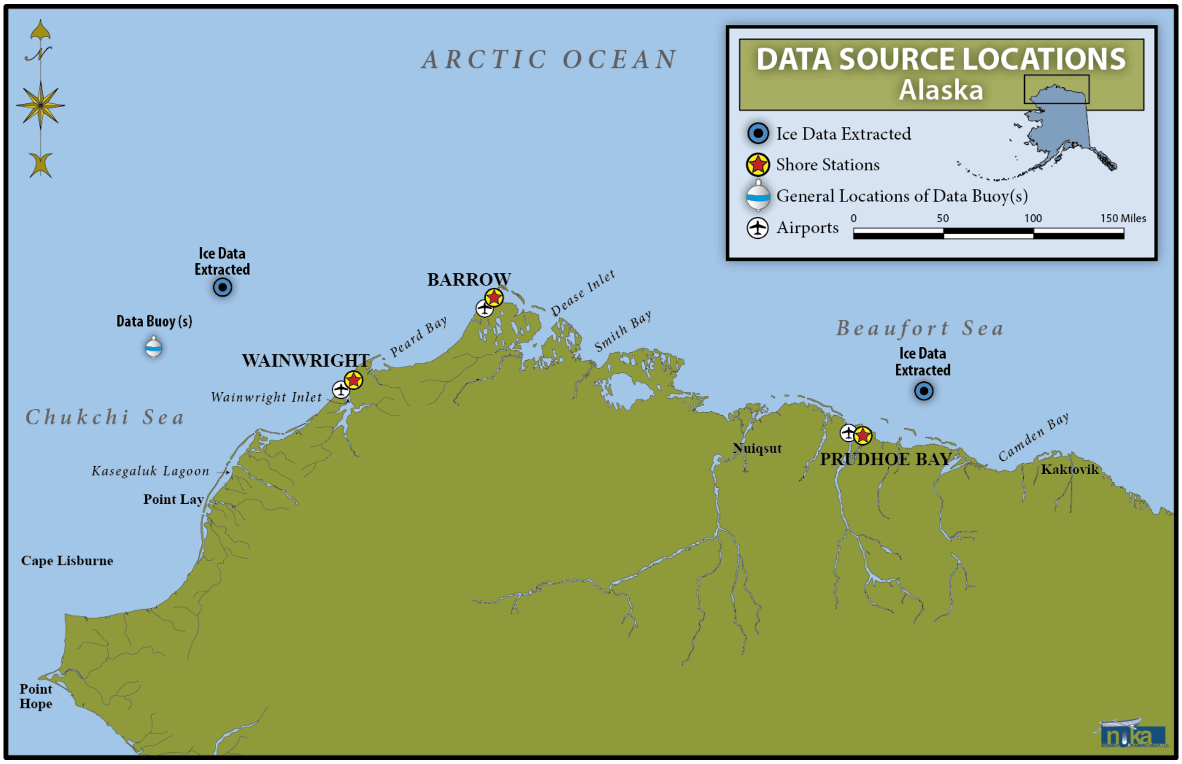

Figure 2. Coastal and offshore data source locations in Chukchi and Beaufort Seas (exact buoy location could not be determined, nor whether the 2010 and 2011 buoys were in the exact same location).

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[6] See: http://www.nodc.noaa.gov/cgi-bin/OAS/prd/accession/download/0093399

[7] natice.noaa.gov

3.3 Onshore Wind, Air Temperature, and Visibility Data

Onshore data were collected from airports in Wainwright, Barrow, and Prudhoe Bay for January 1, 2008 - December 31, 2012.[8] Data on the following parameters were collected: wind speed and gusts, air temperature, cloud ceiling, and horizontal visibility (see details in Table 2). Shore station datasets are very complete and consistent throughout the five-year study period (Table 3).

Table 2. Summary of data measurements used for wind, visibility, and air temperature (based on weatherspark.com).

PARAMETER	METRIC USED
WIND	
WIND DIRECTION	Direction wind comes from based on true compass bearing (nearest 10 degrees)
WIND SPEED	Average wind speed (knots) (averaged over a 2-minute period)
GUSTS / MAXIMUM WIND SPEED	Peak wind speed (knots) during a 2-minute period
VISIBILITY	
HORIZONTAL VISIBILITY	Maximum distance at which a given reference point or light can be clearly discerned, measured in kilometers (km) (Converted to feet)
CEILING	Measured in meters above ground level (AGL) (converted to feet)
DAYLIGHT	Total hours of daylight/darkness
TEMPERATURE	
AIR TEMPERATURE	Temperature measured (Celsius) at time of recording (Converted to Farenheit)

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[8] Nuka Research applied an internal quality control procedure to airport data purchased from Weatherspark. This consisted of examining and deleting anomalous values, deleting duplicate entries, and examining data statistics.

Table 3. Shore station data completeness, 2008-2012.

PARAMETER	WAINWRIGHT	PRUDHOE BAY	BARROW
Sustained Wind Speed	97%	100%	100%
Gusts	97%	100%	100%
Air Temperature	96%	100%	100%
Horizontal Visibility	97%	100%	100%
Cloud Ceiling	96%	100%	100%
Wind Direction	93%	95%	97%

3.3 Limited Buoy Data

Nuka Research identified offshore data, including wind, air temperature, sea state, and water temperature, collected from buoys operated by ConocoPhillips, Statoil and Shell, with the data sourced via the National Oceanographic Data Center.[9] Buoy data are available for a total of 128 days during the summers of 2010 and 2011 (Table 4). The location and records from 2010 and 2011 are similar. The usefulness of these data is limited by the short time periods for which data are collected and by limited documentation, but they represent the only consistent, if not continuous, source of offshore data. (Vessel observations would be expected to be even more sporadic and qualitative in nature.)

Buoy data are fairly complete for the applicable coverage periods, but the coverage periods vary between the two data years. See Appendix B.

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[9] Data from buoys placed by Shell Arctic in Camden Bay and Harrison Bay from August through October in 2011-2013 became available late in the development of this analysis. The buoys were in place for roughly five months each. The buoy in Harrison Bay collected wind and temperature data; the buoy in Camden Bay collected wind, temperature, and sea state data. New datasets were reviewed to determine whether these buoys would provide information that would significantly change the results of the analysis. Overall, the differences between this additional buoy data and onshore data were similar to the differences between the buoy data already included and the onshore data. In both cases, the marine influence that would be expected is evident: air temperatures are less extreme than onshore.

Table 4. Offshore meteorological and oceanographic data sources.

DATA STATION	SOURCE	LOCATION	DATA TYPE	PERIOD
Conoco Philips / Statoil Buoy 101	NODC	Latitude 70.87 N Longitude 165.24 W, Roughly 70 nm offshore	Hourly wind, sea state, and air temperature	July 27 to September 18, 2010
Joint MetBuoy MOB2	NODC			August 2 to October 7, 2011
Shell 2011 Chukchi Observations	Shell, 2011	Undefined Chukchi Sea Shell lease locations, 52 nm or more offshore	Monthly wind statistics	June through November, 1980, 1982, 1983

2.4 Sea Ice Interpretation

Finally, data on sea ice coverage were drawn from the National Ice Center, as summarized in Table 5. Ice data are extracted for specific locations in the Chukchi and Beaufort Seas from National Ice Center weekly[10] ice concentration maps using GIS software. Nuka Research examined both daily and weekly ice maps for this study, and selected weekly ice maps because they identified ice concentration, while daily ice maps indicated only the presence or absence of ice. Estimates of daily ice concentrations were extrapolated from the weekly data, assuming a linear transition between the data points for each week. While data were extracted for two individual locations, the maps present ice coverage over a broader area – we simply record the percentage of ice coverage identified for the study locations.[11]

Table 5. Summary of continuous data sources used for sea ice.

PARAMETER	METRIC USED	DATA SOURCE
Ice Coverage	Ice concentrations correspond to the fraction of water surface area covered by ice. General groupings are No Ice/Open Water, < 10%, and increments of 10% up to total ice coverage. Ice is frequently classified in 30% ranges (such as 40% to 70% coverage concentration).	National Ice Center (www.natice.noaa.gov)

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[10] During shoulder months, ice concentration maps are sometimes produced more frequently than once per week. All available data were used.

[11] This study focuses on the feasibility of deploying a tactic at a given location (or locations), and does not include a scenario approach.

4. Characterization of Environmental Data

This section characterizes the data compiled for wind, air temperature, water temperature, visibility, and sea ice. Data are characterized based on the time periods for which they are available. For shore stations, the data are year-round while for buoys, the data are available for 128 days across two years, during a late summer/early fall time period. See Appendix B for more detailed buoy data and Appendix C for more detailed shore station data.

4.1 Wind

Wind data from airport stations are presented for wind speed and wind direction. Figure 3 shows the wind speeds for the three airport shore stations at Wainwright, Barrow, and Prudhoe Bay. Table 6 summarizes the combined buoy data, which are spread across varied and partial months. Figure 4 presents the distribution of wind speed and direction using wind roses, both for the shore station sites and the limited offshore buoy data in the Chukchi Sea (summer only).

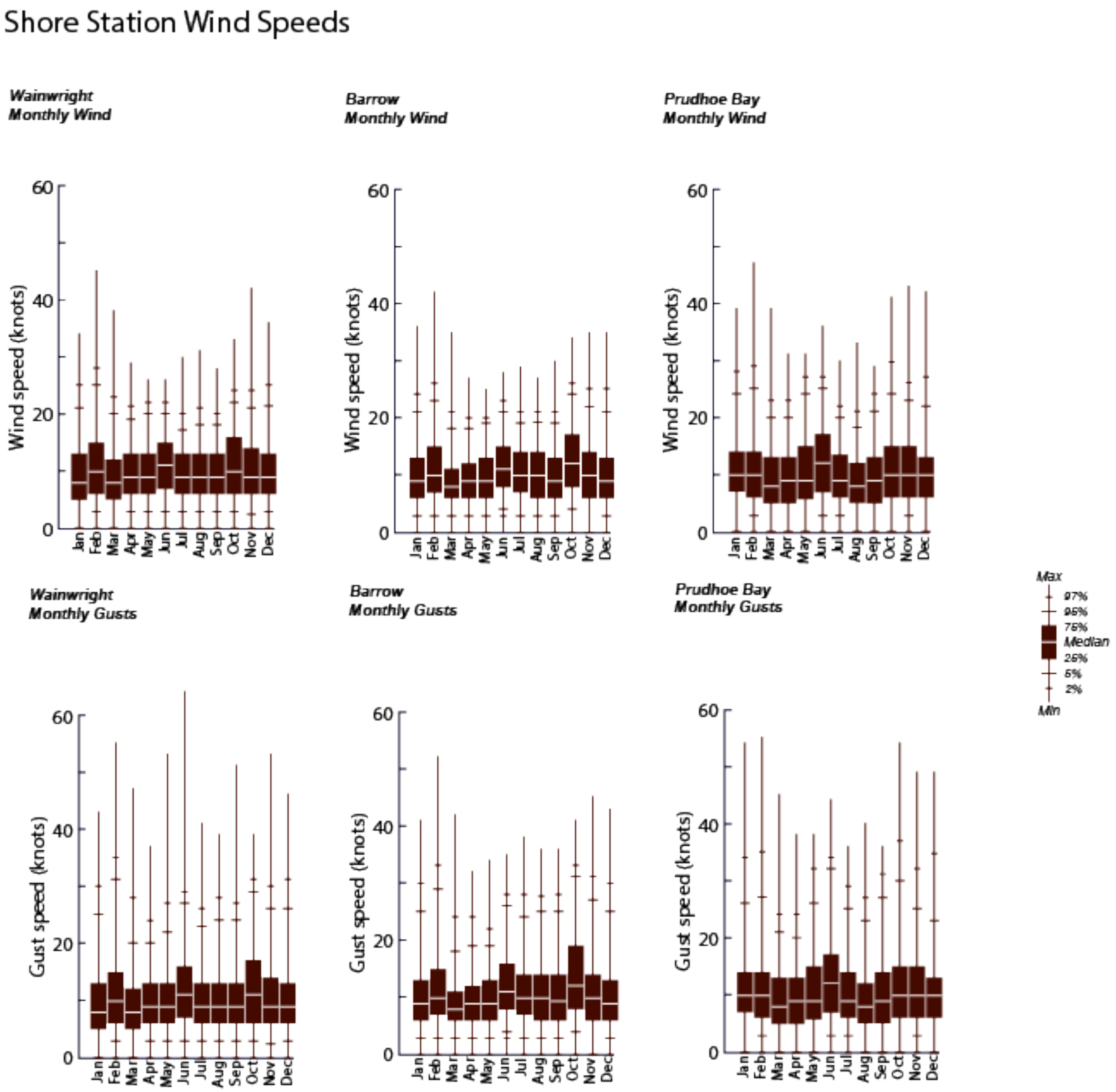
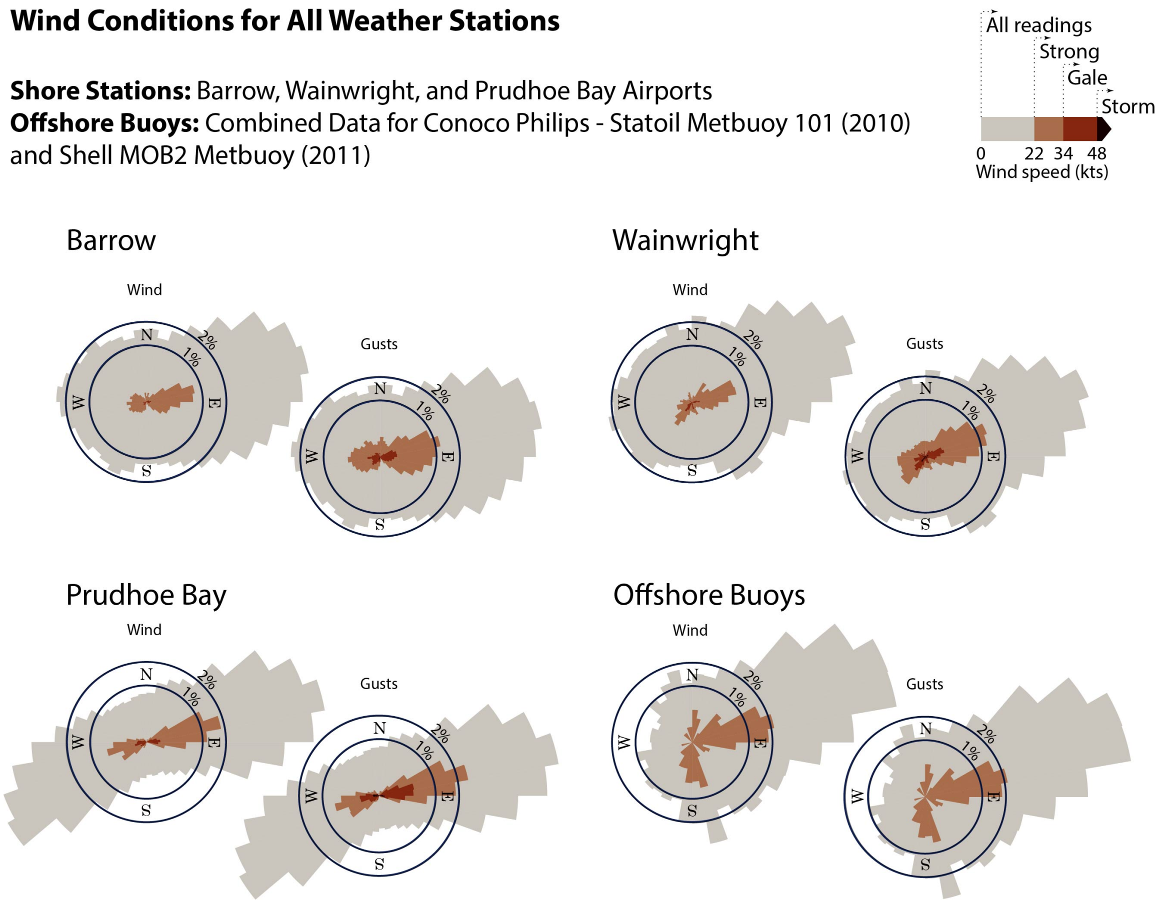


Figure 3. Box-whisker plots of sustained wind speed and gust speed recorded at Wainwright, Barrow, and Prudhoe Bay, 2008 – 2012.

Table 6. Buoy data – summary of wind speed recordings (July 27 – September 18, 2010 and August 2 – October 7, 2011).

	MINIMUM	5th PERCENTILE	AVERAGE	95th PERCENTILE	MAXIMUM
Sustained Wind Speed (knots)	0.0	4.2	13.1	23.4	28.4



Wind Conditions for All Weather Stations

Shore Stations: Barrow, Wainwright, and Prudhoe Bay Airports
Offshore Buoys: Combined Data for Conoco Philips - Statoil Metbuoy 101 (2010) and Shell MOB2 Metbuoy (2011)

Figure 4. Wind roses for all shore stations (2008-2012) and offshore buoys (available 2010 and 2011 data).

4.2 Sea State

There are no continuous offshore sea state records available for the Chukchi and Beaufort Seas. Offshore conditions, including wave height, are estimated from onshore observations, given the lack of continuous data records offshore. The accuracy of this approach is assessed by comparing our approach to the limited offshore data that is available. This section describes the approach used to estimate sea state for the offshore locations that are the focus of this study using onshore wind data.

4.2.1 Efforts to Identify Sea State Data

Nuka Research worked with BSEE to identify potential sea state data sources.[12] The following sources were consulted:

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[12] Environment Canada has developed a wind-wave reanalysis for the Canadian Beaufort Sea, though data are available for Canadian waters only. Information is available at:

- National Ice Center, U.S. Navy/National Oceanic and Atmospheric Administration/U.S. Coast Guard
- Data Accession Program, National Oceanographic Data Center
- Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army
- Dr. Martin Jeffries, University of Alaska at Fairbanks/Office of Naval Research
- Arctic Environmental Response Management Application (ERMA), NOAA
- Alaska Ocean Observing System (AOOS)
- Dr. Oceana Francis, University of Hawaii
- Dr. Jim Thomson, University of Washington[13]
- W. Erick Rogers, Naval Research Laboratory

Sea state models cannot be readily imported from other areas, due to the unique basin geometry and bathymetry, meteorology, and dynamic ice conditions of the Arctic Ocean. Although the Army Corps of Engineer's Wave Information Stations include wave-model outputs for the Chukchi Sea, Nuka Research did not use these outputs, since they are not yet well-validated for the arctic environment. At the the time of the original project, the Corps was seeking validation of its Chukchi Sea models, and it may be that in the future the Wave Information Studies would provide reliable data for quantitative analyses (Dr. Oceana Francis, personal communication).[14]

4.2.2 Using Onshore Winds for Offshore Sea State

Without sustained sea state data (either actual or modeled), we used onshore wind data to generate our best estimate of offshore waves. Figure 5 shows offshore waves from the limited buoy data during the summers of 2010 and 2011 and onshore winds from Wainwright for each hourly observation during the same time period. It also shows the Beaufort Scale, a widely recognized framework for understanding the relationship between wind and waves in the marine environment, and the median wave height by wind speed.

The median wave heights from the buoys were identified for each onshore wind speed recording and used estimate sea state in our response gap analysis. Section 10 describes the extent to which this may have affected the results of the analysis. Because of this approach, and unlike previous response gap analyses, the limit sets estimate sea state using wind (and ice limits, due to the assumed dampening effect of sea ice on waves beginning at 33% coverage). For example, in mechanical recovery conditions transition from green to yellow at 20 knot winds or 3 foot seas. We estimate 3-foot seas to occur when winds exceed 8 knots at the wind gage in Wainwright. So the 20-knot wind limit becomes irrelevant – conditions transition from green to yellow at 8 knot winds because of the associated sea

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http://www.oceanweather.net/MSC50WaveAtlas/. These data were used in SL Ross, 2011. A similar approach could be applied to U.S. waters, though such an effort is outside the scope of this study.

[13] Dr. Jim Thomson provided upward-looking sonar data, but it was determined to be too far offshore (~ 300 miles) to be comparable the focus areas. Proprietary nearshore radar data were identified for some locations in the Beaufort Sea, but were not available. As these data were in the nearshore area, they were determined not to be relevant.

[14] Nuka Research became aware of a hindcast dataset based on onshore winds developed by BOEM, but not during the timeframe of the analysis.

state. This technique made irrelevant the use of separate wind limits because the estimated sea state – expressed in terms of wind – was always lower than wind limits alone would have been. It is important to note that these limits should not therefore be translated to other parts of Alaska or beyond, especially in places where continuous sea state records are available.

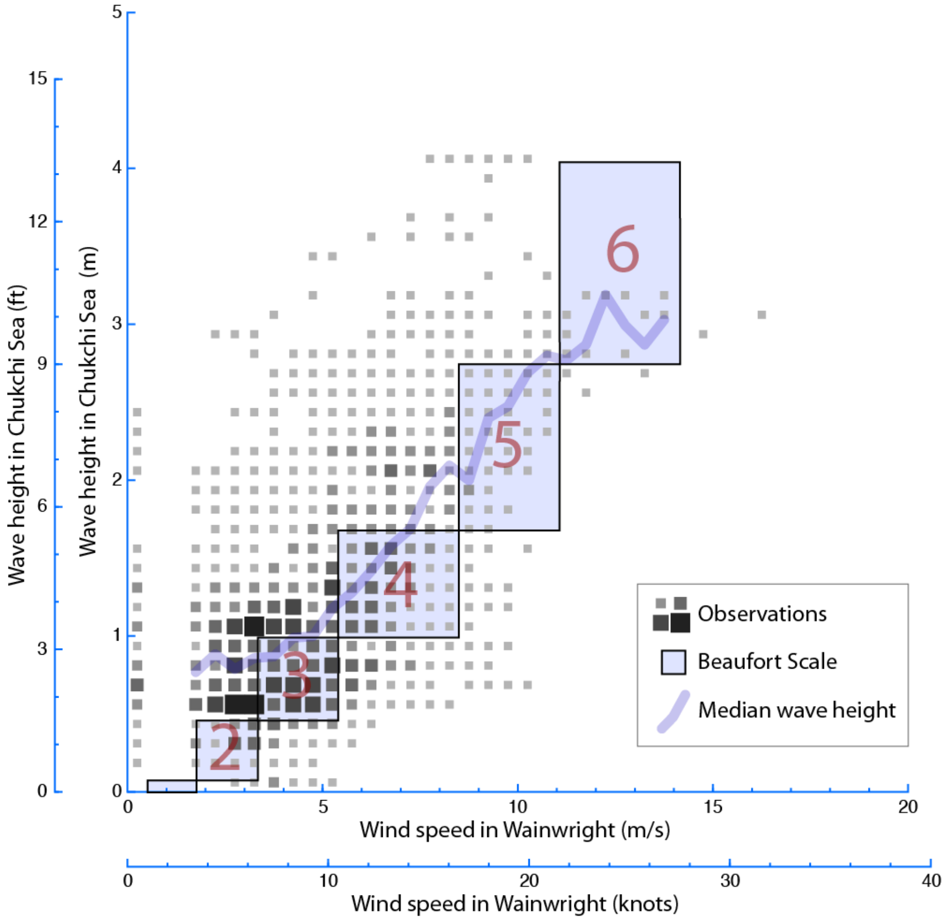


Figure 5. Comparison of wind speeds at Wainwright and offshore waves in the Chukchi Sea for times when both data points are available. Also shows Beaufort Scale and median wave height by wind speed.

4.3 Air Temperature

As shown in Figure 6, all three stations are characterized by cool temperatures in summer (up to a maximum of 70° to 80° F, but more typically 30° to 50° F) and very cold conditions in the winter, typically below 0 degrees Fahrenheit, with occasional conditions of extreme cold (in the range of -50° F). Temperatures recorded at buoys are shown in Table 7.

Air Temperatures, by Month, 2008-2012

Buoy temperatures are not summarized by month due to short and irregular coverage

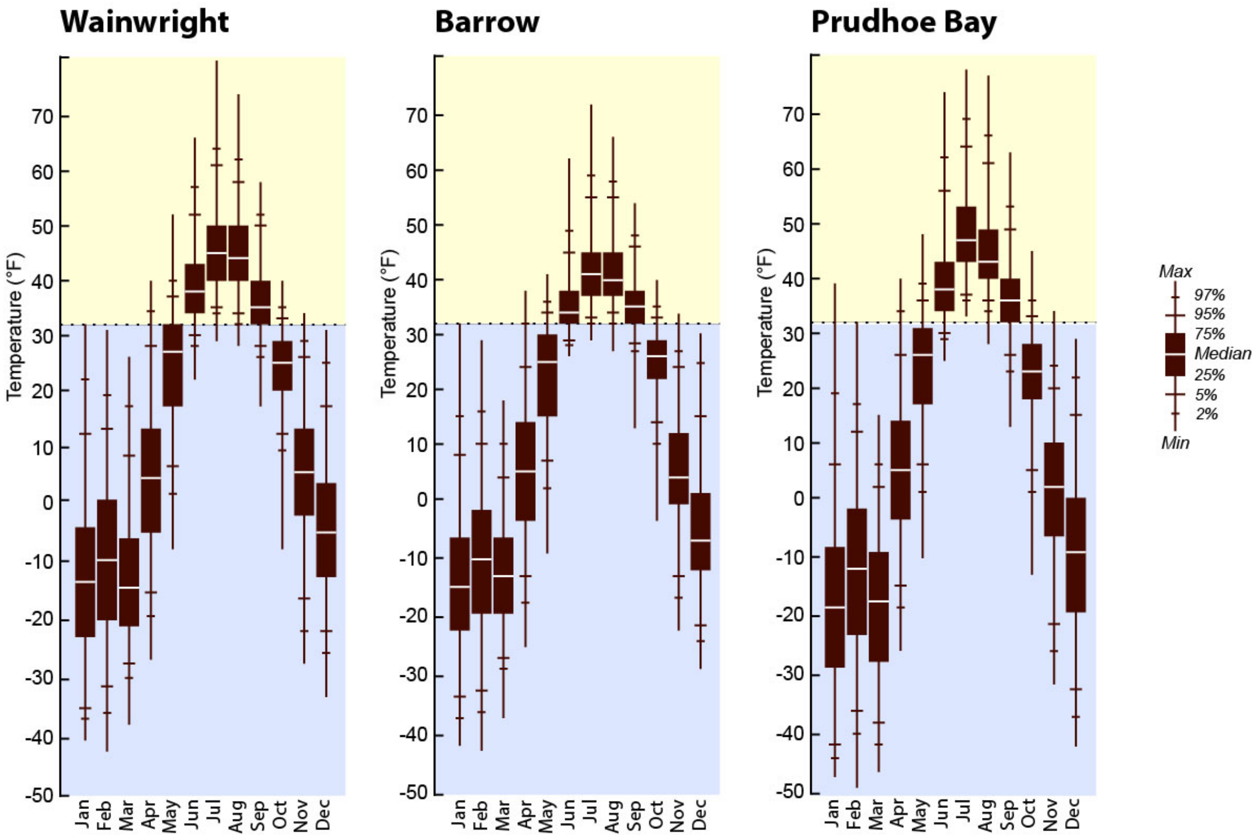


Figure 6. Monthly temperatures at shore stations, including median, maximum, and minimum.

Table 7. Buoy data – summary of air temperature recordings (July 27 – September 18, 2010 and August 2 – October 7, 2011).

	MINIMUM	5th PERCENTILE	AVERAGE	95th PERCENTILE	MAXIMUM
Air Temperature (Fahrenheit)	30.2	33.6	41.7	48.0	55.2

4.4 Visibility

Visibility is measured using three different metrics: horizontal visibility, cloud ceiling, and daylight/darkness (based on civil twilight). Visibility is recorded at the airport stations based on the number of statute miles of horizontal visibility and the height of the cloud ceiling. Aside from weather conditions, the area experiences large seasonal variations in daylight, which will affect operations. See Appendix C for summary tables of the visibility data for each airport location and further discussion of some of the unique challenges related to these measurements.

4.4.1 Horizontal Visibility

As Figure 7 presents the horizontal visibility as recorded at Wainwright, Barrow, and Prudhoe Bay for each month, based on 2008-2012 data. Horizontal visibility is the maximum horizontal distance at which a given reference object or light can be clearly seen, before atmospheric conditions obscure it. Horizontal visibility varies among the three airports and throughout the year.

Federal Aviation Administration (FAA) flight rules require three statute miles of visibility during darkness and one statute mile during daylight for visual flight below 1,200 feet, except in special circumstances (14 CFR 91.155).

Visibility at the airports may be different than visibility on the water, due to variations across distance and the inherent differences in the air/water interface versus the air/land interface. In general, the land mass will heat and cool faster than the water mass and this effects the relationship between dew point and air temperature and thus the formation of fog. Conditions that permit flight from airports may still preclude effective search, rescue, or surveillance of spilled oil on the water.

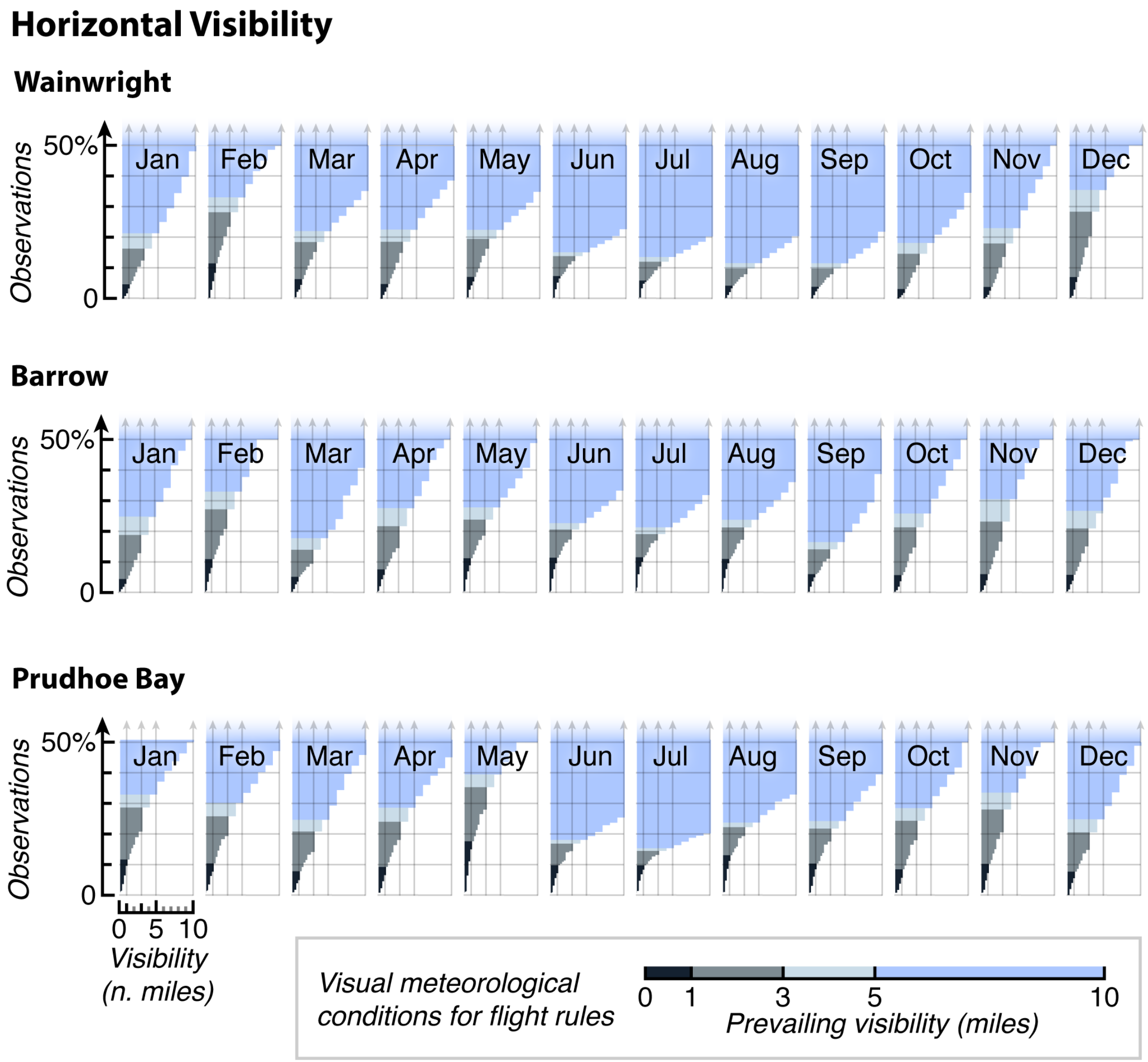
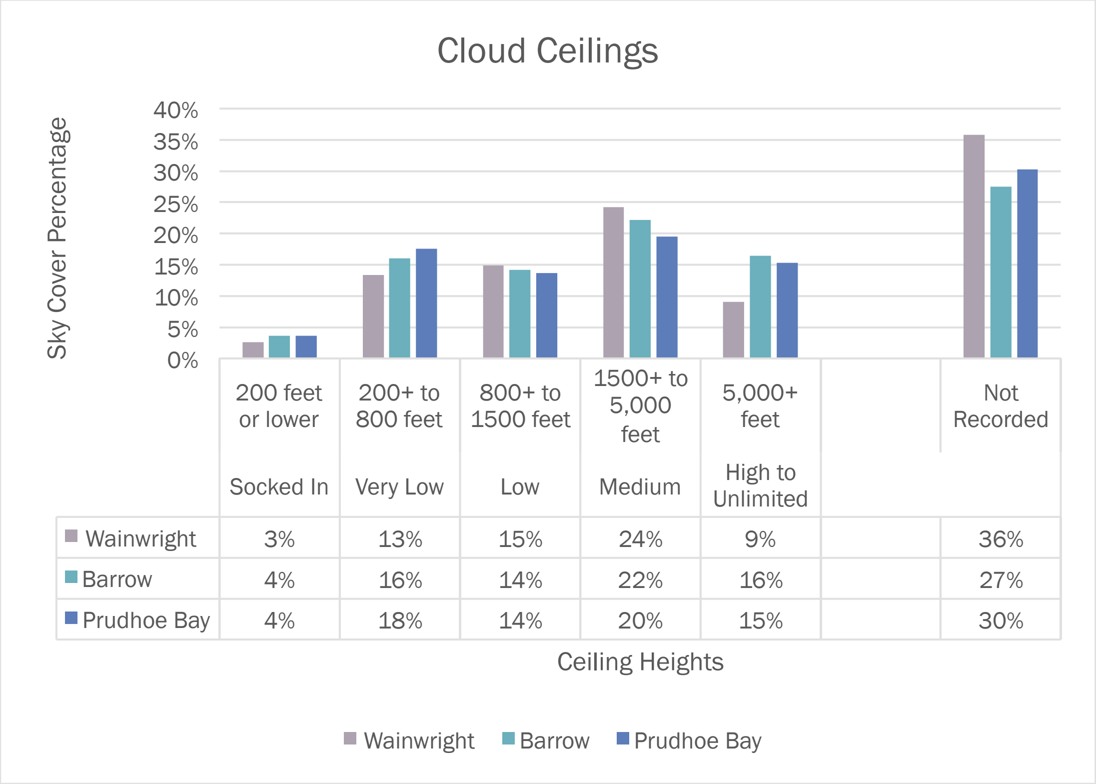


Figure 7. Prevailing horizontal visibility as recorded at Wainwright, Barrow, and Prudhoe Bay for each month, based on 2008-2012 data.

4.4.2 Cloud Ceiling

Airport stations record the observed ceiling (height of cloud cover above ground level). At all three airport stations, data suggests that medium-height ceilings (1,500 to 5,000 feet) are the most common condition encountered, with socked-in conditions being relatively rare. In Figure 8, the slight preponderance of medium-height ceilings is highlighted. Descriptors like "low" and "medium" ceiling heights are subjective. We define 800 feet as very low. Less than 200 feet was selected as suggestive of very low visibility or "socked in" conditions, on the basis that measurement of very low ceilings may become unreliable.



	200 feet or lower Socked In	200+ to 800 feet Very Low	800+ to 1500 feet Low	1500+ to 5,000 feet Medium	5,000+ feet High to Unlimited		Not Recorded
Wainwright	3%	13%	15%	24%	9%		36%
Barrow	4%	16%	14%	22%	16%		27%
Prudhoe Bay	4%	18%	14%	20%	15%		30%

Figure 8. Cloud ceiling heights at Wainwright, Barrow, and Prudhoe Bay, based on 2008-2012 data.

4.4.3 Daylight

Daylight in the study area varies dramatically throughout the year, with 2-3 month periods of continuous daylight in the summer and continuous darkness in winter, bracketed by shoulder periods of respectively very long days and short nights during summer, and very long nights with short days in winter. (See Table 8.) The metric used for the response gap analysis is the length of visible light in hours as defined by civil twilight. Civil twilight is the length of time between when the sun is 6° below the horizon before sunrise until it is 6° below the horizon after sunset. This metric is also used by the FAA as the boundary between daylight and night operations for aircraft.

Table 8. Approximate number of days of 24-hour darkness and 24-hour light[15]

LOCATION	DAYS OF 24-hour LIGHT	DAYS OF 24-hour DARKNESS
Wainwright	75 days (May 14 to July 28)	57 (November 22 to January 18)
Barrow	83 days (May 11 to August 1)	64 (November 19 to January 21)
Prudhoe Bay	74 days (May 16 to July 28)	55 (November 24 to January 17)

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[15] Naval Observatory, 2014. Slight variations occur year-to-year. Based on civil twilight.

4.5 Water Temperature

Shore stations do not measure water temperature; Table 9 presents the water temperature recordings from the limited offshore buoy datasets.

Table 9. Buoy data – summary of water temperature recordings (July 27 – September 18, 2010 and August 2 – October 7, 2011).

	Number of Days	Average Temperature	Median Temperature	Minimum Temperature	Maximum Temperature	
KEY STATISTICS						
JULY	5	45.0	44.4	41.7	49.4	
AUGUST	60	43.7	44.2	36.2	47.3	
SEPTEMBER	48	44.4	44.6	39.0	48.7	
OCTOBER	7	39.6	39.6	38.8	41.0	
OVERALL*	128	43.8	44.2	36.2	49.4	
PERCENTILES						
	2nd	5th	25th	75th	95th	98th
JULY	43.1	43.4	44.0	45.9	47.6	48.2
AUGUST	38.5	39.6	41.9	45.3	46.8	47.0
SEPTEMBER	39.6	40.1	42.6	46.2	48.0	48.4
OCTOBER	39.0	39.0	39.6	39.7	39.9	41.0
OVERALL*	39.2	39.6	42.0	45.9	47.1	48.2

Overall statistics and percentiles are compiled from combined data.

4.6 Sea Ice Coverage

Ice conditions are determined using National Ice Center ice maps (see Figure 9 and Appendix D). Ice coverage data are observed in tenths (10%) and extracted from these maps for the study locations. These data are thus independent of the meteorological stations (shore stations and buoys).

Ice concentrations as presented in the dataset are predominantly ice-free or pack ice conditions. Mixed ice conditions are concentrated during short periods during autumn and fall. For instance, in the Chukchi Sea (Figure 10; Beaufort Sea in Figure 11), only 6% of the weeks in the 5-year sample period exhibited ice concentrations other than ice-free or pack ice. The data suggest relatively brief transitional periods. However, anecdotal observations indicate that the overall ice pattern for the area is not typically one of static freeze-up and thaw within the area, but of the advance and retreat of previously formed ice masses. This causes relatively rapid changes in ice conditions, which may be accompanied by infrequent transitional conditions either along pack ice margins or as ice forms or melts within the area. Ice concentrations are not necessarily uniform over a broad area, or over a day or even hours.

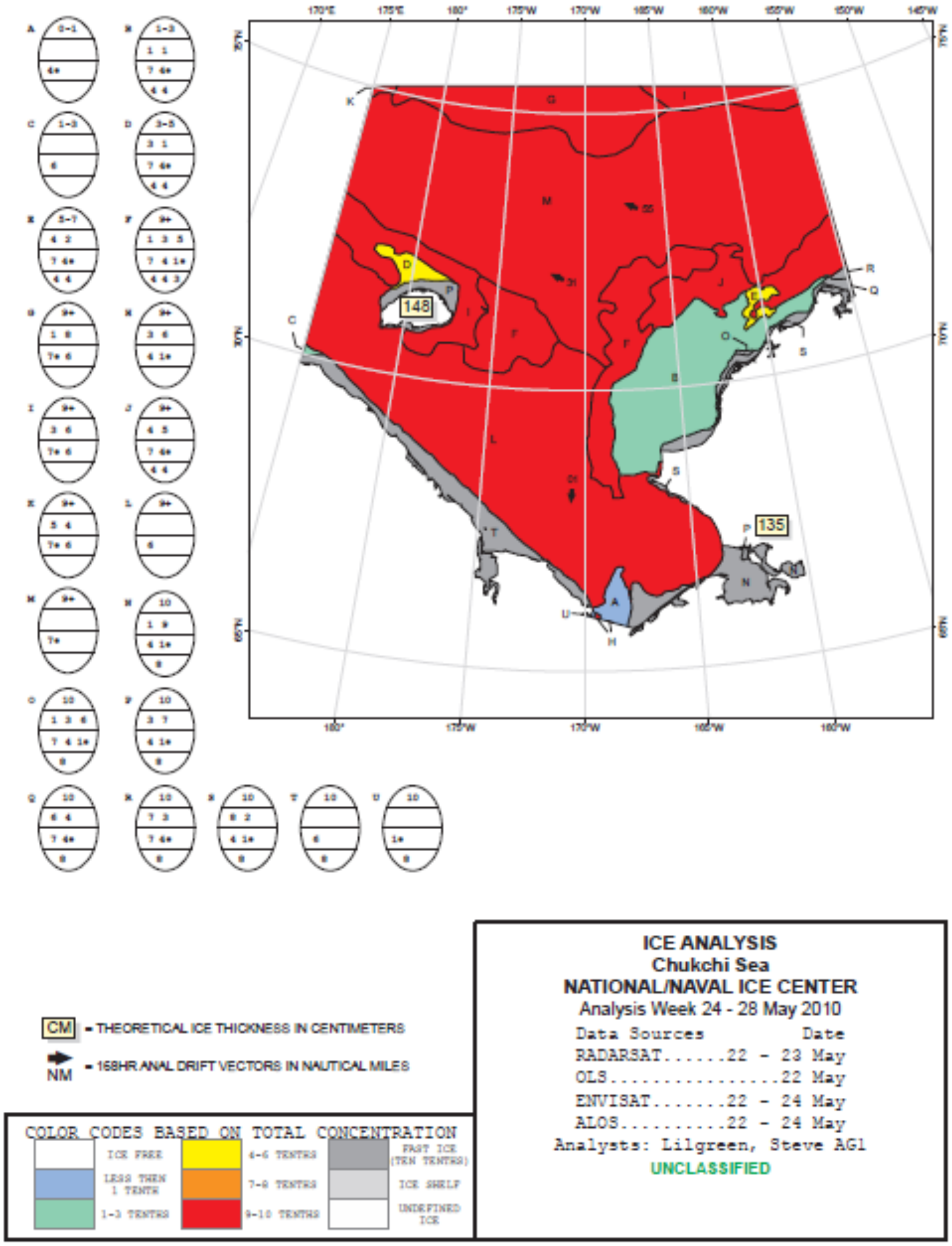


Figure 9. Example weekly ice concentration map, reproduced from the National Ice Center.

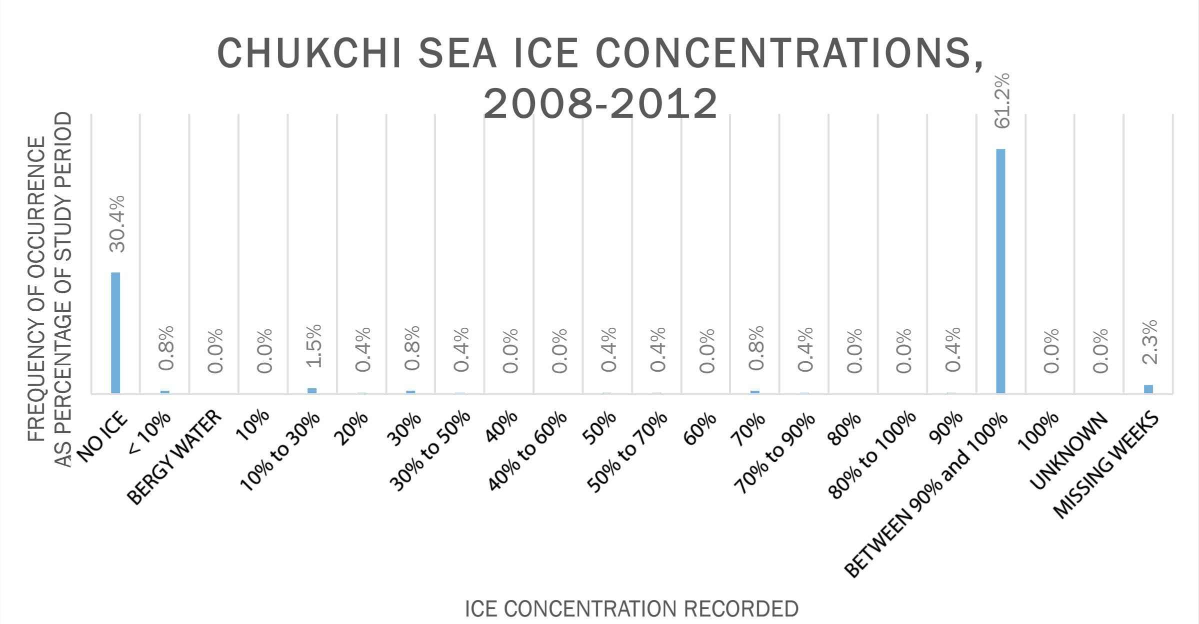


Figure 10. Annual distribution of sea ice concentrations based on 2008-2012 data for the Chukchi Sea location.

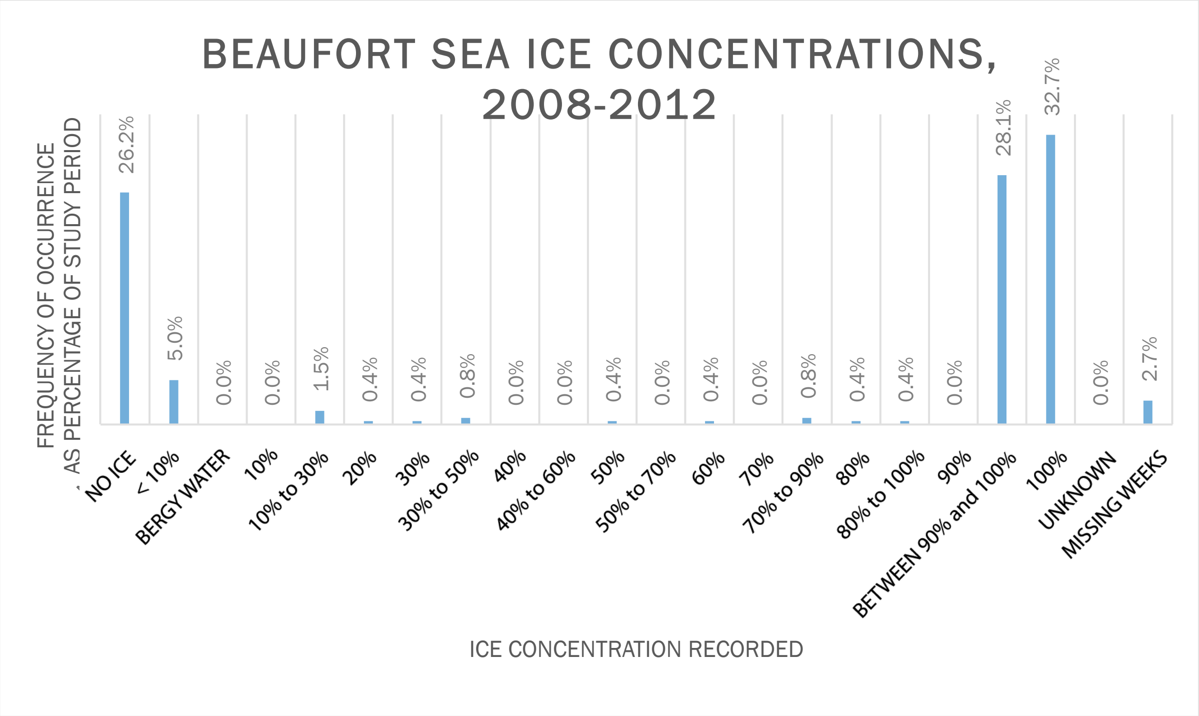
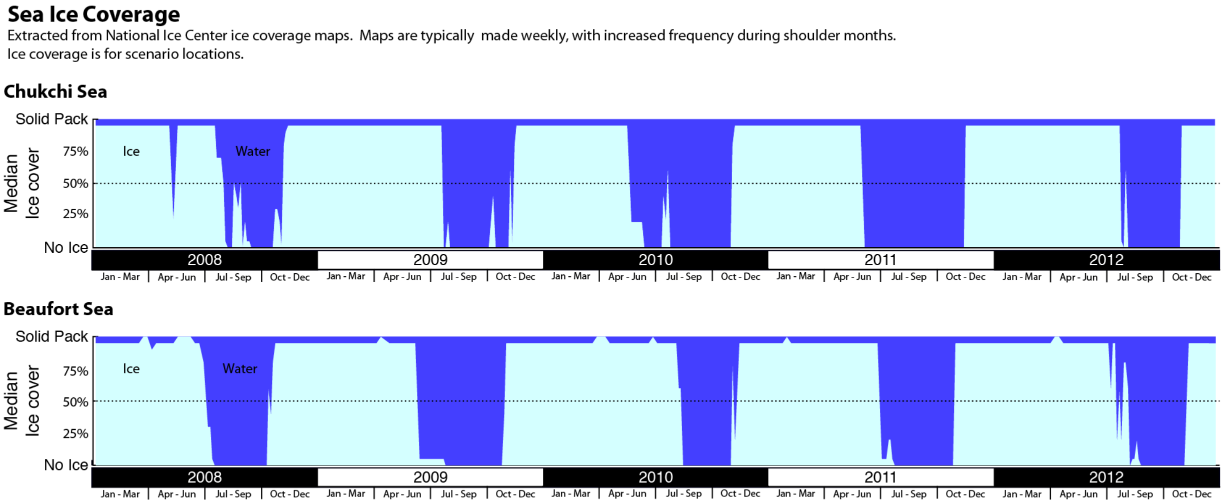


Figure 11. Annual distribution of sea ice concentrations based on 2008-2012 data for the Beaufort Sea location.

Figure 12 highlights the extreme annual changes between ice-free and full pack ice conditions. The relatively small periods of time through the annual cycle when ice coverage is between zero and 100% are clearly visible.



Sea Ice Coverage

Extracted from National Ice Center ice coverage maps. Maps are typically made weekly, with increased frequency during shoulder months.
Ice coverage is for scenario locations.

Figure 12. Median sea ice coverage as extracted from sea ice maps for the Chukchi and Beaufort Seas, 2008-2012.

4.7 Icing and Wind Chill

In the case of vessel icing and wind chill, the appropriate raw inputs described above were used to combine wind speed, water temperature, and air temperature (in the case of icing), and wind speed and air temperature (in the case of wind chill). The algorithms used for icing (Overland, 1990) and wind chill (NWS, 2001) are in Appendix E. Icing rates resulting from the use of the algorithm were identified as none, light, moderate, heavy, or extreme (based on Overland, 1990).

Aircraft are also affected by icing, but data on the air temperature aloft were not available and so aircraft icing was not included in this analysis.

5. Open-water Mechanical Recovery

This section describes the open-water mechanical recovery tactic, limits identified for that tactic, and the corresponding results of the response gap analysis.

5.1 Overview of Tactic

The objective of open-water mechanical recovery of floating oil is to contain and recover spilled oil, thus minimizing impact to the environment. This approach relies on the use of containment boom and skimming devices deployed from vessels or barges to recover oil and water, which is then stored until it can be processed as appropriate. There are multiple variations on the way that boom can be deployed. For open-water recovery, boom is typically moved through the water by a vessel to capture oil and concentrate it at a skimming device. The American Society for Testing and Materials (ASTM) and the U.S. Coast Guard define open-water conditions as those characterized by waves up to 6 feet (USCG, 2013; ASTM, 2000).

Mechanical recovery system components (vessels, boom, and skimmers) for open water operations should be able to deploy and operate in seas up to 6 feet and in winds up to 30 knots. Vessels deploying, towing, and tending the boom should be able to safely transit seas exceeding the boom's operating limitation. Open water free-oil recovery systems are usually based on large vessels with high volume skimmers and large primary storage devices, such as barges. In many cases, the components of these systems are dedicated to oil spill response. Open-water systems are usually deep draft, operating at depths of greater than 6 feet (ADEC, 2014).

Figure 13 shows one type of booming/skimming configuration from the STAR Manual; other configurations are possible (ADEC, 2014).

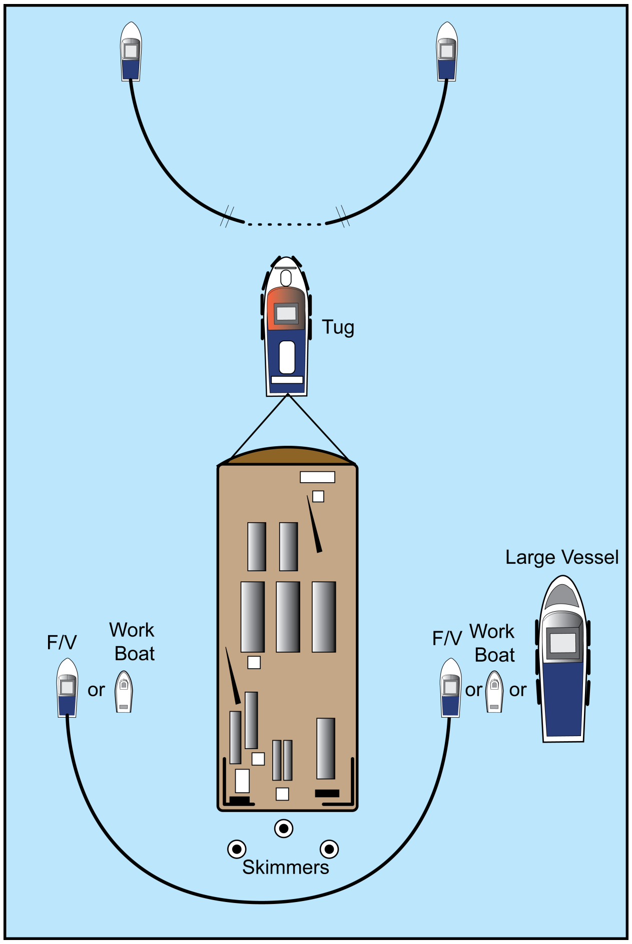


Figure 13. Example of U-booming formation with skimming systems and associated storage (ADEC, 2014).

Mechanical Recovery in the Arctic

Mechanical recovery in broken ice may be difficult to deploy and operate because of ice interfering with the boom and skimming system (Robertson and DeCola, 2000). Free-oil recovery systems deployed in broken ice should be highly maneuverable, utilizing vessels that can safely operate in ice. Sometimes, ice leads can act to contain and concentrate oil so that a marine recovery system can be used for collection without a containment boom. Skimming system viability is generally reduced in broken ice (Nuka Research, 2007b; ADEC, 2014). ACS also describes the deployment of a skimming device from crane on a barge in broken ice conditions (Tactic R-31; ACS 2012). There is no data on the limits associated with these ice lead tactics, however, so they are not being evaluated in this study.

ACS tactics R-15 to R-20 describe different configurations of boom and skimmers deployed from one or more vessels. While in most cases boom will be moved through the water, if the conditions permit and there is a current, it may also be anchored in a position to collect oil moving towards it. In the open-water, skimmers may be deployed from barges which can also support storage of recovered oil.

Equipment for Mechanical Recovery

Equipment needs vary depending on the size and geographic spread of the spill and the specific booming/skimming configurations deployed. While the components may vary, the general equipment needs for open-water mechanical recovery are summarized in Table 10.

Table 10. Example equipment for open-water mechanical recovery.

RESOURCE	COMMENTS
VESSELS – BOOM TOWING	Tow boom to concentrate oil. Must be capable of safely maneuvering in operating environment and conditions.
VESSELS – SKIMMING	Platform for skimming and possibly storage. Must be capable of safely maneuvering in operating environment and conditions. Barge may also be used to deploy skimming system(s).
OIL BOOM (> 42" HEIGHT)	Used to concentrate oil. Depends on configuration and oil concentration.
SKIMMING SYSTEM(S), OPEN WATER	Used to recover concentrated oil. Depends on oil type and weathering, as well as operating environment.
ENHANCED RECOVERY DEVICE(S)	Used to concentrate and recover oil. May speed oil recovery. Depends on oil type and weathering, as well as operating environment.
PRIMARY STORAGE DEVICE(S)	Typically large barge(s) or bladders used to store recovered fluids.

5.2 Response Limits

Mechanical response equipment is subject to challenges posed by winds, sea state, visibility, and sea ice. There is currently no specialized equipment for mechanical recovery that would change the application of these limits (other than ice) in the Arctic Ocean context, though it is possible to use ice deflection or management methods to try to minimize the impact of sea ice.

Wind: Winds greater than 20 knots (Owens et al., 1998) will degrade the effectiveness of open-water recovery systems due to their impact on both containment (boom) and recovery (skimmers). At 30-40 knots these systems will typically become ineffective (ADEC, 2014; CISPRI, 2013; RPG, 2012; SL Ross, 2011). Degradation could also begin as low as around 6-8 knots (Fingas, 2004) or 10 knots (Allen, 1988). These cut-offs were used to establish limits for the Prince William Sound and Aleutian Islands studies.[16] *Wind limits applied in the quantitative analysis were based on the modeling of sea state, as discussed in Section 4.2.2.*

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[16] Additionally, a small craft advisory is issued in Alaska for sustained winds or frequent gusts of 23 – 33 knots (NWS, 2006).

Sea State: Containment using boom is typically compromised starting at a wave height of 3 feet (Allen, 1988; Fingas, 2004; ACS, 2012; RPG, 2012; USCG, 2013; CISPRI, 2013; RPG, 2012; EPPR, 2015). Both ASTM and the U.S. Coast Guard classify or rate boom based on the sea state in which it is capable of operating, and both use a maximum of 6-foot waves (ASTM, 2000, USCG, 2013). This was incorporated into the wind limit, as discussed in Section 4.2.2. It is assumed that the associated vessels can transit safely in seas up to 6 feet.

Temperature: Cold air can compromise open-water recovery in two significant ways related to safety: 1) it can be unsafe for responders or require frequent crew rotations for warming, and 2) it can cause structural icing conditions that can affect vessel stability. ACS uses a wind chill of – 35° F as an operating limit based on personnel safety (ACS, 2012). However, icing can occur at warmer temperatures. The National Weather Service issues a "Freezing Spray Advisory" when freezing water droplets accumulate at a rate of less than 0.8 inches per hour, which corresponds to moderate icing (NWS, 2013). Once icing conditions begin to occur, there is little that can be done to prevent further icing and still allow for recovery operations. Therefore, the onset of moderate icing conditions is considered a response limit.

Visibility: Poor visibility due to darkness, precipitation, or fog can affect the ability of vessels to operate safely and to find and track oil on the water in order to target booming or skimming efforts effectively. Vessels generally need at least 0.5 nm visibility to be able to track oil (RPG, 2012); these limits apply the affects of daylight vs. darkness as well as horizontal visibility.

Ice: The limits used for sea ice coverage (measured as a percentage of coverage in a given area) are based on studies showing that traditional containment equipment typically can function in brash ice up to around 30% coverage (EPPR, 2015; Evers et al., 2006; Dickins and Buist, 1999; Owens et al., 1998; Robertson and DeCola, 2000), though the effectiveness begins to decrease at around 10% coverage (Potter et al., 2012; ACS, 2012; SL Ross, 2011) or as low as 1% ice coverage during freeze-up (Robertson and DeCola, 2000).[17] Note that sea ice conditions will vary around Alaska, and the limits in the Chukchi or Beaufort Seas will not necessarily be the same as those in Cook Inlet, for example (Steve Russell, ADEC, personal communication).

It may also be feasible to deploy skimmers in small pockets of oil contained by broken ice, though a limit for this is not established and it would require that the vessels can operate safely in high concentrations of ice. This method is unlikely to provide a large-scale cleanup operation (Nuka Research, 2007b).

Table 11 summarizes the response limits used in this study.

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[17] The one advantage that sea ice conditions may yield is the ability to recover small amounts of oil that is contained within pack ice that is thick enough to support equipment and personnel. (This also requires the ability to find the oil in these locations.) However, while this opportunity should be pursued when possible, we have not included it in the proposed sea ice limits since we are unable to estimate how often necessary leads or other sea ice formations would be present during periods of winter pack ice.

Table 11. Response limits used for open-water mechanical recovery tactic. Also shows wind and wave limits separately: these would be used if independent sea state data were available.

ENVIRONMENTAL FACTOR	**GREEN Response: *Favorable***	**YELLOW Response: *Marginal***	**RED Response: *Not favorable***
Estimated Sea State based on W (Wind in knots)*	$W \leq 8$	$8 < W < 15$	$W \geq 15$
W (Wind in knots) *not used in analysis*	$W \leq 20$	$20 < W < 30$	$W \geq 30$
H (Wave height in feet) *not used in analysis*	$H \leq 3$	$3 < H < 6$	$H \geq 6$
T_W (Wind Chill)	$T_W > -25$	$-25 > T_W > -35$	$-35 > T_W$
T_I (Extent of icing)	T_I = None or Light	T_I = Moderate	T_I = Heavy or Extreme
V (Visibility in nautical miles) **Daylight/Darkness**	$V \geq 0.5$ & **Daylight**	$0.5 > V \geq 0.125$ & **Daylight** or $V \geq 0.5$ & **Darkness**	$V < 0.125$ & **Daylight** or $V < 0.5$ & **Darkness**
I (Ice in % cover)	$I < 10$	$10 \leq I \leq 30$	$I < 30$

***Incorporates use of onshore winds to estimate median offshore wave height.**

6.3 Results

Overall, open-water mechanical recovery would not be recommended 73-77% of the year at the Chukchi and Beaufort Sea locations, respectively. While almost impossible in winter (not favorable 94-98% of the time), summer response would be favorable 21-22% and marginal 43-48% of the time – for a combined potential viability of more than 60% of the time at both locations (based on combining the green and yellow results).

Figure 14 presents the results graphically for each location. The results across the five-year study period are combined into a single annual cycle and show the extent of yellow and red conditions using shading (green requires that all conditions are green, so there is no shading). Similar annual cycles are shown for each location for just one environmental condition each – based on these, we see that sea ice is a dominant factor and the source of many of the red hours in the winter for this tactic. Wind conditions (here based on the sea state modeling as discussed Section 4.2.2) are generally favorable or marginal for this tactic, but still have an effect through the summer months.

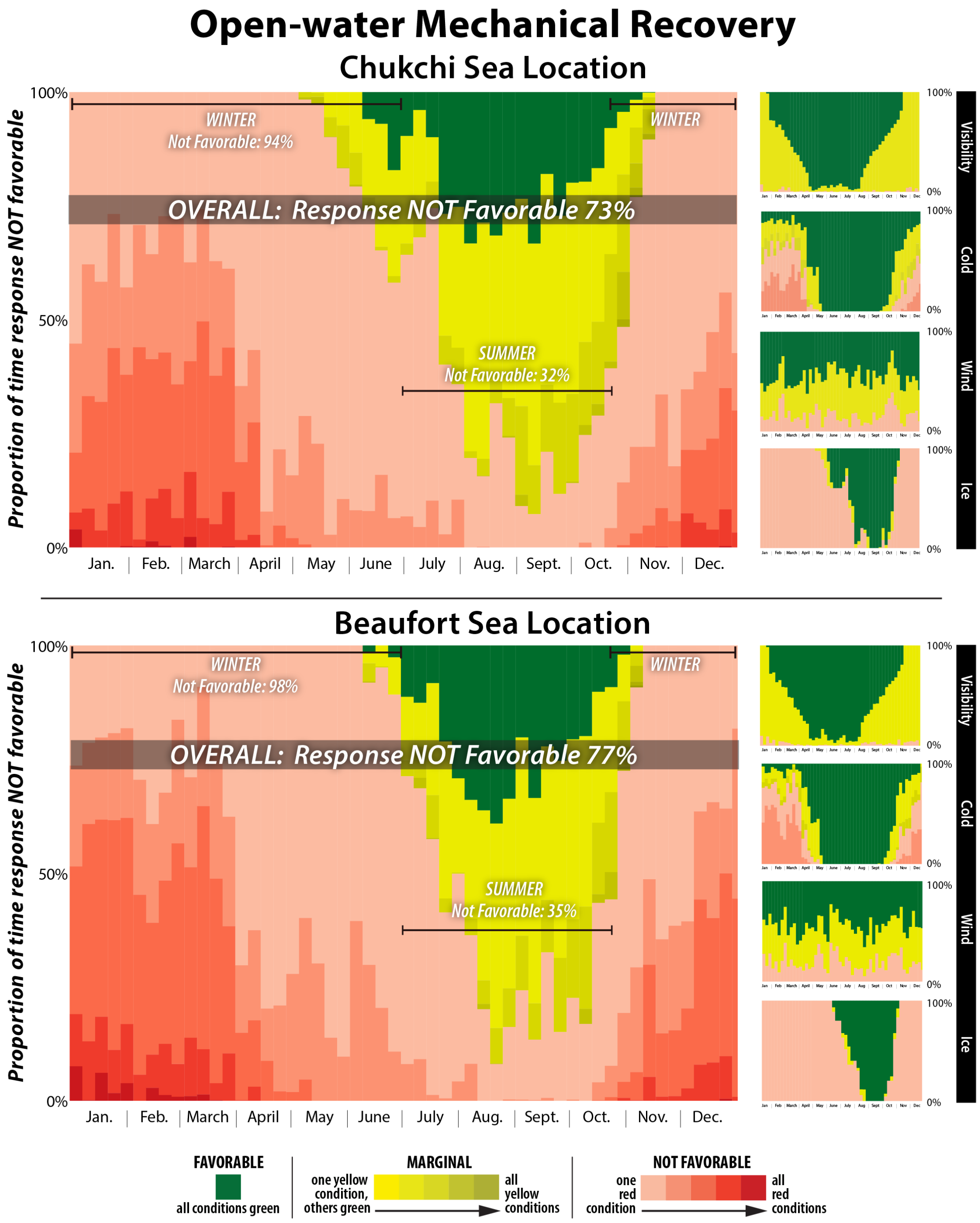

Figure 14. Graphic depiction of RGI for open-water mechanical recovery in the Chukchi and Beaufort Seas.

6. Dispersant Application

This section describes the two dispersant application tactics analyzed (application from aircraft and vessels), limits identified for those tactics, and the corresponding results of the response gap analysis.

6.1 Overview of Tactics

The objective of the application of dispersants is to chemically disperse spilled oil while it is floating on the sea's surface. Dispersants do not remove the oil, but break it into very small droplets that mix into the water column, promoting biodegradation. Dispersants are applied to the water's surface using either a vessel- or aircraft-mounted spraying unit. All spray systems consist of tanks for dispersant storage; a power source (diesel engine or electrical power source); a pump; control valves and metering equipment; spray arms; and nozzles (Figure 15). (ADEC, 2014)

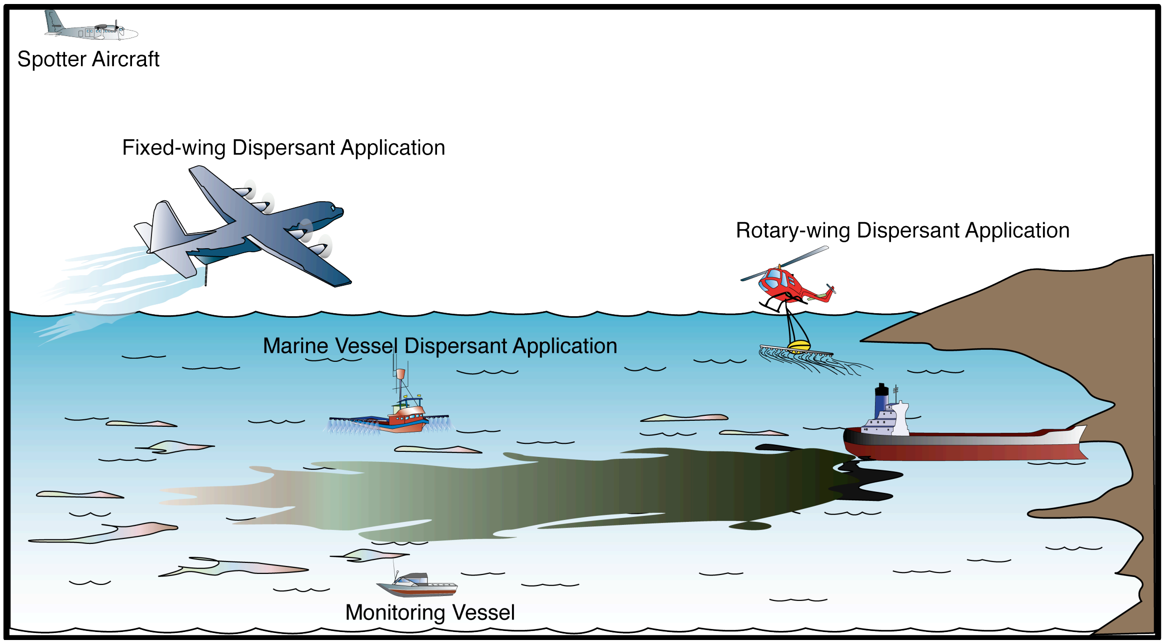

Figure 15. Examples of dispersant system elements, including aircraft and vessels both for dispersant application and monitoring (ADEC, 2014).

Spray systems must apply the appropriate dispersant dosage. Droplets that are too small can be subject to wind drift; those that are too large will pass through the oil slick. Both the flow rate and the droplet size are a function of the spray bar pressure and nozzle type. Application systems should be calibrated prior to use, preferably with the specific dispersant type to be used. (ADEC, 2014)

Aerial application can be accomplished from either fixed-wing or rotary-wing aircraft (ACS, 2012). This study focused on application from helicopters: their maneuverability and slower speed enables them to target pockets of oil in sea ice better than fixed-wing aircraft (Lewis and Daling, 2007).

Aerial application systems are generally able cover more area more quickly than vessel-based systems. However, aerial application may be less precise than vessel-based systems, resulting in irregular application or loss of dispersants. Aerial systems apply dispersants at a constant rate and cannot be adjusted during the sortie except by changing aircraft speed. Aerial systems may also be more limited by low visibility than vessel application (ADEC, 2014). Spotter aircraft will typically be used with both aerial and vessel applications to aid in targeting the dispersant application most effectively. (ACS, 2012)

Regardless of the platform, Special Monitoring of Advanced Response Technologies (SMART) protocols will typically be implemented to monitor the effectiveness of the dispersant application. SMART requires an observer aircraft to fly at low elevations even if vessels apply the dispersant, and a vessel for water sampling even if aircraft applies the dispersant (USCG et al., 2006). All ACS tactics refer to implementing the SMART protocols (ACS, 2012). (The limits below do not include SMART protocols.)

Dispersant Application in the Arctic

The application of dispersants does not change significantly in Arctic conditions as long as the aircraft or vessel application platforms can be deployed. The presence of ice may dampen waves and therefore reduce mixing energy, but the relative movement of the ice within the water is also observed to add mixing energy (Lewis, 2013). For small spills, vessel propellers may be used to introduce some energy back into the system if the ice concentration does not preclude this (Nedwed, 2014).

Equipment for Dispersant Application

General equipment needs for dispersant application (Table 12) include the application platform (whether a plane, helicopter, or vessel) and crew, spray pump system, and dispersant. A spray pump system may be built-in or operated as a separate unit integrated for the purpose of the response.

In addition, a different spotter aircraft and/or vessel with a fluorometer is needed to implement the SMART protocols. Communications equipment and procedures must be defined for all participants to facilitate communication between the spotter aircraft and the aircraft or vessel applying dispersant.

Table 12. Example equipment list for dispersant application.

RESOURCE	COMMENTS
DISPERSANT APPLICATION	
APPLICATION PLATFORM(S)	Vessel, fixed-wing aircraft, or helicopter used for application of dispersant.
DISPERSANT	Corexit 9500 is stockpiled in Alaska.
DISPERSANT SPRAY SYSTEM	May be portable or built into application platform. Example includes helicopter-deployed spray bucket system or handheld device.
MONITORING	
MONITORING PLATFORM	Vessel, fixed-wing aircraft, and/or helicopter used for monitoring of dispersant effectiveness. (Monitoring platforms are not included in the analysis.)
FLUOROMETER	For slick monitoring. Requires observers trained in use of this or other equipment and tools.
MAPS/CHARTS, HAND-HELD GPS, JOB AIDS, CAMERA, & OTHER MISCELLANEOUS	Used to document and record accurate observations to inform Command.

6.2 Response Limits

In general, arctic conditions present additional challenges to the application and effectiveness of dispersants; however, these same conditions may also slow the process by which the oil weathers, and therefore lengthen the window of opportunity for effective dispersant application (Daling et al., 2010). While there has been extensive testing of the application of dispersants in the Arctic, the basic need remains to operate an aircraft or vessel safely and to visualize and successfully target the oil. These aspects of the system are the primary basis for the limits presented here. Water temperature, pH, and salinity may affect the effectiveness of dispersants, but not their application.

This study considers both the application of dispersants from aircraft (helicopters) and from vessels. Helicopters were chosen as the aircraft for this study because they maximize the ability to target oil in broken ice (Lewis and Daling, 2007). Due to limited range, a helicopter would require vessel support if the response takes place too far offshore to use a land base. Except for ice, these limits are based on those used for the Aleutian Islands analysis, which, in turn, built on previous studies (Nuka Research, 2007a and 2014).

Wind: While winds may drive waves, which generate mixing energy, winds more than 25-27 knots will likely prevent dispersants from reaching the slick in the intended concentrations (NRC, 2005; Lewis, 2013; CISPRI, 2013; RPG, 2013). JIP/SINTEF research cites 30 knots as the maximum wind speed for dispersant application (Lewis and Daling, 2007). Fingas (2004) states that dispersants become approximately 50% less effective at 19 knots. While a helicopter could likely operate in higher winds, the limits are driven by the ability to target the slick. *Wind limits applied in the quantitative analysis were based on the modeling of sea state, as discussed in Section 4.2.2.*

Sea State: Dispersants are generally understood to require some mixing energy to be effective, either from natural waves, using vessel propellers for small spill,[18] or the movement of ice floes. Assuming vessels can be used, dispersants could be applied and effective even in very calm seas, making any limit expressing minimum required sea state unnecessary. Recent study of dispersant application during the Deepwater Horizon spill indicates that dispersants were effective in the Gulf of Mexico even when waters were very calm (Huber, 2014). The limits do not use a lower limit for sea state. This gives the benefit of the doubt to the above assumptions. Additionally, the use of median waves associated with onshore winds means there no periods during which sea state is estimated to be 1-foot or lower (except where ice is involved). An *upper* limit for sea state is used, however, based on the fact that natural mixing energy caused by waves above a certain height will disperse the oil and make the application of chemical dispersants unnecessary (Allen, 1988), so the deployment of dispersants in such conditions could be considered unfavorable.

Temperature: The temperature limits for the application of dispersants from aircraft are based on the potential for equipment to fail at low temperatures, as has been observed in exercises in Alaska (personal communication from Leslie Pearson, December 2013). The Canadian Helicopters Ltd. uses a helicopter operating limit of -40C (as reported in Lewis and Daling, 2007).

In 2012, the JIP summarized literature on tests of dispersant application in cold air and water conditions. One study concluded that dispersants could be effective in temperatures as low as -40 F, but more recent studies – all small-scale - only considered air temperatures of 30 F and above. Current research is focusing on making dispersants more effective on viscous oils, which is one of the key challenges of treating oils at cold temperatures (Potter et al., 2012).

Air temperature limits for aerial dispersant application are based on the functioning of the application pumping system. For vessel dispersant application, the limits are driven by the ability of the crew to operate safely on deck and avoid icing, and are therefore the same limits used for mechanical recovery. (Some dispersant delivery systems are heated to overcome temperature limitations.)

Icing: The combination of relative humidity and low temperature can cause ice to accumulate on the surfaces of vessels or aircraft. Icing can render operations unsafe and preclude response. In this study we consider icing conditions for vessels, but not for aircraft due to lack of data on conditions aloft.

Visibility: Helicopters operate best under daylight and civil twilight conditions. For uncontrolled airspace, helicopters must have at least 0.5 nm visibility, be able to see the ground (or water), and have no clouds (as reported in Lewis and Daling, 2007). Darkness is therefore considered red.

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[18] Tested in an ice basin using a scale-model vessel (Nedwed, 2014). A 2009 field release demonstrated that the prop wash from a small vessel resulted in the effective dispersion of oil (Sørstrøm, 2009).

Using the operational limits in the Interagency Helicopter Operations Guide (IHOG)[19] as a guideline, we apply a red limit to conditions with 0.5-mile visibility (or worse), and designate green conditions beyond one mile of visibility. IHOG interprets VFR conditions as those with ½ mile horizontal visibility, while FAA code designates VFR as horizontal visibility greater than one mile, with the exception that: "a helicopter may be operated clear of clouds if operated at a speed that allows the pilot adequate opportunity to see any air traffic or obstruction in time to avoid a collision," (14 CFR 191).

Ice: The presence of sea ice is known to dampen waves, and therefore reduce the amount of mixing energy in the system (SINTEF, 2009 in Potter et al., 2012). Vessels may add mixing energy using vessel propellers or bow thrusters, assuming that the vessels are capable of operating in high ice concentrations (Potter *et al.,* 2012) and able to access the site; however, this may not be practical over a large areas. As noted above, the extent to which mixing energy is required is unclear.

Dispersant application in up to 10% ice coverage is generally not affected (CISPRI, 2013). It may not even be affected up to 20-30% ice coverage, depending on the nature of the ice (Lewis and Daling, 2007). Some studies have concluded that dispersants can be effective in ice up to 90% coverage if azimuthal-drive ice breakers or other suitable vessels can be used to generate mixing energy (Potter *et al.,* 2012); however, applying dispersants in greater than 80-90% ice coverage will be difficult (Lewis and Daling, 2007).

Applying dispersant from an aircraft to a slick in ice will naturally be less efficient because some of the chemical will reach ice instead of oil. Helicopters are more maneuverable and therefore better able to target oil spread among broken ice than fixed wing aircraft even though fixed-wing aircraft have larger payloads and are considered to be able to apply dispersant to areas with up to 50% ice coverage or possibly greater (Lewis and Daling, 2007).

Additionally, the dispersant can be assumed to have a different effect on a slick in the process of freezing up or breaking up, since brash ice during freeze up may uniformly coat the water's surface with a light layer of ice. This difference is not quantified in the current literature and therefore is not included in the limits, but the effect is noted.

Tables 13 and 14 summarize the limits used for the two dispersant tactics.

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[19] The IHOG is widely accepted, being used for wildfire operations by 7 agencies, including the U.S. Forest Service (USFS), Bureau of Land Management (BLM), Bureau of Indian Affairs, Fish and Wildlife Service (FWS), National Park Service (NPS), and other participating federal and state agencies. The USFS, BLM, and NPS use the IHOG for all agency helicopter operations, regardless of mission. See: http://www.nwcg.gov/pms/pubs/pms510/00_pms510.pdf

Table 13. Response limits used for the aerial application of dispersants, assuming vessel agitation is available or not needed. Also shows wind and wave limits separately: these would be used if independent sea state data were available.

ENVIRONMENTAL FACTOR	GREEN Response: *Favorable*	YELLOW Response: *Marginal*	RED Response: *Not favorable*
Estimated Sea State based on W (Wind in knots) and **I** (Ice in % cover)*****	$W < 20$ & $I < 33$ or $W < 22$ & $I \geq 33$	$22 < W \leq 27$ & $I \geq 33$	$W \geq 20$ & $I < 33$ or $W > 27$ & $I \geq 33$
W (Wind in knots) *not used in analysis*	$W < 22$	$22 \leq W < 27$	$W \geq 27$
H (Wave height in feet) *not used in analysis*	$H < 9$	not used	$H \geq 9$
T (Temperature ºF)	$T > -40$	not used	$T \leq -40$
V (Visibility in nautical miles) **Daylight/Darkness**	$V > 1$ & **Daylight**	$1 \geq V > 0.5$ & **Daylight**	$V \leq 0.5$ & **Daylight** or **Darkness**
C (Ceiling in feet)	$C > 1200$	$1200 \geq C > 500$	$C \leq 500$
I (Ice in percent coverage)	$I < 10$	$10 \leq I < 50$	$I \geq 50$

***Incorporates use of onshore winds to estimate median offshore wave height.**

Table 14. Response limits used for the vessel application of dispersants, assuming vessel agitation is available or not needed. Also shows wind and wave limits separately: these would be used if independent sea state data were available.

ENVIRONMENTAL FACTOR	GREEN Response: *Favorable*	YELLOW Response: *Marginal*	RED Response: *Not favorable*
Estimated Sea State based on W (Wind in knots) and **I** (Ice in % cover)*	$\mathbf{W} < 20$ & $\mathbf{I} < 33$ or $\mathbf{W} < 22$ & $\mathbf{I} \geq 33$	$22 < \mathbf{W} \leq 27$ & $\mathbf{I} > 33$	$\mathbf{W} \geq 20$ & $\mathbf{I} < 33$ or $\mathbf{W} > 27$ & $\mathbf{I} \geq 33$
W (Wind in knots) *not used in analysis*	$\mathbf{W} < 22$	$22 \leq \mathbf{W} < 27$	$\mathbf{W} \geq 27$
H (Wave height in feet) *not used in analysis*	$\mathbf{H} < 9$	not used	$\mathbf{H} \geq 9$
$\mathbf{T_W}$ (Wind Chill)	$\mathbf{T_W} > -25$	$-25 > \mathbf{T_W} > -35$	$-35 > \mathbf{T_W}$
$\mathbf{T_I}$ (Extent of icing)	$\mathbf{T_I}$ = None or Light	$\mathbf{T_I}$ = Moderate	$\mathbf{T_I}$ = Heavy or Extreme
V (Visibility in nautical miles) **Daylight/Darkness**	$\mathbf{V} \geq 0.5$ & **Daylight**	$0.5 > \mathbf{V} \geq 0.125$ & **Daylight** or $\mathbf{V} \geq 0.5$ & **Darkness**	$\mathbf{V} < 0.125$ & **Daylight** or $\mathbf{V} < 0.5$ & **Darkness**
I (Ice in % cover)	$\mathbf{I} < 10$	$10 \leq \mathbf{I} < 90$	$\mathbf{I} \geq 90$

***Incorporates use of onshore winds to estimate median offshore wave height.**

6.3 Results

This section presents the results for both aerial and vessel based dispersant application.

6.3.1 Aerial Dispersant Application

Overall, aerial dispersant application are may not be favorable an estimate 79% of the time at the Chukchi Sea location and 84% at the Beaufort Sea locations. While almost impossible in winter (not favorable 95-99% of the time), it would be more likely viable in the summer when response could be favorable 32-37% of time, and marginal an additional 14% of the time. This assumes that agitation by vessels is available, or is not needed.

Figure 16 presents the periods of the year when this type of response would be possible or impossible with a graphic depiction of the results. From the annual cycles showing the effect of individual environmental conditions, we see that while ice dominates the winter, visibility is the dominant factor (with the most red) in the summer.

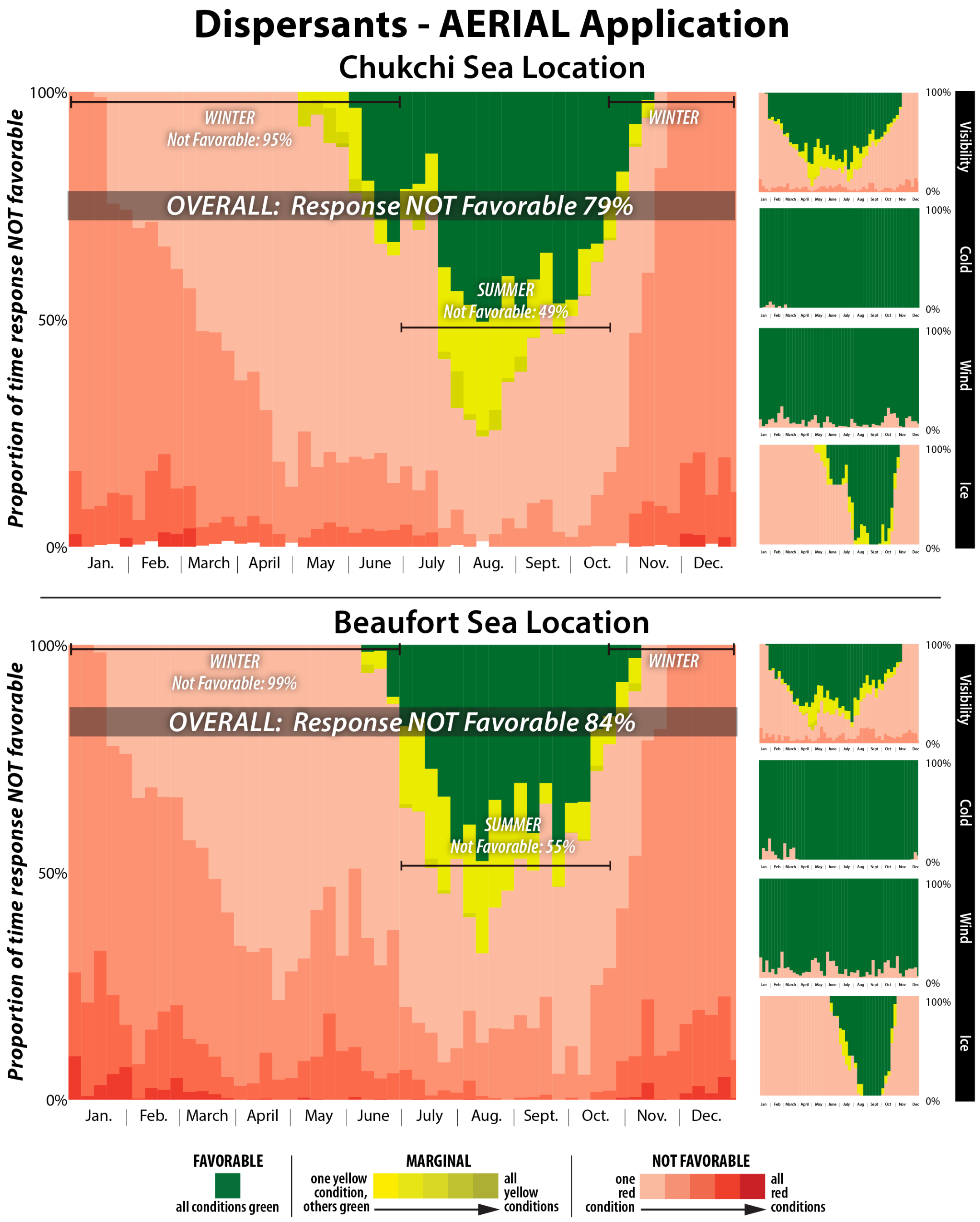

Figure 16. Graphic depiction of results for aerial dispersant application in the Chukchi and Beaufort Seas.

6.3.2 Vessel Dispersant Application

Overall, vessel-based dispersant application may not be favorable an estimated 65% of the time at the Chukchi Sea location and 70% at the Beaufort Sea locations. Similar to the application of dispersants from an aircraft, vessel application is not favorable much of the year due to sea ice. In summer, however, conditions would be favorable more than half the time, and not favorable only 15-17% of the time in that ice-free season. (This assumes that agitation by vessels is available, or is not needed.)

From the cycle graphics in Figure 17 showing the effect of each environmental condition, the relative effects are again similar to those for the aerial application for ice, cold, and wind. Visibility, however, results in favorable and marginal conditions for this vessel-based tactic, whereas it dominated red conditions for the summer in the aerial-based tactic discussed previously.

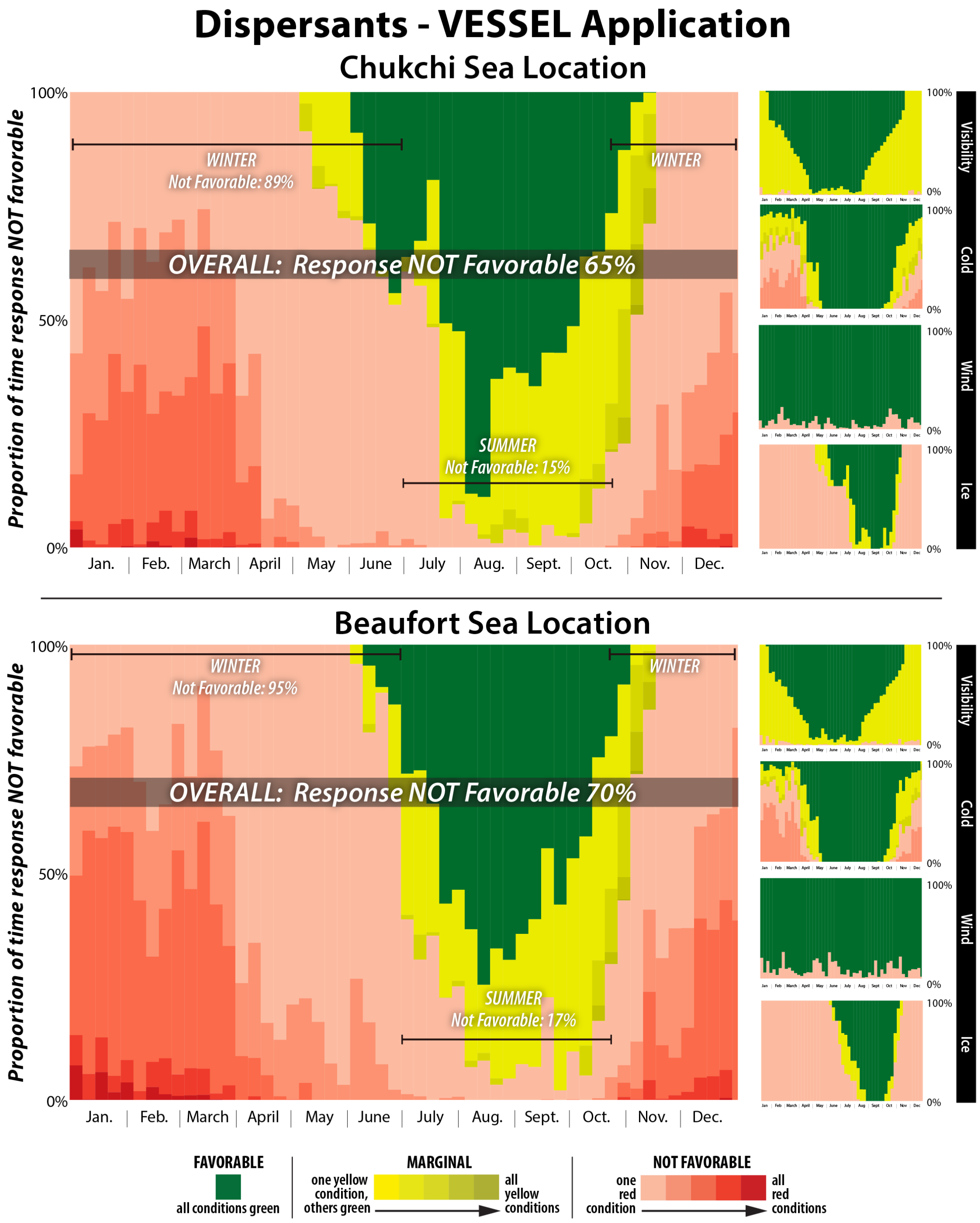

Figure 17. Graphic depiction of results for vessel dispersant application in the Chukchi and Beaufort Seas.

7. In-situ Burning

This section describes the two in-situ burning application tactics analyzed (ignition from aircraft and ignition from vessels), limits identified for those tactics, and the corresponding results of the response gap analysis.

The objective of in-situ burning is to conduct a controlled burn of spilled oil pooled on the water's surface. In-situ burning may be used to augment mechanical removal of oil under certain conditions. In-situ burning systems on water generally consist of a containment mechanism, an ignition system, and fire suppression equipment (ADEC et al., 2008).

Oil must be fresh (typically less than 2-3 days of exposure) and collected in sufficient quantity to sustain combustion. In-situ burning guidelines for Alaska cite a 1997 S.L. Ross study concluding that Alaska North Slope Crude must be 1 mm thick in order to be ignited (ADEC et al., 2008). The U.S. Environmental Protection Agency recommends that the oil not be more than 25% emulsified or more than 30% evaporated. (ADEC, 2014) How long it will remain in an ignitable state depends on both the oil type and the conditions at the time (Allen, 1988).

When sea ice is present, it can provide natural containment of the slick to maintain the necessary thickness for a burn. Otherwise, oil is contained for in-situ burning in much the same way as for mechanical recovery (Section 5), but with fire-resistant boom. Oil is contained to maintain the necessary slick thickness for a burn using fire boom. Fire boom deployment is subject to the same weather and operational constraints as boom used in mechanical recovery, although the fire boom is typically heavier and less flexible. Fire boom is typically constructed of either metal or fabric coated with a fire-resistant substance. (ADEC, 2014)

Ignition systems for small, fresh oil spills can be a handheld weed burner/torch or incorporate gelled fuel that is placed in the oil and ignited. A heli-torch may be used for larger areas. (ADEC, 2014)

Figure 18 shows the different elements of this approach.

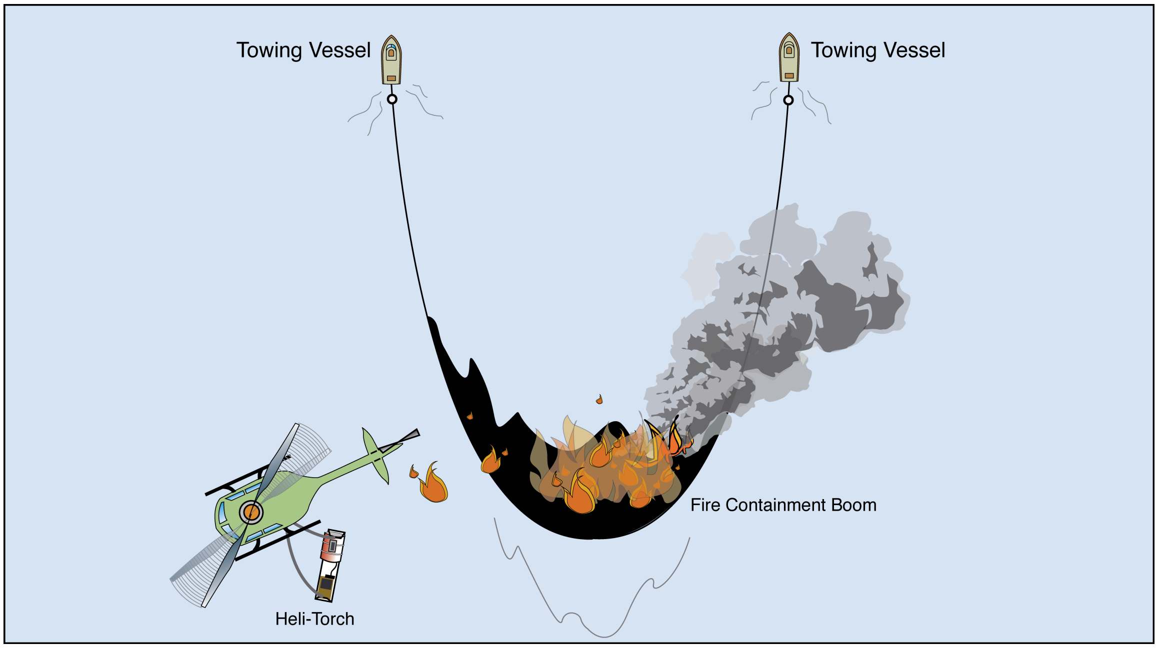

Figure 18. Example of in-situ burning conducted with ignition from a helicopter and fire booming for containment (ADEC, 2014)

The ignitability of oil slicks on water is affected by oil type, slick thickness, wind speed, emulsification of the oil, igniter strength, ambient temperatures, and sea state. When oil is ignited and begins to burn, it is actually the oil *vapor* that burns. Thus, the fire ignited must be hot enough to maintain a vapor flow. Most oils will burn on water if the oil is present in sufficient thickness to avoid the heat sink effect, caused when heat from the oil layer is transferred to the water and thus extinguishes the fire. (ADEC, 2014)

In-situ burning may be used in sea ice under certain conditions. In circumstances where the ice concentrates the oil and prevents it from spreading (usually in ice concentrations greater than 70%), burning may be able to remove a high percentage of the slick. Solid ice may also slow the evaporative loss process. However, partial sea ice coverage may complicate vessel operations and fire boom deployment if needed to concentrate the oil. (ADEC, 2014)

The SMART protocol used for in-situ burning operations focuses on air quality and the safety of personnel and downwind communities. Plume delineation or other methods are used to ensure that downwind emissions do not threaten sensitive populations (USCG et al., 2006). Safety standards for in-situ burning operations are included in the multi-agency Unified Plan for the State of Alaska through the incorporation of In Situ Burning Guidelines for Alaska (ADEC et al., 2008).

Residue Collection

In-situ burning results in residue after the burn is complete, which will vary depending on the efficiency of the burn and other factors. Most burns result in taffy-like layers of weathered, viscous material that is relatively buoyant. Some residues may become neutrally or negatively buoyant quickly after combustion and/or sediment uptake. By combining the residue with fresh oil in subsequent burns, a large portion of the residue may be eliminated. The residue that remains should be collected, but this technique is not included in the analysis. Whether recovered from secondary booms or the fire boom, the burn residue can normally be picked up with large strainers or hand tools, with viscous-oil sorbents, or with standard viscous-oil skimmers. If it is not recovered, burn residue will usually break up into smaller tar balls or tar mats, and sink or disperse.

In-situ Burning in the Arctic

If in-situ burning was determined by the Unified Command to be an appropriate response tactic, this could be done using a Heli-torch ignition system slung below a helicopter, or a hand-held ignition system tossed from a vessel or helicopter (ACS Tactic B-3). ACS Tactic B-4 describes the use of fire containment boom, noting that this approach would not be used if ice provides natural containment. Tactic B-6 describes the recovery of burn residue using viscous oil skimmers, sorbent, or strainers. (ACS, 2012)

Equipment for In-situ Burning

The equipment needed for in-situ burning depends on the platform and type of ignition device used (Table 15). An ignition device and fuel are needed for best results, as well as fire boom (if used) for containment; vessels, boom, and skimmers or other resources for recovery of residue; and back-up fire suppression equipment and vessels. SMART monitors will need both an operating platform (likely a vessel) and equipment for monitoring air quality.

Table 15. Example equipment list for in-situ burning.

RESOURCE	COMMENTS
CONTAINMENT AND BURNING	
Application platform(s) and crew	Vessel, fixed-wing aircraft, or helicopter used for ignition
Ignition system (handheld burner, propane tank and hoses, Heli-torch, or gelled fuel)	May be portable or built into application platform. Example includes helicopter-deployed spray bucket system or handheld device.
Fire suppression system	Used to control burn, if necessary. Multiple, hand-held fire extinguishers are acceptable for vessels.
Fire boom with tow lines and bridles, anchors, and boom repair kit	Used if containment is based on booming. Containment is necessary to ensure adequate slick thickness.
MONITORING	
Monitoring platform	Vessels, fixed-wing aircraft, and/or helicopter used for monitoring.
Particulate monitoring instrument, data sheets, job aid checklist, binoculars, humidity meter, anemometer, and other miscellaneous	Used for air quality monitoring.
RESIDUE RECOVERY	
Hand tools, large strainers, viscous-oil sorbent, viscous-oil skimmers, and fire extinguisher	Recovery and fire suppression if needed during recovery operations.
Work boat	Platform for recovery.

7.3 Response Limits

Similar to the application of dispersants, we propose limit sets for the ignition of a slick from both aircraft and vessel platforms.

As one indication of the impact of arctic conditions on in-situ burning, an October 2013 report released from the JIP identifies the following differences when conducting in-situ burning in brash ice as compared to open water: (1) the slick must be twice as thick in order to ignite, (2) flames will spread more slowly, (3) burn rates will be half as fast, and (4) the amount of residue expected will be 50 – 100% greater (Buist et al., 2013). Many studies have focused on whether oil is ignitable in different ice conditions or at different thicknesses; these studies have found variability in the burn efficiency (Buist et al., 2013).

Because our analysis considers limits in terms of environmental factors, we do not include slick thickness or weathering in the limits; instead, we understand that in-situ burning will require the ability to contain a slick to a sufficient thickness, or for the slick to be contained by ice. Thus, the limits for sea state and wind relate primarily to the ability to contain the oil, track it, and access it for ignition.

Regardless of the ignition platform, access via vessel will be necessary for the collection of residue if required. *Collection and management of burn residue is not included in the limits*, and would likely increase the response gap since vessel operations would be necessary even if an aerial platform is used for ignition. Access to the area is necessary within several hours of the burn in order to recover any floating residue (ACS, 2012); thus, determining the burn window requires consideration of future conditions as well as current conditions, though this falls outside the scope of this analysis.

Wind: While aircraft and vessels may be able to operate in higher winds, wind conditions are unfavorable for ignition and sustaining a burn at 20 knots and above (ACS, 2012; ADEC et al., 2008), and are considered marginal between 10-20 knots (Buist et al., 2003). Alaska's Guidelines for In-situ Burning (2008) and ACS (2012) also cite winds of less than 20 knots as being optimal for ignition. *Wind limits applied in the quantitative analysis were based on the modeling of sea state, as discussed in Section 4.2.2.*

Sea State: Sea state affects the ability to contain oil for burning. This may also be affected by the presence of ice, but considering sea state alone we apply the same limits as those used for mechanical recovery. Additionally, in general, waves less than 2-3 feet are optimal for the ignition and burning (Tactic B-3 in ACS, 2012; ADEC et al., 2008). This is incorporated in the wind limit used.

Temperature: From an operational perspective, the primary effect of air temperature is on the ability of vessel crews to operate safely on deck and either implement containment using boom. The temperature limits for vessels are therefore the same as those used for mechanical recovery.

Icing: The combination of relative humidity and low temperature can cause ice to accumulate on the surfaces of vessels or aircraft. Icing can render operations unsafe and preclude response. Icing conditions are considered for vessels but not for aircraft due to a lack of data on conditions aloft.

Visibility: The visibility limits are the same as those used for dispersants (Section 6.3), since they relate to the ability to fly an aircraft and identify and target the spill or operate a vessel to ignite the slick (and recover residue).

Ice: Oil must be accessible for ignition and pooled or contained to a sufficient thickness, so in-situ burning can only be used in open water, low ice concentrations, or, when pooled on top of pack ice (Buist et al., 2013). The presence of sea ice may also make it harder to ignite a slick, or may reduce the efficiency of the burn (Fingas, 2004; Buist et al., 2003). The limits applied generally assume that either ice concentrations are very low, or are high enough that they are provided containment in lieu of boom. One field trial demonstrated a small scale burn in ice coverage up to 70% (Sørstrøm, 2009).

While it may be feasible to ignite small patches of oil in ice concentrations greater than 30%, it is not practical to assume that any sort of post-burn monitoring or recovery of residue would take place in those conditions.

Table 16 summarizes the limits for in-situ burning when the slick is ignited from an aircraft. This does not consider the limits on vessels seeking to operate to collect residue. Table 17 presents the limits for in-situ burning that is ignited from a vessel.

Table 16. Response limits used for the aerial ignition of an in-situ burn. Also shows wind and wave limits separately: these would be used if independent sea state data were available.

ENVIRONMENTAL FACTOR	**GREEN Response: *Favorable***	**YELLOW Response: *Marginal***	**RED Response: *Not favorable***
Estimated Sea State based on W (Wind in knots) and **I** (Ice in % cover)*	**W** < 8 and **I** < 33 or **W** < 15 and **I** ≥ 33	8 ≤ **W** < 15 & **I** < 33 or 15 ≤ **W** < 20 & **I** ≥ 33	**W** ≥ 15 and **I** < 33 or **W** ≥ 20 and **I** ≥ 33
W (Wind in knots) *not used in analysis*	**W** < 15	15 ≤ **W** < 20	**W** ≥ 20
H (Wave height in feet) *not used in analysis*	**H** < 3	≥ 3 **H** < 6	**H** ≥ 6
$\mathbf{T}_W$ (Wind Chill)	$\mathbf{T}_W$ > -25	-25 > $\mathbf{T}_W$ > -35	-35 > $\mathbf{T}_W$
$\mathbf{T}_I$ (Extent of icing)	$\mathbf{T}_I$ = None or Light	$\mathbf{T}_I$ = Moderate	$\mathbf{T}_I$ = Heavy or Extreme
V (Visibility in nautical miles) **Daylight/Darkness**	**V** > 1 & **Daylight**	1 ≥ **V** > 0.5 & **Daylight**	**V** ≤ 0.5 & **Daylight** or **Darkness**
C (Ceiling in feet)	**C** > 1500	1500 ≥ **C** > 800	**C** ≤ 800
I (Ice in percent coverage)	**I** ≤ 10 OR **I** > 90	not used	10 < **I** ≤ 90

***Incorporates use of onshore winds to estimate median offshore wave height.**

Table 17. Response limits used for the vessel ignition of an in-situ burn. Also shows wind and wave limits separately: these would be used if independent sea state data were available.

ENVIRONMENTAL FACTOR	GREEN Response: *Favorable*	YELLOW Response: *Marginal*	RED Response: *Not favorable*
Estimated Sea State based on W (Wind in knots) and **I** (Ice in % cover)*	**W** < 8 and **I** < 33 or **W** < 15 and **I** ≥ 33	8 ≤ **W** < 15 & **I** < 33 or 15 ≤ **W** < 20 & **I** ≥ 33	**W** ≥ 15 and **I** < 33 or **W** ≥ 20 and **I** ≥ 33
W (Wind in knots) *not used in analysis*	**W** < 15	≥ 15 **W** < 20	**W** ≥ 20
H (Wave height in feet) *not used in analysis*	**H** < 3	≥ 3 **H** < 6	**H** ≥ 6
$\mathbf{T_W}$ (Wind Chill)	$\mathbf{T_W}$ > -25	-25 > $\mathbf{T_W}$ > -35	-35 > $\mathbf{T_W}$
$\mathbf{T_I}$ (Extent of icing)	$\mathbf{T_I}$ = None or Light	$\mathbf{T_I}$ = Moderate	$\mathbf{T_I}$ = Heavy or Extreme
V (Visibility in nautical miles) **Daylight/Darkness**	**V** ≥ 0.5 & **Daylight**	0.5 > **V** ≥ 0.125 & **Daylight** or **V** ≥ 0.5 & **Darkness**	**V** < 0.125 & **Daylight** or **V** < 0.5 & **Darkness**
I (Ice in percent coverage)	**I** ≤ 10 OR **I** > 90	not used	10 < **I** ≤ 90

***Incorporates use of onshore winds to estimate median offshore wave height.**

7.3 Results

This section presents the results for in-situ burning with ignition from both aircraft and vessels.

7.3.1 Aerial In-situ Burn Ignition

Overall, aerial in-situ burning would not be favorable an estimated 65% of the time at the Chukchi Sea location, and 69% of the time the Beaufort Sea location. Compared to the previous tactics discussed, sea ice plays is not as significant to this tactic which is instead more impacted by wind (sea state) and visibility. Because it is more dominated by these factors that are present throughout the summer, while in-situ burning with aerial ignition is more likely viable in winter than any other tactic at 20-21% (combining green and yellow), conditions may not be favorable more than half the time in the summer (53-59% red). The annual cycles presenting these results are shown in Figure 19.

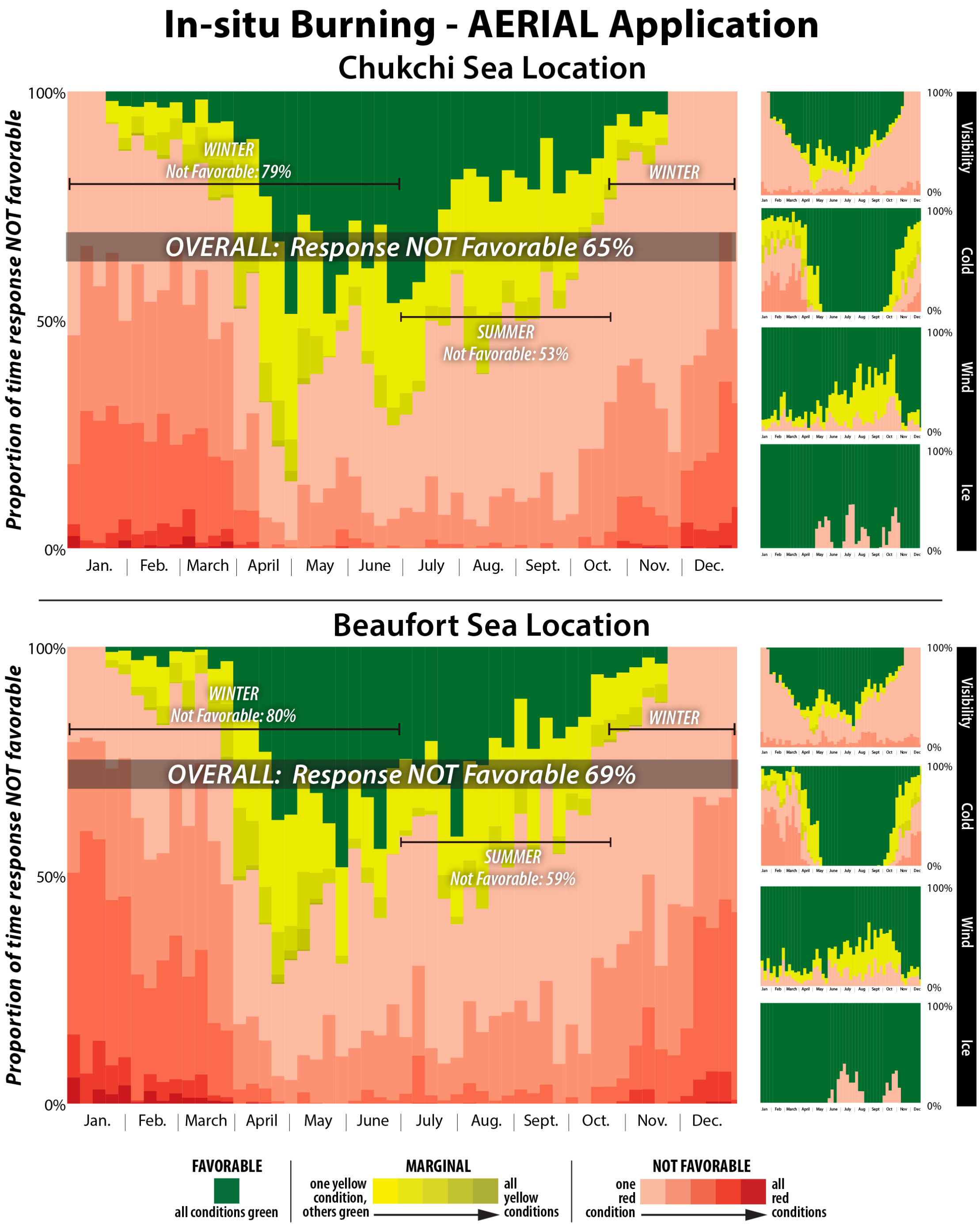

Figure 19. Graphic depiction of results for aerial in-situ burning in the Chukchi and Beaufort Seas.

7.3.2 Vessel In-situ Burn Ignition

Overall, vessel-based in-situ burning may not be favorable 36% of the time at the Chukchi Sea location and 42% of the time at the Beaufort Sea locations. While not favorable a little less half the time in winter (41-49% of the time), it would be more viable in the summer when response would be favorable 29-30% of the time and marginal an additional 41-44% of the time (overall potentially viable 70-74% of the summer at each location, based on combining yellow and green).

Figure 20 presents the results for each location, both overall and based on individual environmental factors. As with the preceding in-situ burning tactic, ice does not play a significant role, and as with the other vessel-based tactics, visibility does not result in red conditions the way it does for the aircraft-based tactics.

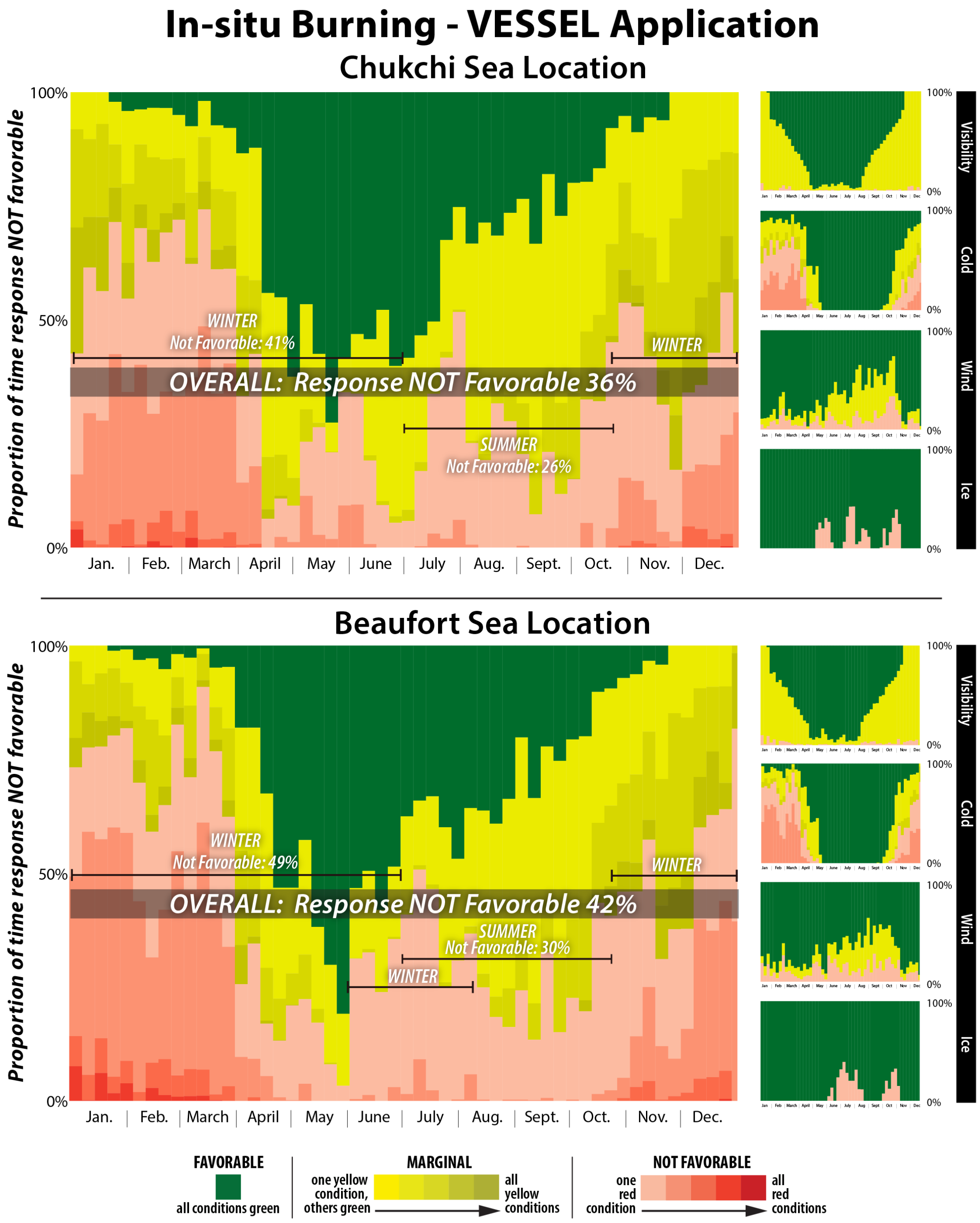

Figure 20. Graphic depiction of results for vessel-based in-situ burning in the Chukchi and Beaufort Seas.

8. Summary of Response Gap Analysis Results & Time Window Sensitivity

This section summarizes the results of the response gap analyses conducted for open-water mechanical recovery, application of dispersants (via aircraft and vessel), and application of in-situ burning (via aircraft and vessel). The response limits and more detailed results for each tactic are found in the previous three sections, with a general discussion of the results in Section 9. This section also presents the results of the time window sensitivity analysis.

8.1 Summary of Response Gap Results for Each Tactic

Table 18 shows the percentage of hourly intervals that are green, yellow, and red for each tactic, overall, seasonally, and based on location. This is the same information presented graphically in the preceding sections, but in tabular format.

The results are very similar for the two locations studied, within just a few percentage points in all cases. Not surprisingly, conditions are more likely favorable for all tactics studied in the ice-free months (here considered "summer") as compared to the ice-infested winter months. In summer, the application of dispersants by vessel is most likely to be favorable, as it is only expected to be not favorable 15% of the time (Chukchi Sea location). In winter, however, either of the in-situ burning tactics are most likely to be favorable, with a slight preference towards ignition from a vessel. However, aerial-based ignition may still not be favorable 41% of the time, and vessel-based ignition not favorable 79% of the time at the Chukchi Sea location.

Table 18. Results for Chukchi Sea Location and Beaufort Sea Location, overall and for summer and winter.

	OVERALL (Year round)			SUMMER (July – Oct)			WINTER (Nov – June)		
CHUCKHI SEA LOCATION									
	green	**yellow**	**red**	**green**	**yellow**	**red**	**green**	**yellow**	**red**
Open-water Mechanical Recovery	8%	20%	73%	21%	48%	32%	1%	5%	94%
Dispersants (Aerial)	15%	7%	79%	37%	14%	49%	2%	2%	95%
Dispersants (Vessel)	20%	16%	65%	51%	34%	15%	2%	9%	89%
In-situ Burning (Aerial)	17%	19%	65%	22%	25%	53%	10%	11%	79%
In-situ Burning (Vessel)	23%	40%	36%	30%	44%	26%	15%	44%	41%
BEAUFORT SEA LOCATION									
Open-water Mechanical Recovery	7%	15%	77%	22%	43%	35%	0%	2%	98%
Dispersants (Aerial)	11%	5%	84%	32%	14%	55%	1%	1%	99%
Dispersants (Vessel)	17%	14%	70%	48%	35%	17%	1%	4%	95%
In-situ Burning (Aerial)	15%	16%	69%	20%	21%	59%	9%	11%	80%
In-situ Burning (Vessel)	23%	35%	42%	29%	41%	30%	14%	37%	49%

8.2 Time Window Sensitivity Analysis

The amount of time required for a response deployment will depend on several factors: the tactic, forecasted or actual conditions before and after deployment (for mobilization and demobilization), conditions at other relevant locations (such as the airport from which an aircraft must take off or land), spill volume and area and other slick characteristics, and related logistics. By providing an estimate of how often conditions will be favorable or marginal for a response consecutively, the time window sensitivity analysis can be used to consider the viability of mounting different tactics. Figure 21 summarizes the results of this analysis, showing the percentage of time that consecutive green, or combined green/yellow hours occur at the different locations and for the different tactics. Table 19 shows the same information for 3, 6, 9, 12, and 24-hour consecutive time windows.

Time-window sensitivity

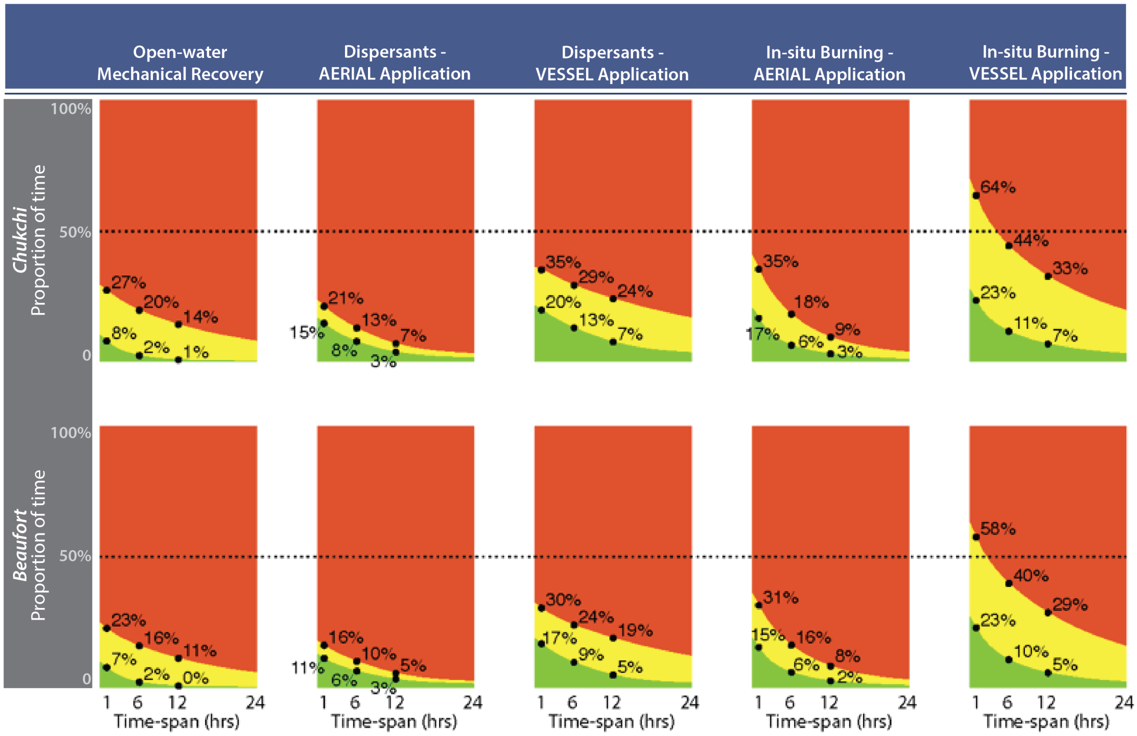

Figure 21. Time window sensitivity results, showing the percentage of time consecutive hourly increments are green, green/yellow, or red.

As would be expected, the percentage of time during which a response would be favorable or marginal drops significantly going from 1 hour to 24 hours. In-situ burning from a vessel is the most likely to be viable as it is the most likely to have green or yellow conditions (64% of the year, when combined); when considering 6-hour time increments, however, the combined green and yellow conditions drop to 44% of the time (combined). Depending on logistics and whether the conditions on either side of those 6-hour time windows preclude deployment and/or demobilization, this could still be sufficient time to deploy the tactic though may not allow for residue collection or monitoring. Ultimately, deployment decisions will be made in part based on *forecasted* conditions, which will be different than the actual (or modeled) conditions used here.

Table 19. Percentage of time that consecutive hours are green (g) or green/yellow (g/y) for 3, 6, 9, 12, and 24 hourly windows at both locations.

	3 hours		6 hours		9 hours		12 hours		24 hours	
	g	g/y	g	g/y	g	g/y	g	g/y	g	g/y
CHUKCHI SEA LOCATION										
Mechanical	4	24	2	20	1	17	1	14	0	8
Dispersants - air	11	17	8	13	5	9	3	7	1	3
Dispersants - vessel	17	33	13	29	10	26	7	24	3	17
ISB - air	10	26	6	18	4	13	3	9	1	4
ISB - vessel	16	53	11	44	9	38	7	33	3	20
BEAUFORT SEA LOCATION										
Mechanical	4	19	2	16	1	13	0	11	0	6
Dispersants - air	8	13	6	10	4	7	3	5	1	2
Dispersants - vessel	13	27	9	24	7	21	5	19	2	12
ISB - air	9	23	6	16	4	11	2	8	1	3
ISB - vessel	16	48	10	40	7	34	5	29	2	16

9. Discussion

This section synthesizes our observations from the analysis and recommendations based on the analysis conducted.

9.1 Seasonal Impacts

Not surprisingly, summer and winter are starkly different in the study area, with the sea ice, cold, and darkness of the winter months presenting the most significant differences. Summer and winter were defined for this study based primarily on the ice-free and ice-dominated seasons. Considering also the variability in daylight at these locations, these also can be considered to represent the best-case and worst-case seasons, though even in summer there are still times when other factors may render a response tactic not favorable.

In-situ burning using a vessel as the ignition platform is the most likely to be favorable or marginal among the tactics studied; however, this is driven primarily by the fact that burning is indicated possible, if challenging, in the “winter” months (November – June) because it can be implemented in higher ice concentrations than the dispersant or open-water mechanical recovery tactics.

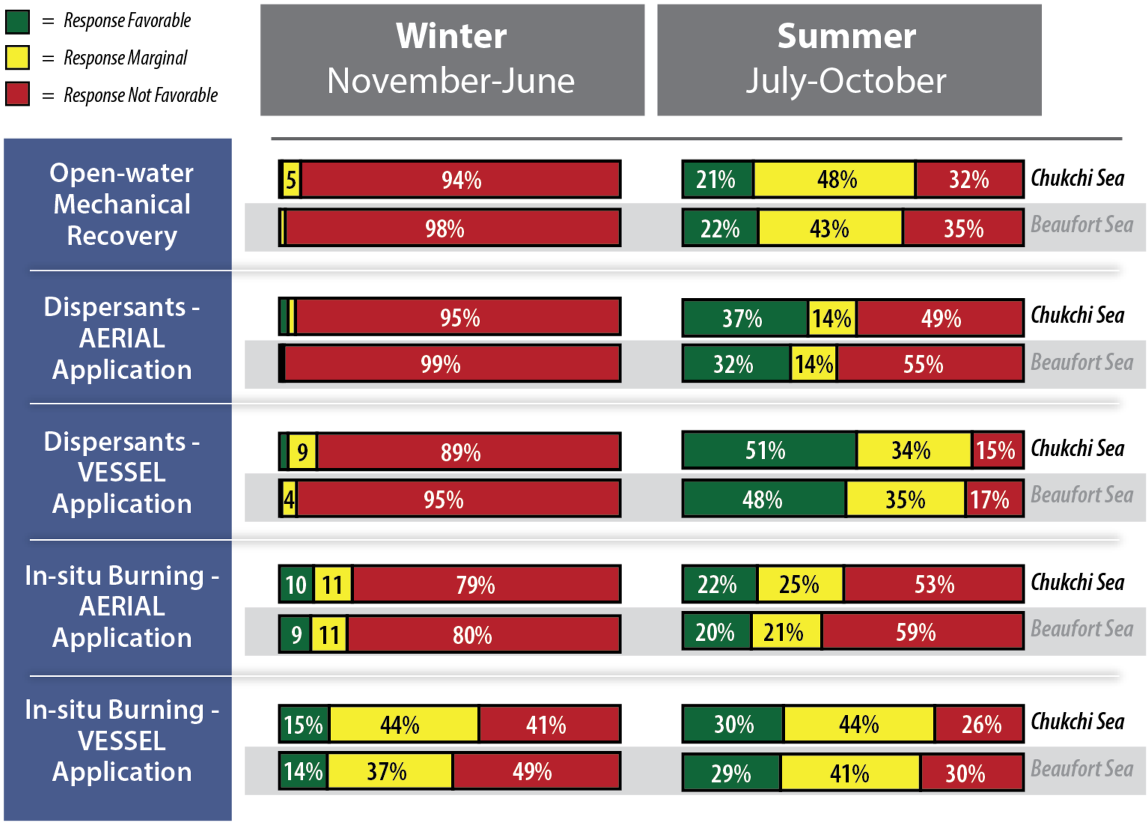

Figure 22. Percentage of time each tactic studied would be favorable, marginal, or not favorable during the summer and winter. Summer and winter are defined primarily based on the ice-free and ice-dominated seasons, respectively.

9.2 Impact of Individual Factors on Tactics

The various environmental factors impact response tactics to different degrees. Ice poses a significant challenge, particularly to dispersant application and mechanical recovery, but it is absent for part of the year. Cold air temperatures particularly affect vessel operations due to superstructure icing and navigational challenges, but are generally not a problem in the "summer" months. Visibility is a dominant limiting factor for the dispersant and in-situ burning tactics that use aircraft; unlike ice and cold, visibility remains an issue even during the summer.

Figure 23 presents a summary of the cycle graphics for the Chukchi Sea location to show the relative contributions of different environmental conditions to the portion of green, yellow, or red for each tactic. Variability throughout the seasons is also shown. This comparison across conditions and tactics clearly shows the dominant effect of sea ice on the mechanical recovery and dispersant tactics studied. The relative impact of visibility on the aircraft-based tactics (for dispersants and in-situ burning) as compared to the vessel-based tactics is also apparent.

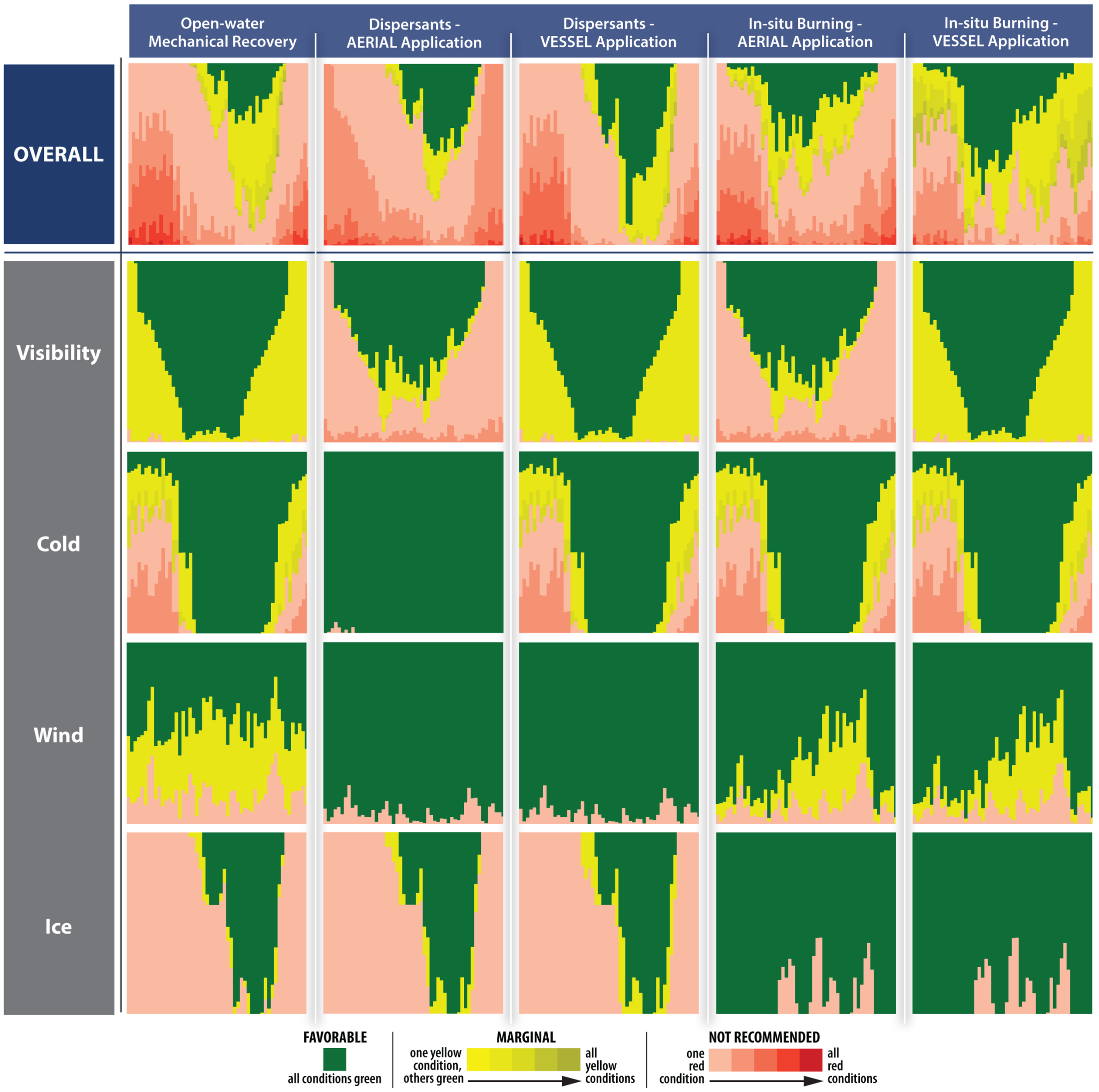

Figure 23. Comparison of impact of different environmental factors on different tactics. (Chukchi Sea location only; "wind" refers to the sea state as estimated using onshore winds.) Each square on the grid represents an annual cycle (Jan-Dec) for one factor for one tactic. These combine into the annual cycle for the overall tactic. Where any one factor has red, the overall cycle will show red.

9.3 Considering Deployment Platform (Vessels vs. Aircraft)

While vessels appear to provide the most viable platform for both dispersant application and in-situ burning, this assumes that suitable vessels are available and able to operate not only on-scene, but between the response location and a port. Because this response gap analysis considers conditions only in terms of individual hours, this may significantly overestimate how often these tactics could be deployed, since conditions would have to be amenable for the time it takes to transit to and from the site. (Conditions that would prohibit transit are not included here; presumably a vessel could travel in worse conditions than required to deploy response tactics.) If suitable vessels are not available in the region, or cannot operate far offshore for sustained periods of time, then the vessel-based tactics would not be possible. Year-round, conditions are less favorable for the aircraft-based tactics based primarily on visibility (as shown in Figure 23, above). Vessels will also reach the area more slowly than aircraft, so for locations far offshore it may be that aircraft are the preferred option if they are better able to take advantage of limited time windows suitable for deployment. Differences between fixed-wing aircraft and helicopters will also come into play, particularly when considering the conditions each can handle safely, how far each can travel over water, and speed.

9.4 SMART Protocols and In-situ Burn Residue Collection

For in-situ burning and dispersant application conducted with aircraft, the ability to deploy vessels may still be relevant.

For in-situ burning, the collection of residue is not included in the limits, but could be assumed to generally mirror the limits used for mechanical recovery since it requires vessels, containment, and recovery of the residue from the water. Residue recovery would not be possible as often as the ignition and burning itself would be. Based on the results for open-water mechanical recovery, which also involves boats, containment, and collection, it appears that residue collection may be not favorable (red) 73-77% of the time year-round in the study areas if the limits were determined to be the same as those for mechanical recovery.

Similarly, the aerial application of dispersants would still require a vessel to be able to operate safely if water sampling is conducted according to the SMART protocols (USCG et al., 2006). Sampling does not necessarily require the same conditions as the deployment of recovery equipment, so is not as readily equated with the mechanical recovery tactic as the collection of in-situ burn residue.

Applying limits for the use of SMART protocols and collection of burn residue represents a next logical step to the use of the response gap analysis approach to provide the best possible picture of the feasibility of response tactics in real-world conditions. Policy decisions are needed regarding whether or not these tactics can be implemented without the ancillary activities of residue collection and monitoring.[20]

9.5 Impact of Assumptions Related to Offshore Waves on Results

As noted in Section 4, the lack of continuous sea state data for the offshore locations necessitated the use of an alternative approach. Our approach was to determine the correlation between onshore wind speeds and median wave heights for the limited months for which actual offshore data were available in the Chukchi Sea. This section considers the potential impact that choice had on the results for each tactic by comparing the percentage of the time that response would not be favorable generated using this approach with the

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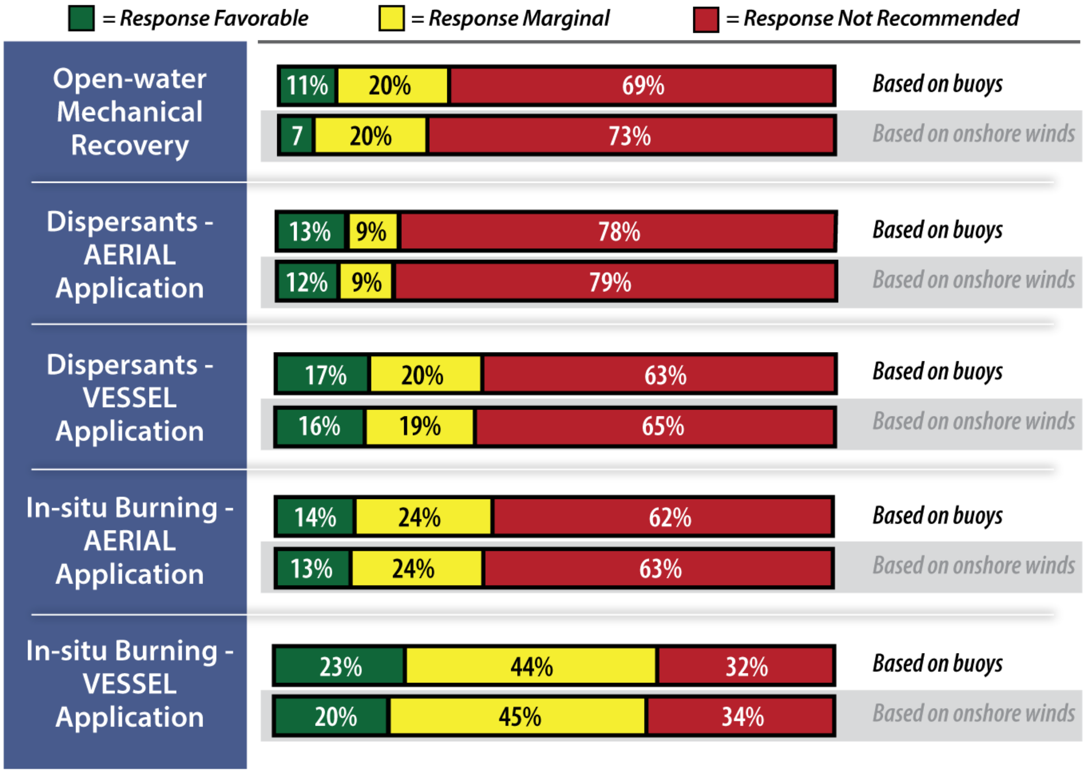
[20] Planning for in-situ burn residue recovery is required for state waters in the State of Alaska's In-situ Burning Guidelines (2008).

percentage of time that response would not be favorable based on using actual buoy data *only for the months that buoy data were available* (Figure 24).[21] Overall, the percentage of time resulting in red observations based on onshore winds (for sea state) is similar to the results based on marine observations for sea state during this limited period of time.

Figure 24. Percentage of red hours generated using sea state data from buoys as compared to results based on "modeled" wave data derived from onshore winds (only for the months for which those data were available).



9.6 Recommendations

This section offers recommendations on future developments that would improve an oil spill response gap analysis for this region. The collection of better data on response limitations in different conditions would benefit similar analyses in other locations, while the collection of more and better environmental data for the Beaufort and Chukchi Seas would likely benefit studies on other topics in this region. Studying additional tactics, or improved tactics, will add to the understanding of response viability in this region and the potential benefits of tactic modifications or technological improvements.

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[21] Because these results are only for the months when data were available, they do not match the overall, summer, or winter results generated as results in the preceding sections.

9.6.1 Better Documentation of Response System Limits

This analysis and practical response planning and decision-making would be strengthened by having better documentation (and quantification) of limits for the different response system components. Effort is underway in both of these areas, but needs to continue and expand. While environmental data are of interest to a wide range of parties, quantifying limits is of interest only to those concerned with oil spill response. Although there has been growing research in this area generally, much of it does not focus on identifying limits related to deployment. Tests have also largely been conducted in tanks or small-scale field trials. Test also do not typically focus on identifying a limit – they may establish, for example, that in-situ burning was implemented in certain conditions, but not necessarily explore further to determine a condition or conditions beyond which burning would not be feasible. Documenting limits from larger scale tests or actual exercises or deployments would enhance the field. The best information is that obtained by experience, and that experience is best shared and most readily applied when it is carefully documented at the time.

9.6.2 Better Data on Environmental Conditions

This analysis would also benefit from better sea state data, including offshore areas, as well as continuous, consistent observations of other offshore conditions. Sea state could be obtained as in other parts of the country with NOAA weather buoys, and/or developed through models that are continuously refined as real-world data becomes more readily available.

The collection of environmental data in this changing region would benefit from the use of consistent data collection protocols of some type. It is beyond the scope of this study to recommend what these should be, but we recognize that there are many and diverse needs for such information. Using environmental data across a longer time span could highlight trends over time in the viability of response systems in this region. This could include the impact of climate change on response viability.

9.6.3 Incorporate Additional Tactics and Time Periods

A future analysis could apply the same approach to additional or modified tactics, or other response elements such secondary storage, remote sensing, air logistics, or SMART monitoring activities. This could include studying how technological improvements or the use of new or emerging technology might impact the response gap or viability.

10. Conclusion

The response gap analysis focuses on the chances that a response system could be deployed, assuming all resources and logistics are in place. Despite the lack of environmental data and documented limits, the response gap analysis is yet one more tool for response planners to calibrate their approach and expectations based on consideration of environmental conditions in a particular area. This is important in areas such as the U.S. Arctic Ocean that are generally believed to represent a challenging operating environment. Quantifying such general assumptions provides a means to compare different options and identify priorities for improving oil spill response preparedness.

The results of this analysis indicate the need for very different planning and approaches during the few summer months than in the longer winter. This may also inform the types of activities conducted during different seasons. Summer's warmer air and lack of sea ice are more amenable to on-water vessel activities, which are virtually impossible in winter. Aerial operations may be possible in both seasons, but remain compromised by visibility in summer even if less than in winter.

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Appendix A: Comparison of Onshore and Offshore Data

Buoys and shore stations both record wind and air temperature. This section compares buoy and shore station data, by matching the limited buoy data to shore station data during corresponding time periods. Wind and air temperature are the only two environmental factors for which data are available both onshore and offshore.

A.1 Comparison of Onshore and Offshore Winds

Nuka Research compared sections of shore station and buoy wind data, to determine the qualitative relationship between wind speeds and direction, onshore and offshore (See Figure A-1).

In addition, a third source of data was available only for wind. Nuka Research compared shore station data to monthly summary data for the Chukchi Sea, compiled from the 1980s and summarized in Shell's contingency plan for the Chukchi Sea operations (Shell, 2011). The 1980s offshore wind statistics indicate that maximum wind speeds were slightly lower offshore: from June – November, the maximum offshore wind speeds were 98% of the Wainwright maximum, and 93% of the Barrow maximum. On the other hand, average wind speeds were *higher* offshore: 33% higher than Wainwright, and 14% higher than Barrow. These statistics were collected at variable locations 50 miles or more offshore in the Chukchi Sea. The sampling conditions for the offshore wind statistics (such as anemometer height and continuity of recording) could not be verified. Nuka Research is investigating further the relationship between onshore and offshore wind speeds.

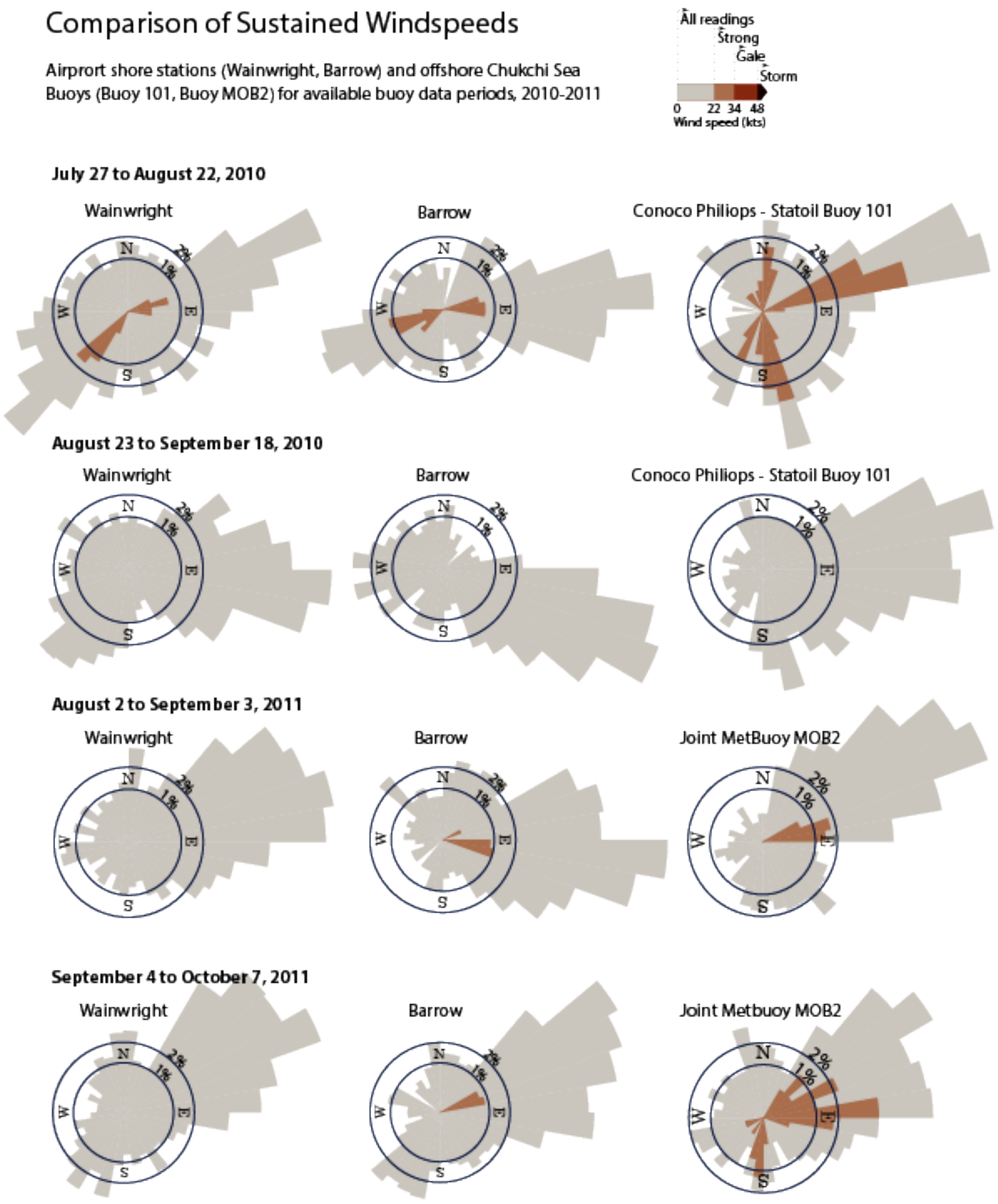


Figure A-1. Comparisons of sustained wind speeds for time periods when both buoy data and shore station data are available

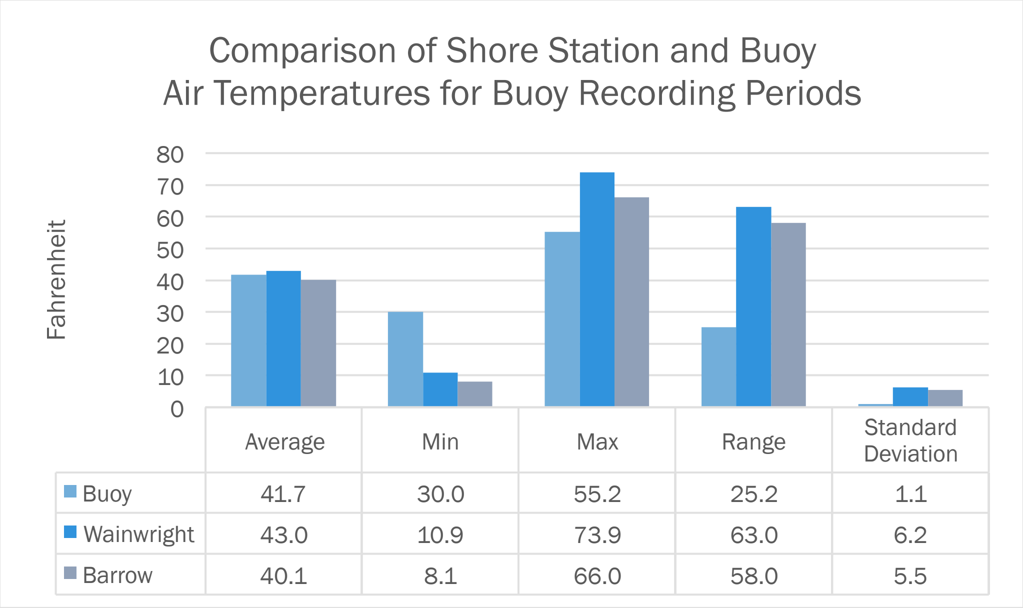
Table A-1. Shell Offshore Monthly Wind Statistics vs. Shore Station Observations (1980, 1982, 1983)

	Shell Offshore Data		Wainwright		Barrow	
MONTH	Maximum Wind speed (knots)	Average Wind speed (knots)	Maximum Wind speed (knots)	Average Wind speed (knots)	Maximum Wind speed (knots)	Average Wind speed (knots)
June	21	9.6	27	8.4	25	10
July	25	9.9	21.9	8.4	52.8	10.4
Aug	25	11.5	27.9	8	49.9	10.6
Sept	36	13.3	31	9.3	26	11.3
Oct	32	13.1	29.9	8.4	27	10.2
Nov	34	15	40	11.9	28.9	10.7

A.2 Comparison of Onshore and Offshore Air Temperature

Table A-2 and Figure A-2 compare combined buoy data from 2010 and 2011, with shore station data from the same period of time. The general phenomenon observed is that the large heat mass of the Chukchi Sea creates a damping effect on temperature changes compared to onshore locations.

Air temperature is much more variable over land. Although onshore (shore station) and offshore (buoy) air temperature averages are similar, shore station temperatures oscillate over a much wider range. As indicated by the much larger standard deviations (and percentile distributions located in Appendix B), this variability in shore temperatures affects the full distribution of temperatures, not just extremes.



	Average	Min	Max	Range	Standard Deviation
Buoy	41.7	30.0	55.2	25.2	1.1
Wainwright	43.0	10.9	73.9	63.0	6.2
Barrow	40.1	8.1	66.0	58.0	5.5

Figure A-2. Comparisons of air temperatures during periods for which both buoy data and shore station data are available (July 27 to September 18, 2010 and August 2 to October 7, 2011).

Table A-2. Comparative statistics for buoy and airport air temperatures (Fahrenheit).

		AVERAGES			STANDARD DEVIATIONS	
Time Period	**Buoy**	**Wainwright**	**Barrow**	**Buoy**	**Wainwright**	**Barrow**
July 27 - Aug 22, 2010 (Buoy 101)	42.4	49.8	44.7	1.5	7.4	6.8
Aug 23 - Sept 18, 2010 (Buoy 101)	44.2	45.9	41.0	0.8	5.1	4.3
Aug 2 - Sept 3, 2011 (MOB2)	43.5	44.8	41.9	1.0	5.7	4.1
Sept 4 - Oct 7, 2011 (MOB2)	37.7	34.4	34.1	1.1	6.6	6.5
Combined	41.7	43.0	40.1	1.1	6.2	5.5
		Minimums			**Maximums**	
Time Period	**Buoy**	**Wainwright**	**Barrow**	**Buoy**	**Wainwright**	**Barrow**
July 27 - Aug 22, 2010 (Buoy 101)	33.8	36.0	34.0	55.2	73.9	66.0
Aug 23 - Sept 18, 2010 (Buoy 101)	37.8	30.0	32.0	50.2	57.9	54.0
Aug 2 - Sept 3, 2011 (MOB2)	38.1	30.0	34.0	47.8	64.0	57.0
Sept 4 - Oct 7, 2011 (MOB2)	30.0	10.9	8.1	47.1	55.4	51.1
Combined	30.0	10.9	8.1	55.2	73.9	66.0

Appendix B: Buoy Data

This section presents combined readings for July 27 to September 18, 2010 and August 2 to October 7, 2011 from the buoys discussed in Sections 3 and 4.

Table B-1. Sustained wind speed (knots)

KEY STATISTICS				
	Number of Days	**Average Wind speed**	**Median Wind speed**	**Maximum Wind speed**
July	5	9.6	8.4	21.2
August	60	13.2	12.5	28.4
September	48	13.9	14.0	26.0
October	7	9.6	9.7	22.0

Overall	120	13.1	12.6	28.4	
PERCENTILES					
	2nd	5th	25th	75th	95th	98th
July	1.4	2.0	5.0	14.9	17.8	19.5
August	3.3	4.8	8.7	17.3	24.1	25.6
September	3.2	4.7	9.3	18.4	22.8	24.3
October	1.5	2.9	7.1	11.6	16.3	18.3

Table B-2. Air temperature (Farenheit).

KEY STATISTICS					
	Number of Days	Average Temperature	Median Temperature	Minimum Temperature	Maximum Temperature
July	5	44.9	45.8	36.7	55.2
August	60	42.6	42.4	33.8	50.2
September	48	41.2	41.4	32.0	50.2
October	7	34.2	33.8	30.2	37.2
Overall	120	41.7	41.9	30.2	55.2

PERCENTILES						
	2nd	5th	25th	75th	95th	98th
July	37.2	37.4	39.7	48.9	52.5	54.4
August	37.4	38.1	40.3	45.1	46.9	47.7
September	32.4	33.3	36.9	45.3	48.6	49.5
October	32.2	32.4	33.1	35.4	36.7	37.0

Table B-3. Wave height (feet).

KEY STATISTICS				
	Number of Days	Average Wave Height	Median Wave Height	Maximum Wave Height
July	5	1.9	1.3	5.5
August	60	4.0	3.3	11.0
September	48	4.4	4.3	11.8
October	7	3.6	3.3	6.6
Overall	120	4.0	3.5	11.8

PERCENTILES

	2nd	5th	25th	75th	95th	98th
July	0.2	0.2	0.6	3.3	4.8	5.2
August	1.0	1.4	2.2	5.1	8.8	9.7
September	1.2	1.4	2.8	5.7	7.7	8.7
October	1.7	1.9	2.8	4.3	6.0	6.2

Table B-4. Wave period (seconds)

KEY STATISTICS				
	Number of Days	**Average Wave Period**	**Median Wave Period**	**Maximum Wave Period**
July	5	4.5	4.2	28.6
August	60	5.8	5.7	9.1
September	48	6.4	6.5	9.5
October	7	6.6	6.9	8.7
Overall	120	6.0	6.1	28.6

PERCENTILES						
	2nd	5th	25th	75th	95th	98th
July	1.9	2.2	3.5	5.1	6.5	6.5
August	3.1	3.7	4.9	6.7	8.0	8.3
September	3.4	4.0	5.7	7.1	8.3	8.7

Table B-5. Wave steepness.

KEY STATISTICS				
	Number of Days	**Average Wave Steepness**	**Median Wave Steepness**	**Maximum Wave Steepness**
July	5	0.00291	0.00316	0.00602
August	60	0.00351	0.00347	0.00817
September	48	0.00343	0.00348	0.00732
October	7	0.00260	0.00238	0.00653
Overall	120	0.00340	0.00339	0.00817

	PERCENTILES					
	2nd	5th	25th	75th	95th	98th
July	0.00028	0.00035	0.00114	0.00422	0.00539	0.00577
August	0.00160	0.00182	0.00270	0.00424	0.00532	0.00598
September	0.00095	0.00124	0.00235	0.00449	0.00552	0.00598
October	0.00134	0.00146	0.00195	0.00322	0.00424	0.00488

Appendix C: Shore Station Summary Data

C.1 Wind Speed

Wainwright Wind Speeds, 2008-2012

Month	Average Wind speed (knots)	Median Wind speed (knots)	Maximum Wind speed (knots)	Average Gusts (knots)	Maximum Gust (knots)
January	9.2	8.0	34.0	9.7	43.0
February	11.2	9.9	45.1	12.0	55.0
March	8.9	8.0	38.1	9.1	47.0
April	9.6	8.9	29.0	9.7	36.9
May	9.8	8.9	26.0	10.1	53.1
June	11.0	11.1	26.0	12.3	64.0
July	9.7	8.9	29.9	10.5	41.0
August	9.7	8.9	31.1	10.7	39.1
September	9.4	8.9	28.0	10.4	51.1
October	11.2	9.9	33.0	12.6	39.1
November	10.0	8.9	42.0	10.7	53.1
December	10.0	8.9	36.0	10.5	46.1
Annual Average	**10.0**	**9.1**	**33.2**	**10.7**	**47.4**

Barrow Wind Speeds, 2008-2012					
Month	**Average Wind speed (knots)**	**Median Wind speed (knots)**	**Maximum Wind speed (knots)**	**Average Gusts (knots)**	**Maximum Gust (knots)**
January	9.8	8.9	36.0	10.3	41.0
February	11.1	9.9	42.0	11.7	52.1
March	9.1	8.0	35.0	9.3	42.0
April	9.5	8.9	27.0	9.7	32.1
May	9.4	8.9	25.1	9.6	34.0
June	11.7	11.1	28.0	12.3	35.0
July	10.3	9.9	29.0	10.9	38.1
August	10.1	9.9	27.0	11.0	36.0
September	9.9	8.9	29.9	10.9	36.0
October	12.5	12.1	34.0	13.9	41.0
November	10.6	9.9	35.0	11.2	45.1
December	10.3	8.9	35.0	10.8	43.0
Annual Average	**10.4**	**9.6**		**11.0**	**39.6**

Prudhoe Bay Wind Speeds, 2008-2012					
Month	**Average Wind Speed (knots)**	**Median Wind Speed (knots)**	**Maximum Wind Speed (knots)**	**Average Gusts (knots)**	**Maximum Gust (knots)**
January	11.0	9.9	39.1	11.4	54.0
February	11.1	9.9	47.0	11.4	55.0
March	9.4	8.0	39.1	9.5	45.1
April	9.6	8.9	31.1	9.7	38.1
May	10.5	8.9	31.1	10.9	38.1
June	12.6	12.1	36.0	13.8	44.1
July	10.0	8.9	29.9	10.6	36.0
August	9.0	8.0	33.0	9.6	40.0
September	9.6	8.9	29.0	10.4	36.0
October	11.0	9.9	41.0	11.6	54.0
November	11.0	9.9	43.0	11.3	49.0
December	10.4	9.9	42.0	10.6	49.0
Annual Average	**10.4**	**9.4**		**10.9**	**44.9**

C.2. Air Temperature

Wainwright Temperatures, 2008-2012

Month	Average Temperature (F)	Minimum Temperature (F)	Maximum Temperature (F)
January	-14.0	-44.0	32.0
February	-11.0	-45.9	30.9
March	-14.5	-41.1	26.1
April	4.1	-29.2	39.9
May	24.2	-9.0	52.0
June	38.9	21.9	66.0
July	46.0	28.9	80.1
August	45.1	28.0	73.9
September	36.4	17.1	57.9
October	24.2	-9.0	39.9
November	4.4	-29.9	34.0
December	-5.1	-36.0	30.9
	Annual Average: 14.9	**Absolute Minimum: -45.9**	**Absolute Maximum: 80.1**

Barrow Temperatures, 2008-2012

Month	Average Temperature (F)	Minimum Temperature (F)	Maximum Temperature (F)
January	-14.8	-45.0	32.0
February	-11.2	-45.9	28.9
March	-13.4	-40.0	18.0
April	5.2	-27.0	37.9
May	22.5	-9.9	41.0
June	35.4	26.1	62.1
July	41.7	28.9	72.0
August	41.8	27.0	66.0
September	35.7	12.9	54.0
October	25.0	-4.0	39.9
November	4.9	-24.0	33.8
December	-5.8	-31.0	30.2
	Annual Average: 13.9	**Absolute Minimum: -45.9**	**Absolute Maximum: 72.0**

Prudhoe Bay Temperatures, 2008-2012

Month	Average Temperature (F)	Minimum Temperature (F)	Maximum Temperature (F)
January	-19.5	-51.0	39.0
February	-13.8	-53.0	32.0
March	-19.4	-50.1	15.1
April	5.0	-27.9	39.9
May	23.6	-11.0	48.0
June	39.6	25.0	73.9
July	48.6	33.1	78.1
August	45.1	28.0	77.0
September	36.3	12.9	63.0
October	21.9	-14.1	45.0
November	1.0	-34.1	34.0
December	-10.0	-45.4	28.9
	Annual Average: 13.2	**Absolute Minimum: -53.0**	**Absolute Maximum: 78.1**

C.3 Visibility

Statistical summaries of cloud ceiling and visibility can be more easily misleading than other environmental factors. Both factors typically use a maximum distance to indicate a ceiling height or horizontal visibility from that distance, out to “unlimited.” This makes statistical summaries like “average ceiling” potentially deceptive.

We summarize these factors by median, minimum, and in the case of visibility, 25th percentile, and describe the meaning of each.

Median Ceiling & Visibility: This indicates the most common measurement. In ceiling records, a ceiling below maximum/unlimited is the most common measurement, indicating that prevailing conditions have a measured cloud ceiling, i.e., it is generally cloudy. In the case of visibility however, the median visibility is typically 10 statute miles, the maximum visibility. This indicates that typical conditions have visibility of 10 miles *or greater*, i.e., effectively unlimited.

Minimum Visibility & Ceiling: This indicates the minimum measurement. In the case of visibility, this drops to zero visibility, indicating thick fog. However, in the case of ceiling, the minimum recorded value is 100ft. A minimum of 100 therefore indicates a ceiling of 100 ft or lower, i.e. ground-level ceiling.

25th Percentile Visibility: Statistically capturing the visibility profile in a meaningful way can be difficult. 25th Percentile is included in the tables below to indicate the highest visibilities in the lowest-visibility 25% of the data. I.e., “25% of the time, visibility was less than or equal to this number." At Wainwright, for example, records indicate that 8 months a year, visibility is below the maximum more than 25% of the time. However, in no case is the 25th percentile below 3 miles. Even in the worst months, visibility is expected to be three miles or greater, 75% of the time.

Wainwright Cloud Ceiling and Horizontal Visibility, 2008-2013

Month	Median Ceiling (ft)	Minimum Ceiling (ft)	Median Visibility (sm)	Minimum Visibility (sm)	25th Percentile Visibility (sm)
January	Unlimited	100	10.0	0	5
February	6000	100	9	0	3
March	Unlimited	100	10	0	6
April	4600	100	10	0	5
May	1400	100	10	0	6
June	2800	100	10	0	10
July	4500	100	10	0	10
August	2000	100	10	0	10
September	2000	100	10	0	10
October	3100	100	10	0.25	7
November	2700	100	9	0.25	5
December	4300	100	8	0	3

Barrow Cloud Ceiling and Horizontal Visibility, 2008-2013

Month	Median Ceiling (ft)	Minimum Ceiling (ft)	Median Visibility (sm)	Minimum Visibility (sm)	25th Percentile Visibility (sm)
January	Unlimited	100	9.0	0	5
February	8500	100	7	0	3
March	Unlimited	100	10	0	7
April	6000	100	9	0	4
May	1300	100	10	0	4
June	1500	100	10	0	6
July	2700	100	10	0	7
August	1000	100	10	0	5
September	1800	100	10	0	7
October	2500	100	9	0.12	4
November	2300	100	8	0.12	4
December	9000	100	9	0	4

Prudhoe Bay Cloud Ceiling and Horizontal Visibility, 2008-2013

Month	Median Ceiling (ft)	Minimum Ceiling (ft)	Median Visibility (sm)	Minimum Visibility (sm)	25th Percentile Visibility (sm)
January	Unlimited	100	10.0	0	3
February	12000	0*	10	0	3
March	Unlimited	100	10	0	5
April	6500	100	10	0	4
May	1100	100	7	0	2
June	1800	100	10	0	10
July	7000	100	10	0	10
August	1500	100	10	0	5
September	1700	100	10	0	5
October	2300	100	9	0.00	4
November	2400	100	8	0.12	3
December	6000	100	10	0	5

*0-height ceiling in February is attributed to a recording anomaly. 100 feet is the typical minimum record value. Clouds often lack discrete, measurable boundaries the small scale, making very small-scale ceiling distinctions marginal.

Appendix D: Sea Ice Concentrations

Sea Ice Concentrations

Extracted from National Ice center maps, 2008-2012

	Chukchi Sea		Beaufort Sea	
Ice Concentration	**Data Occurrences**	**Weekly Occurrences**	**Data Occurrences**	**Weekly Occurrences**
No Ice	155	79	137	68
< 1/10	4	2	21	13
Bergy Water	0	0	0	0
1/10	0	0	0	0
1/10 to 3/10	6	4	4	4
2/10	4	1	2	1
3/10	3	2	1	1
3/10 to 5/10	2	1	3	2
4/10	1	0	0	0
4/10 to 6/10	0	0	0	0
5/10	3	1	1	1
5/10 to 7/10	3	1	1	0
6/10	0	0	1	1
7/10	3	2	0	0
7/10 to 9/10	2	1	4	2
8/10	1	0	2	1
8/10 to 10/10	0	0	1	1
9/10	1	1	0	0
Between 9 & 10 tenths	185	159	77	73
10/10	0	0	85	85
Unknown	0	0	0	0

Data occurrences and weekly occurrences are different because sampling is inconsistent. In rare cases, a week of sampling is skipped in NIC ice mapping, during summer or winter. Frequently, ice maps are made more-than-weekly during the shoulder months, when sea ice conditions are most dynamic.

Appendix E: Algorithms Used for Icing and Wind Chill

E.1 Prediction of Vessel Sea Spray Icing

We used the following formula (Overland, 1990):

$$\mathbf{PPR} = \frac{\mathbf{V_a (T_f - T_a)}}{\mathbf{1 + 0.3(T_w - T_f)}}$$

PPR = Icing Predictor ($m^{o}Cs^{-1}$)

$\mathbf{T_a}$ = Air Temperature (^{o}C)

$\mathbf{V_a}$ = Wind Speed ($m\ s^{-1}$)

$\mathbf{T_w}$ = Sea Temperature (^{o}C)

$\mathbf{T_f}$ = Freezing point of seawater (usually -1.7 ^{o}C or -1.8 ^{o}C)

The following table shows the expected icing class and rates for 20 - 75 meter vessels that are steaming into the wind.

Icing Class & Rate*

PPR	<0	0-22.4	22.4-53.3	53.3-83.0	>83.0
Icing Class	None	Light	Moderate	Heavy	Extreme
Icing Rates (cm/hour)	0	<0.7	0.7-2.0	2.0-4.0	>4.0
(inches/hour)		<0.3	0.3-0.8	0.8-1.6	>1.6

* **These icing rates are only a guide**. Actual icing rates depend on ship characteristics, cold soaking and exposure to sea spray.

Ref: Guest, P. (2008). Prediction of vessel sea spray icing. Retrieved from http://www.met.nps.edu/~psguest/polarmet/vessel/predict.html

Overland, J.E. (1990). Prediction of vessel icing for near-freezing sea temperatures. *Weather and Climate*, **5**, 62-77.

E.2 Prediction of Wind Chill

To calculate the New Wind Chill Index:

New Wind Chill $T(wc) = \mathbf{35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})}$ where $T(wc)$ is the Wind Chill in degrees F, V is the Wind Speed in MPH, and T is the temperature in degrees F.

Ref: National Weather Service. (2001). Wind Chill Chart. Dodge City, Kansas. NOAA. Retrieved from: http://www.crh.noaa.gov/ddc/?n=windchill#New

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