EPPR
EMERGENCY PREVENTION, PREPAREDNESS AND RESPONSE

# CIRCUMPOLAR OIL SPILL RESPONSE VIABILITY ANALYSIS

## TECHNICAL REPORT

ARCTIC COUNCIL

Circumpolar Oil Spill Response Viability Analysis: Technical Report

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CIRCUMPOLAR OIL SPILL RESPONSE VIABILITY ANALYSIS

# Technical report

## BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT

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Objective:The analysis estimates how often different type of oil spill systems could be deployed in the Arctic based on defined operational limits and a comparing these to a hindcast of metocean data.


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# EXECUTIVE SUMMARY

The purpose of this circumpolar Arctic response viability analysis is to better understand the potential for different oil spill response systems to operate in the Arctic marine environment. There is increasing concern about the risk of oil spills as human activity increases in the Arctic. The Arctic Council's Emergency Prevention, Preparedness, and Response (EPPR) Working Group commissioned this study of oil spill response viability for the circumpolar Arctic region, co-sponsored by Norway, the United States, and Denmark. DNV GL and Nuka Research and Planning Group, LLC conducted the study under contract to the Norwegian Coastal Administration and the U.S. Bureau of Safety and Environmental Enforcement.

A response viability analysis estimates the percentage of time that metocean conditions may be favourable, marginal, or not favourable for a particular oil spill response system. This study considers the combined effects of wind, waves, air temperature, wind chill, sea ice, superstructure icing, horizontal visibility, and daylight/darkness on 10 marine oil spill response systems. Those systems represent 9 examples of proven mechanical recovery, dispersant, and in-situ burning response systems currently in use somewhere in the Arctic region. The tenth system analyzed, in-situ burning with herders, is currently under development.

Metocean data are compiled into a gridded dataset covering the Arctic Marine Assessment Programme (AMAP) area, encompassing the Arctic Ocean and adjacent seas. A 10-year hindcast was used in this analysis.

While each system studied had at least some time during which conditions were favourable or marginal, overall conditions were more often not favourable to response. However, the results varied widely by system, season, and location. Conditions were favourable at least 10% of the time for all three dispersant systems studied and a mechanical recovery system involving the use of two vessels with containment boom. On the other hand, conditions were not favourable at least 90% of the time for the ignition of in-situ burning from a helicopter (both for the system using ice for containment as well as the use of herders), and also for the use of vessels of opportunity with containment boom for mechanical recovery.

Response viability varied significantly throughout the year and is generally much better during the months that are ice-free in most areas (July to October). In winter, conditions are generally not favourable to response (with few exceptions). Response viability in the fall is generally better than in the spring.

Response viability also varied with location. Conditions in the Bering Sea, Barents Sea, Norwegian Sea, Baffin Bay, Hudson Bay, and North Atlantic are more likely to be favourable for a spill response than other areas within the Arctic region.

Waves, sea ice coverage, and visibility were the metocean conditions most likely to affect the deployment of response systems, though this depends on location. Aerial and vessel-based platforms were similarly impacted differently.

This project benefitted from input provided by EPPR and their invited oil spill response experts.

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# 1 INTRODUCTION

With the expansion of human activity in the Arctic, there is increasing concern about the risk of oil spills in the region. The Arctic Council's Emergency Prevention, Preparedness, and Response (EPPR) Working Group identified the need to better understand oil spill response options in Arctic conditions throughout the year to inform response planning and optimize oil spill response options in the region.

The EPPR Working Group commissioned this study of oil spill response viability for the circumpolar Arctic region, co-sponsored by Norway, the United States, and Denmark. DNV GL and Nuka Research and Planning Group, LLC conducted the study under contract to the Norwegian Coastal Administration and U.S. Bureau of Safety and Environmental Enforcement.

## 1.1 PURPOSE OF THE STUDY

The purpose of this Arctic circumpolar response viability analysis is to better understand the ability of existing[1] spill response systems to operate in the Arctic marine environment. A response viability analysis estimates the percentage of time that conditions may be favourable, marginal, or not favourable for a particular response system based on past conditions for a given area. It takes into account the combined effect of a subset of metocean conditions on the response systems studied.

This approach, which has been used in several subarctic areas (DNV GL, 2014, 2015a; Nuka Research, 2016, 2014, 2008, 2007a, 2007b; SL Ross, 2011), quantifies the effects of Arctic meteorological and ocean, or "metocean," conditions on different response techniques by establishing operating limits for different response systems and comparing these to a hindcast of available metocean parameters.

The results provide information regarding when conditions for various response strategies and systems would be viable and when their use may be constrained or precluded given certain metocean conditions in the circumpolar Arctic region. It also provides a comparison across sub-regions of the study area, seasons, and different oil spill response systems. The results illustrate some of the fundamental challenges to oil spill response in the region, with the intent of informing response planners and responders seeking to maximize the potential to mount a response despite challenging conditions. Response plans must still consider the particular conditions for a particular location, as well as the full range of factors relevant to planning beyond those addressed in this study. Those conducting operations in the region could use these results to inform risk mitigation efforts in addition to spill response planning.

1 One of the techniques studied, the use of herders for in-situ burning, remains under development.

This project benefitted from the input of a diverse group of oil spill response experts. Experts convened by EPPR in Copenhagen, Denmark in October 2015 (DNV GL, 2015b) provided input on the project formulation and scope. Subsequent input was obtained from these and additional experts on the response systems and limits proposed for the analysis through a webinar and opportunity for written comments in May 2016. Several changes were made based on the input received, however all inputs and results are the full responsibility of the DNV GL and Nuka Research and Planning Group, LLC team.

This study will be presented in to the EPPR Working Group. The project may be used to inform a future EPPR Circumpolar Marine Environmental Risk Assessment.

## 1.2 SCOPE

The scope of a response viability analysis has three elements: (1) geographic area; (2) metocean dataset (parameters included and timespan covered); and (3) the response systems studied.

This study does *not* describe the likelihood of an Arctic oil spill or consequences to people or the environment if one occurs. The study does not include the immediate or long-term human or environmental effects, impacts, and consequences of the use of selected response countermeasures evaluated in this report. It also does not provide a comprehensive overview of Arctic oil spill response options or implementation. Many factors related to the ability to mount a response in any given situation are not included in this study.

> The results of this response viability analysis do not estimate the amount of time that a response could be mounted, but rather the percentage of time that various metocean conditions may affect it.

### 1.2.1 Geographic area

The study area is comprised of the marine waters within the boundary used by the Arctic Marine Assessment Programme (AMAP) of the Arctic Council. See Figure 1-1.

The AMAP area covers approximately 19,756,989 $km^2$ (7,628,216 $mi^2$) of ocean, including the intersecting national waters of Denmark (Faroe Islands), Canada, Greenland, Iceland, Norway, Russia, and United States. The region is characterized by high natural variation, described as the Sub-Arctic, Low-Arctic, and High-Arctic regions. The AMAP area was applied to this study based on input from EPPR. Several alternative definitions of the Arctic exist, such as the Arctic Circle and the 10°C isotherm.

### 1.2.2 Metocean conditions

The following metocean parameters were used: (1) wind speed, (2) wave height, (3) air temperature, (4) sea surface temperature, (5) sea ice coverage, (6) horizontal visibility, and (7) daylight/darkness. Wind chill and superstructure icing were calculated based on other parameters.

### 1.2.3 Response systems

Table 1-1 lists the 10 response systems studied. The systems are all intended for a

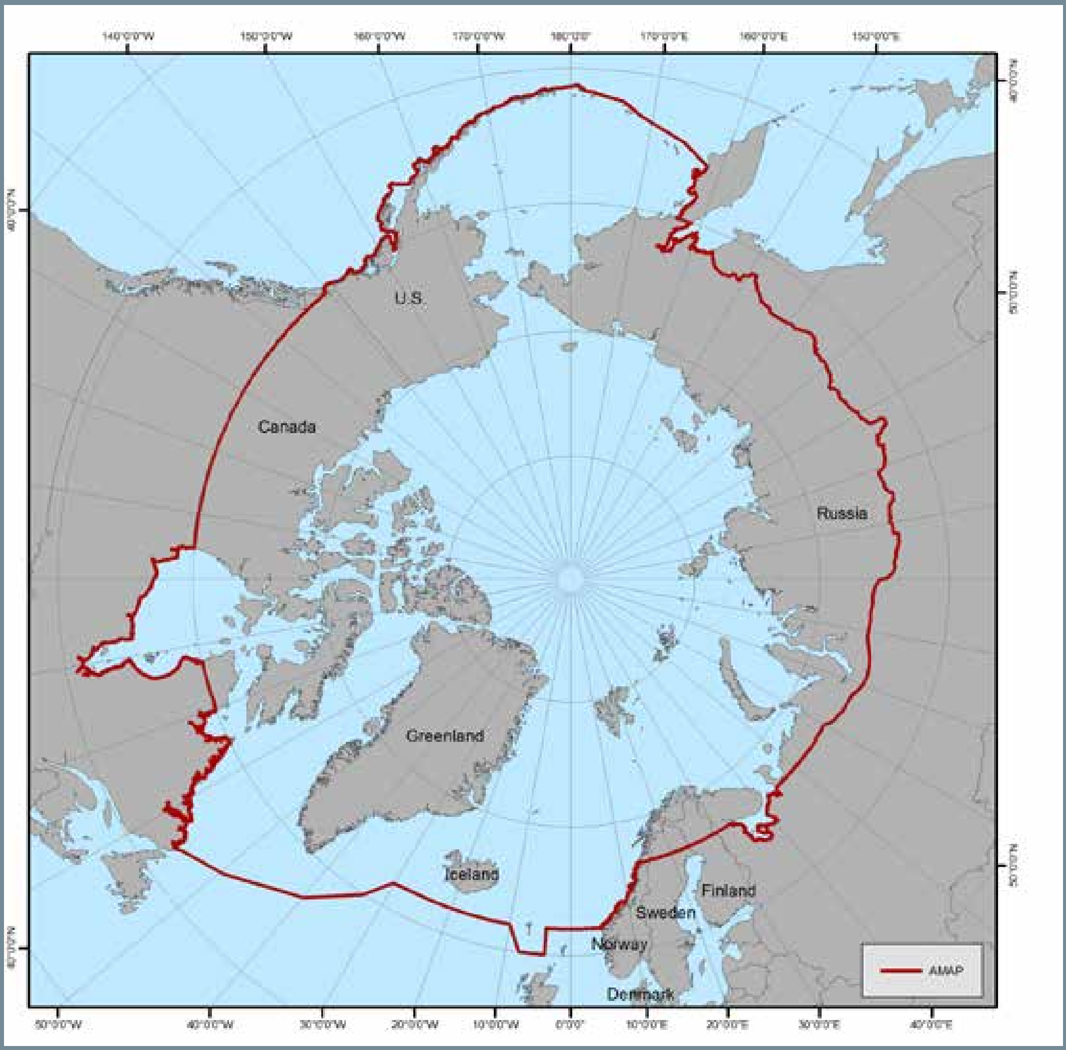



Figure 1-1. Study area based on Arctic Monitoring and Assessment Programme (AMAP) boundary

response to a persistent oil spill in a marine environment. (Response on land, or on top of or underneath solid ice would necessitate different systems or variations on the systems studied.)

## 1.3 ORGANIZATION OF THIS REPORT

Beginning in Section 2, this report provides brief background information about Arctic oil spill response, including how response may be affected by metocean conditions. Section 3 describes the methodology used for the response viability analysis. Section 4 summarizes the metocean datasets used and explains why they were selected. Section 5 describes the response techniques studied, with the results for each discussed in Section 6 (and presented in full in Appendix A, B and C). Observations are presented in Section 7 with a conclusion in Section 8.

| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
|---|---|---|
| Two vessels with boom | Vessel application | Vessels with fire boom |
| Single vessel with outrigger | FIxed-wing aircraft application | Helicopter with ice containment |
| Three vessels of opportunity (VOO) with boom | Helicopter application | Helicopter with herders |
| Single vessel in ice | | |

Table 1-1. Response systems studied

# 2 BACKGROUND

This section provides general background information about the concerns about oil spill response in the Arctic, response options, and some of the impacts of metocean conditions oil spill response.

All the world's oceans experience some amount of wind, waves, and currents, impeded horizontal and vertical visibility, and cycles of daylight and darkness (although the latter are much different at high latitudes than low). On the other hand, while sea ice, wind chill, superstructure icing, and icebergs are not unique to the circumpolar regions, they have greater prominence in the Arctic as compared to lower latitudes. Brief background is provided on these conditions to enhance the reader's understanding of the study and its results.

## 2.1 CONCERNS ABOUT OIL SPILLS IN THE ARCTIC

In response to concerns about oil spills in the Arctic, the eight member states of the Arctic Council established an agreement to cooperate on oil spill response in the Arctic, signed at Kiruna, Sweden in May 2013. That document acknowledges "the increase in maritime traffic and other human activities in the region," as well as, "the challenges posed by harsh and remote Arctic conditions on oil pollution preparedness and response operations" (Arctic Council, 2013). The Arctic Council's *Arctic Marine Shipping Assessment* identified oil spills as the most significant threat to the marine environment from shipping in the Arctic (Arctic Council, 2009). This response viability analysis is one of numerous follow-on activities stemming from the shipping assessment (Arctic Council, 2015a). It is also identified in the Arctic Council's *Arctic Marine Strategic Plan 2015 - 2025* (Arctic Council, 2015b).

The EPPR Working Group also has several initiatives completed or underway related to oil spill response. In particular, we recommend to the reader EPPR's 2015 *Guide to Oil Spill Response in Snow and Ice Conditions* (EPPR, 2015) for a more thorough discussion of Arctic oil spill response than is warranted here.

The potential for oil spills, response infrastructure, regulatory context, logistical support infrastructure, and environmental sensitivity vary widely across the study area. Many of these characteristics also vary significantly throughout the year, or over time due to other changes in the natural environment. This study emphasizes a broad view of the study area but acknowledges that concerns about spills and spill response planning are inherently "local," even as it is instructive to consider the Arctic region as a whole in keeping with the Arctic Council's regional approach.

## 2.2 ARCTIC OIL SPILL RESPONSE

Marine oil spill response in the Arctic will rely on the same general approaches used elsewhere, though they can be modified for Arctic conditions. For an oil slick on the surface of the ocean, as contemplated in this study, there are three common approaches that may be used singularly or in combination:

(1) ***Mechanical recovery:*** Contain and collect oil from the water's surface for disposal. Requires storage of recovered fluids until they can be properly managed.

(2) ***Dispersants:*** Add chemicals to the slick to speed the dispersion of oil droplets into the water column.

(3) ***In-situ burning:*** Conduct a controlled burn of oil on the water's surface. The slick may need to be contained using vessels and boom in order to achieve a thickness adequate for ignition and burning.[2]

A response also requires the ability to locate the oil and target recovery or treatment to the thickest part of the slick. This is particularly important in open-water response activities where the slick may spread over a large area. Finding and assessing the slick requires achieving some height of eye above the affected area, typically with an aircraft but also potentially via satellite, drone, or aerostat. As this is not one of the systems studied, we do not analyze methods for remote sensing in darkness or cloudy conditions that are currently in use or under development.

This section summarizes some of the ways that response deployment may be influenced by metocean conditions typical of the Arctic region, first considering the effects on the deployment and technical operation of the response (such as skimming oil or igniting a slick), then the effects on the vessels or aircraft on which the response is based. Sections 4 and 5 describe the specific metocean parameters and response systems studied in the analysis.

### 2.2.1 Effects of metocean conditions on response operations

Metocean conditions can affect several different aspects of a spill response, including spill response equipment, operational platforms, and the safety of responders or vessel and aircraft crew. The safety of responders and any others involved in an incident (such as the crew or passengers of a stricken vessel, for example) will always be the first priority in any response. While most effects are expected to be *detrimental* to the response, there may be cases where an effect is *positive*, e.g., if ice provides some degree of natural containment of the oil without impeding access for recovery or treatment. This section summarizes some of the possible impacts both to the deployment of response equipment (Table 2-1) and to the response platform (Table 2-2).

Except when conducted on land, mechanical recovery is generally based on a vessel or vessels, but the equipment used to contain and recover the oil (boom and skimmers) can succumb to the effects of wind, waves, and other conditions regardless of the vessels used. Waves or ice can make containment more difficult, or reduce the amount of contained oil that is successfully recovered by the skimmer. Pumps and hoses can be compromised in cold temperatures. High winds, waves, or icy spray may make it difficult or unsafe to deploy or retrieve equipment from the deck of a vessel.

[2] Chemical accelerants may also be used, but are not considered in the systems studied here.

Table 2-1. Effects of Arctic conditions on mechanical recovery, dispersants, and in-situ burning response systems

| METOCEAN CONDITIONS | PRIMARY EFFECTS ON… | | |
|---|---|---|---|
| | **Mechanical Recovery** | **Dispersants** | **In-situ Burning** |
| High winds, gusts, or cross-winds | • Ability to deploy/retrieve system components<br>• Ability to contain oil, due to boom failure (splash-over) | • Ability to apply proper dosage to slick | • Safety of crew, due to winds, inhalation, or fire<br>• Ability to target slick for ignition<br>• Volatile components not maintained in sufficient concentration for ignition/burn |
| Sea state | • High waves may challenge:<br>○ Deployment/retrieval of system components<br>○ Containment, due to boom failure (splash-over, submergence, wave-keeping)<br>○ Recovery, due to skimmer failure | • Sustained calm waters may result in too little mixing energy for effective dispersion<br>• High sea states may physically disperse oil naturally | • High waves may challenge:<br>○ Ability to deploy and retrieve system components<br>○ Ability to contain oil, due to boom failure, if used |
| Fast currents* | • Ability to contain oil (entrainment, submergence) | • (Effect potentially similar to sea state) | • Ability to contain oil in boom or ice |
| Cold air, cold water, wind chill | • Pumps and hoses freezing<br>• Icing clogging skimmer or inhibiting equipment<br>• Failure of boom components from freezing temperatures | • Ability to spray dispersant, due to nozzle icing<br>• Ability to pump fluids, due to increased viscosity or freezing | • n/a |
| Sea ice coverage | • Ability to deploy/retrieve system components due to interference/entanglement by ice<br>• May help to contain oil naturally, or hinder use of boom if ice overwhelms or obstructs<br>• Ice obstruction reduces skimmer recovery efficiency | • Ability to achieve proper mixing energy (dampens waves and reduces mixing energy) | • May help to contain oil naturally, or hinder use of boom to achieve sufficient slick thickness |

* Currents may also exacerbate effects of ice drift and/or sea state.

Table 2-2. Primary effects of metocean conditions on vessel and aircraft platforms

| METOCEAN CONDITIONS | PRIMARY EFFECTS ON: | |
|---|---|---|
| | **Vessel Operations** | **Aircraft Operations** |
| High winds, gusts, or cross-winds | • Safety of crew working on deck<br>• Ability to stay on station | • Safety of aircraft, especially during takeoff and landing (though conditions at the slick may be different than at airstrip)<br>• Ability to carry out mission |
| Sea state | • Safety of crew working on deck<br>• Ability of vessels to stay on station or maintain proper speed | • Extremely high waves could impact low-flying helicopter |
| Fast currents | • Ability to maneuver or stay on station, though effect lessened to the extent that whole slick is moving | n/a |
| Low air or water temperature (including wind chill) | • Superstructure icing may decrease vessel stability<br>• Crew may be unable to operate safely on deck due to cold, wind chill, or icing<br>• Brittle failure in metals | • Safety of aircraft, icing in certain conditions |
| Sea ice coverage | • Safety of vessel operations (hull damage, freezing in)<br>• Ability of vessels to navigate, stay on station, or maintain proper speed | n/a |
| Icebergs | • Safety of vessel operations (hull damage) | n/a |
| Limited horizontal visibility (fog, precipitation) | • Potential for collisions and allisions<br>• Impacts vessels' ability to navigate safely | • Potential for collision with obscured terrain or other aircraft<br>• Ability to carry out mission due to lack of visibility |
| Limited vertical visibility (clouds) | n/a | • Safety of aircraft due to obscured terrain and collision with other aircraft<br>• Ability to carry out mission due to lack of visibility or height of eye for observation |
| Darkness | • Ability to target and maintain operations within an oil slick | • Ability to carry out mission due to lack of visibility |

Both dispersant application and in-situ burning bring the option of deployment from a vessel *or* aircraft, but in both cases it must be possible to see and target the slick as intended. For dispersant application, cold can impede proper spray and dosing (though this may vary with different dispersant products). If there is not enough mixing energy, dispersion may not be effective. Or, if there is abundant natural wave energy, adding chemical dispersants may not be necessary. Burning is generally more difficult in wind and waves.

Effects on response will also vary depending on the nature of the conditions. For example, wind-driven waves will have a greater impact than swell, even at the same wave height. Sea ice thickness and type will also have an effect that is not fully captured by the extent of ice coverage (see discussion in Section 2.3).

Mounting any response requires being able to move equipment and people to the slick area and maintaining them there for as long as needed to deploy the tactic. This is typically done with vessels and/or aircraft. Table 2-2 summarizes some of the effects Arctic conditions may have on the safe operation of vessels and aircraft used in an oil spill response. Vessel particulars or the type of aircraft (helicopter vs. airplane) will determine the exact limitations on a given response. As noted, the effects of limited visibility are particularly tied to the platform.

### 2.2.3 Oil slick behavior

Oil spilled to the marine environment will immediately begin to spread and weather depending on the type of oil and the wind, waves, temperature, currents, and other aspects of the marine environment. The influence of these processes on the slick itself will greatly affect the selection of response options and the effectiveness of those options. This response viability analysis focuses on the ability to deploy response systems and expect them to generally work as intended; it does not consider the relationship between slick behavior and response system selection or response effectiveness.

### 2.2.4 When no response is the best response

When choosing from among available response options, responders typically consider the option of not deploying any response (even if conditions are favourable). For example, if high waves preclude mechanical recovery or in-situ burning, it may still be possible to spray dispersants. However, responders may determine that the wave energy itself will disperse the oil, and so decide there is no added benefit gained by spraying chemicals into the environment. Because it is always feasible to mount no response, and our study assesses the feasibility of different systems, this study does not include "no response" as a response tactic. While conditions may inform the decision to choose this "natural attenuation" approach, there are no operating limits to be applied. It is always technically possible *not* to respond.

### 2.2.5 Other aspects of Arctic context that may impact response

This response viability analysis focuses on the ability to deploy a particular response system in a given area based simply on the metocean conditions that have been documented to occur there. It does not consider whether equipment is available in a location or how long it would take to mobilize and deploy response personnel or resources, nor the many yet critical supporting aspects of a response such as transportation, communications, waste management, housing, meals, medical care, or the need to rescue vessel crew or passengers. These and other aspects of a large-scale response could be particularly challenging in the Arctic context where infrastructure is limited and conditions can be harsh (EPPR, 2015).

## 2.3 SEA ICE

The World Meteorological Association (WMO) defines sea ice as, "any form of ice found at sea which has originated from the freezing of sea water," (WMO, 2014). It is a prominent feature in the Arctic, present year-round at the highest latitudes and extending southward seasonally. Sea ice has the potential to significantly impact spill response, depending on the location of the spill and the timing of seasonal ice cycles and movement. In addition to varying throughout the year, sea ice can be expected to vary significantly across the region, depending on local bathymetry, shore type, river influence, currents and winds, and other features. Ice conditions for a given location can also be expected to change year-to-year, in addition to the significant changes attributed to climate change (EPPR, 2015).

Sea ice exists in many forms based on the area covered, thickness, age, roughness, and stage of the ice as well as the forces acting upon it. While there are hundreds of words used to describe sea ice, "ice concentration" is one simplified way to describe complex and highly variable ice conditions by simply estimating the portion of an area that is covered with ice. Sea ice concentration provides a convenient metric for the viability analysis, but its limitations should be recognized. Other aspects of the ice conditions and seasonal ice cycle can affect  response operations. Table 2-3 shows the sea ice concentration associated with WMO terms as applied in this report.

Table 2-3. Ice concentration categories and WMO nomenclature (WMO, 2014)

| ICE CONCENTRATION | WMO TERMINOLOGY |
|---|---|
| 0-10% | Open water |
| 10-40% | Very open pack ice |
| 40-70% | Open pack ice |
| 70-90% | Close pack ice |
| 90-100% | Consolidated ice/very close pack ice |
| 100% | Compact pack ice |

Sea ice is constantly changing. The frequency of daily recordings of ice concentration of 30% or greater can be used to characterize sea ice for a given place and time, since areas may have different ice conditions not only seasonally, but from one year to the next. Figure 2-1 shows the sea ice frequency for January, April, July, and October: the shading from blue to white indicates areas with 0-100% daily recordings of *at least 30%* ice concentration based on the dataset used in this study.

## 2.4 WIND CHILL

Cold temperatures can have a significant influence on working conditions. The combination of cold air temperature and wind leads to a perceived decrease in air temperature felt by the human body on exposed skin. This "wind chill" effect will reduce the working periods outside (Table 2-4). Outdoor work may require specialized work clothing, which can reduce dexterity and prolong the time it takes to accomplish tasks. Planning for work in this environment requires attention to vessel conditions, crew training and gear, and the number of personnel that may be required (which may

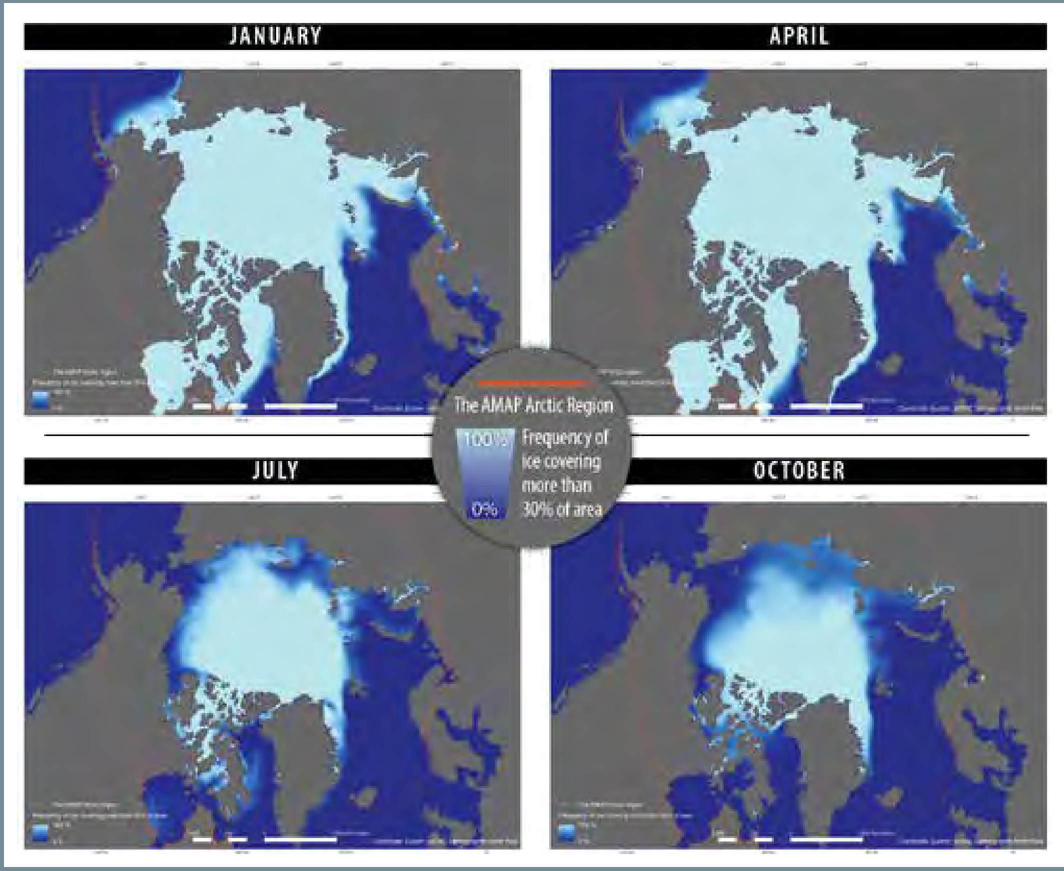



Figure 2-1. Ice frequency within study area based on dataset used for analysis. Shading from blue to white shows the percentage of time that a location has ***at least*** 30% ice concentration during January, April, July, and October.

be higher due to the need to rotate personnel on short shifts for outdoor work). Wind chill is included in the metocean dataset for this analysis as discussed in Section 3.

Table 2-4. Impact of wind chill and wind chill factor (Woodson, 1992)

| WIND CHILL | IMPACT ON HUMAN COMFORT |
|---|---|
| **above -13 °C** | None |
| **below -13 °C, above -24 °C** | Unpleasant |
| **below -24 °C, above -33 °C** | Possible frost nip |
| **below -33 °C, above -50 °C** | Frostbite likely |
| **below -50 °C** | Exposed skin will freeze in 30 seconds |

## 2.5 VESSEL AND AIRCRAFT ICING

Ice accretion on vessels and aircraft is a potential concern for operations in cold climates. Ice accretion on vessels has two principle sources: sea spray (which may build up on vessels when the air temperature drops below sea water's freezing point of about -2°C) and precipitation (freezing rain, freezing fog, or wet snow). Even light ice accretion can lead to: (1) slippery decks, ladders, and handrails; (2) winches, derricks, and valves being coated with ice; (3) interference with navigation due to ice on radar antennas; and (4) life-saving and firefighting equipment can be rendered unusable. Ice accretion can also compromise stability by increasing the draught, reducing freeboard, and raising the center of gravity of the vessel. In this study, we estimate the extent of vessel icing based on air temperature and sea surface temperature using an equation from Overland (1990).

As with vessels on the sea surface, aircraft can also encounter icing during operation. This occurs when cold water freezes on impact with any part of the external structure of an aircraft. Airframe icing can lead to reduced performance, loss of lift, altered controllability, and ultimately stall and subsequent loss of control of the aircraft. Aircraft icing is not included in the quantitative analysis due to a lack of the data needed to calculate values, such as temperatures at different elevations. It should also be noted that resources to conduct chemical de-icing might be severely limited in remote Arctic regions.

## 2.6 ICEBERGS

Icebergs are large pieces of frozen freshwater that have broken off glaciers or ice shelves and drift in the open water or together with sea ice. Icebergs can be very large, but will gradually melt and disappear. The lifespan of an iceberg will depend on its original size and the metocean conditions following its trajectory. Glacial ice is typically significantly stronger than sea ice, and cannot be broken through by vessels. At a safe distance, icebergs are not normally considered as a risk for vessel traffic as they can be circumnavigated. Clusters of small icebergs or debris ice (small icebergs, bergy bits and growlers) are not generally expected to represent absolute limitations to an oil spill response. Due to this understanding as well as a lack of data, icebergs are not included in the analysis though they do occur in parts of the study area.

# 3 METHODOLOGY

The general approach to implementing an oil spill response viability analysis is to compare a set of metocean conditions for a given location to information about the limitations on oil spill response systems.

Compiling the metocean conditions requires building a hindcast of datasets for the parameters being studied. Establishing the system limitations requires first choosing the systems to be studied, then defining the limitations of those systems that correspond to parameters used for the metocean conditions. For each time period recorded in the dataset (or, "timestep"), a rule is applied to determine whether conditions during that time would be favourable, marginal, or not favourable for a response. The results are presented as a percentage of time that the metocean conditions in a given location are categorized as favourable, marginal, or not favourable for a particular system. This is portrayed geographically, numerically, and graphically. This section describes the methodology used to develop the necessary inputs and apply this approach. (See Figure 3-1).

In this study, response viability represents a classification system for the prevailing metocean conditions. It is not a system for the classification of response systems. Although these two perspectives are related, the results of the analysis are extractions from the metocean dataset based on a set of rules. The results, therefore, do not estimate the percentage of time that a response could be mounted, but rather the percentage of time that conditions may affect it (or not).

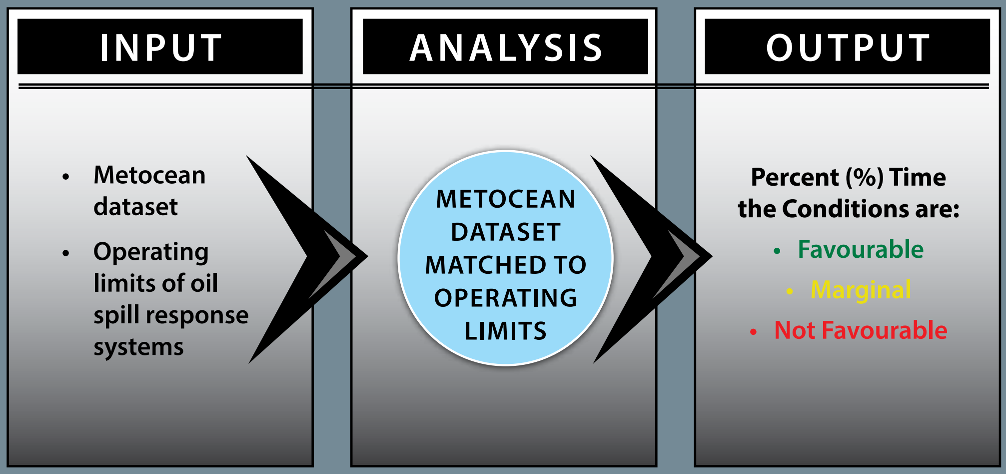



Figure 3-1. Summary of approach to oil spill response viability analysis

## 3.1 ESTABLISHING INPUTS: METOCEAN DATA AND OPERATIONAL LIMITS

The primary inputs to the analysis are the metocean data and operational limits for the systems studied.

### 3.1.1 Metocean data

A metocean dataset was built for this project based on input received from experts and subsequent research of available data sources (described in Section 4). At the 2015 workshop, participants agreed that the response viability analysis should focus on the marine areas within the AMAP boundaries as was shown in Figure 1-1.

The following metocean conditions were identified as being important to the analysis: wind, waves (sea state), sea ice, air and sea temperature, and visibility. These factors translated into the key parameters used for the analysis, as shown in Table 3-1.

Table 3-1. Metocean conditions and parameters for response viability analysis

| Metocean Conditions | Parameters Potentially Impacting Oil Spill Response |
|---|---|
| Wind | Wind speed (m/s) |
| Sea state (waves) | Significant wave height (m) |
| | Average wave period (s) |
| Sea ice | Ice coverage (%) |
| Air and sea temperature | Air temperature (°C) |
| | Superstructure icing (cm/hr)* |
| | Wind chill (w/m$^2$) |
| Visibility | Daylight/darkness |
| | Horizontal visibility (m) |
| | Cloud ceiling (m)** |

* included for vessels, not aircraft
** not included in quantitative analysis due to lack of data

The metocean data are combined in a geospatial dataset based on 25-km x 25-km grid cells. For each metocean parameter, conditions are compiled for every grid cell in 6-hour timesteps over a 10-year period. Section 4 describes the criteria used in researching and selecting metocean data sources, as well as the datasets acquired and the way they were processed for use in the response viability analysis.

### 3.1.2 Response systems and operating limits

Within the general approaches of mechanical recovery, dispersants, and in-situ burning, actual systems vary throughout the study area. To limit the number of systems analyzed, experts at the Copenhagen workshop in October 2015 suggested that the analysis focus on a set of "baseline" systems representative of existing, proven versions of the "best" systems that might be used in Arctic conditions for each of the three response strategies.[3]

[3] The one exception to this is the in-situ burning tactic that includes the application of chemical herders (used to help thicken the slick when containment boom cannot be deployed and the ice is not sufficient to provide adequate containment). This tactic can be considered in development, and was added with input from experts following the vetting of system descriptions and corresponding limits in

A final list of 10 systems and associated limits was refined following further expert input in May 2016, and approved by EPPR project co-leads prior to implementation of the analysis. For each system, response limits were identified to describe the range of conditions that would be favourable, marginal, or not favourable for that system. The limits are defined in three categories to represent the fact that response will not go from favourable to not favourable at an exact point, but will instead degrade more gradually.

The three categories are assigned colors, as described in Table 3-2.

Table 3-2. Response viability categories

| Category | Description |
|---|---|
| Green | Generally ***favourable*** conditions in which the tactic could be expected to be deployed safely and operate as intended. |
| Yellow | Conditions are ***marginal***, such that the tactic could be deployed but operations may be challenged or compromised. |
| Red | Conditions are ***not favourable***, so the tactic would typically not be used due to the impact of metocean conditions on safety or equipment function. |

Where possible, response limits used in the analysis were defined based on published literature on the components specified in the system. However, setting response limits for a particular system is ultimately a subjective combination of best professional judgment, real-world experience, response tactics guides developed by industry or government agencies, government guidance or policies, and published results of studies or observations. Regulatory limits may also come into play (as for aircraft). Limits drawn from the literature may be based on meso-scale or full-scale field trials rather than actual responses or exercises when that provides the best or only documentation available.

As noted, for the purpose of the analysis the limits are expressed for each of the metocean parameters in the dataset. There may be conditions not included in the dataset that will impact a response, however: these could be other metocean conditions such as current or icebergs, or the infinite range of other factors that will determine the decision to deploy a response (weather forecasts, availability of resources, responder availability and qualifications, necessary support logistics, accurate information regarding slick location and movement, etc.) Additionally, not all parameters apply to all systems.

## 3.2 ANALYSIS

Once the metocean dataset, response systems, and corresponding operational limits are established, the analysis can be implemented. The analysis is implemented for each grid cell in the metocean dataset using a custom code. The analysis was first conducted for each timestep in each grid cell in the study area.[4] A subsequent analysis of 11 individual grid cells provided a more in-depth analysis of those points.

May 2016.

[4] 10 years x 365 days x 4 timesteps = total 14,600 timesteps per grid cell x 29,443 grid cells = 429,867,800 calculated timesteps in total for each response system.

### 3.2.1 Geospatial analysis

Each timestep in the dataset (in this case, 6-hour increments) is identified as green, yellow, or red for a particular response system based on concurrent conditions recorded for that timestep and the operational limits established. The following rules are applied to establish the category for each timestep and each grid cell:

- If any condition is ruled RED -> RED
- If all conditions are ruled GREEN -> GREEN
- YELLOW otherwise

After each timestep is identified as green, yellow, or red, the percentage of timesteps of each color is calculated for a given month and for the year overall. This is presented empirically and geospatially.

For each response system studied, 12 standard maps are produced to illustrate the distribution of the three response viability categories (red, green, yellow) across the year using four focus months: January, April, July and October. This results in 120 maps in total (shown in Appendix A). The percentage of time that conditions were identified as favourable, marginal, or not favourable is calculated for each month of the year based the whole study area.

The results are then presented on map based on a five-increment scale for each category. The scale refers to the percentage of time that the viability categories are present in each grid cell for the selected month, based on the calculation illustrated above. Based on this the spatial distribution of the viability can be studied as patterns of changing colors throughout the study area.

### 3.2.2 Response Viability Index (RVI)

The map-based results are also used to present a Response Viability Index (RVI). The RVI maps provide a more aggregated illustration of response viability than the maps showing the green, yellow and red viability categories separately. The RVI maps present for each grid cell, on a scale from 0 – 2, the highest calculated viability when comparing all the 10 systems in the study. This illustrates the optimal baseline of applying the optimal baseline system in terms of response viability. This relates to a key consideration for response planning and speaks to the concept of a "response toolbox" in which planners and responders have more than one option available to them for any given location. This is calculated as follows:

1. Scoring system is established: Favourable = 2, Marginal = 1, Not Favourable = 0.
2. Identify the highest score achieved for any given system for each (relevant) time step, for each grid cell, for each month.
3. Calculate an average RVI number (between 0-2) for each grid cell, for each month, for each system by dividing the sum with number of relevant timesteps.
4. Calculate the RVI by taking the maximum monthly RVI from the 10 systems.
5. Present results for each grid cell in the study area based on color-coding. (Maps are produced for four focus months: January, April, July, and October.)

### 3.2.3 Location-specific analysis

The study area includes 29,443 grid cells. Eleven individual grid cells were selected for more in-depth analysis. The analysis of individual grid cells provides the opportunity to explore the metocean conditions influencing the results and focus on variations across the year. The 11 locations were chosen to contrast results at different latitudes and longitudes within the study area, with a particular focus on areas used for shipping and other activities (see Figure 3-2). The 11 points represent a relatively even and representative geographical distribution throughout the region, but it is important to note that they were chosen randomly prior to analysis and are not based on preliminary results of the study. The analysis of the single grid cells is complementary to the map-based results. It was implemented for each response system in each of the 11 locations. The same metocean data and response limits are used, and the same "rule" for identifying a timestep as green, yellow, or red is applied. Several small differences in analysis between the point analysis and the regional analysis relating to how gaps in the metocean dataset are handled introduce a discrepancy of up to a few percent between the point-location analyses and the gridded results.

The results from the location-specific analyses are presented using annual "cycle graphics" (shown in Appendix B). These show the portion of time in each week of the year (averaged for the 10 years in the dataset) that is green yellow, or red. For red or yellow results, they provide a gradation based on the number of parameters that were yellow or red. They are also produced for single metocean parameters as well as all parameters combined to provide a view of which factors have the greatest influence on results.

### 3.2.4 Sensitivity analysis

A sensitivity analysis was conducted to understand the potential changes to the results of the analysis if systems were more tolerant of wind and waves. Parameters that tend to be very closely associated with safety (visibility, structural icing, cold, etc.) were not analyzed in the sensitivity analysis. Sea ice was not analyzed because based on the metocean dataset, conditions are most often at one extreme or the other of the range from 0-100% coverage so incremental adjustments to the limits would not have a significant effect on the overall results of the analysis.

Wind limits for all systems were changed so that the transitions between favourable/marginal categories and marginal/not favourable categories were each increased by 1 m/s (1.9 kts), 2 m/s (3.9 kts), 3 m/s (5.8 kts), and 4 m/s (7.8 kts). Wave limits were similarly modified by 0.2 m (0.7 ft), 0.4 m (1.3 ft), 0.6 m (2 ft), and 0.8 m (2.6 ft).

This was analyzed across the entire study area, with results compared to those achieved by applying the same method to the 11 locations in Figure 3-2.

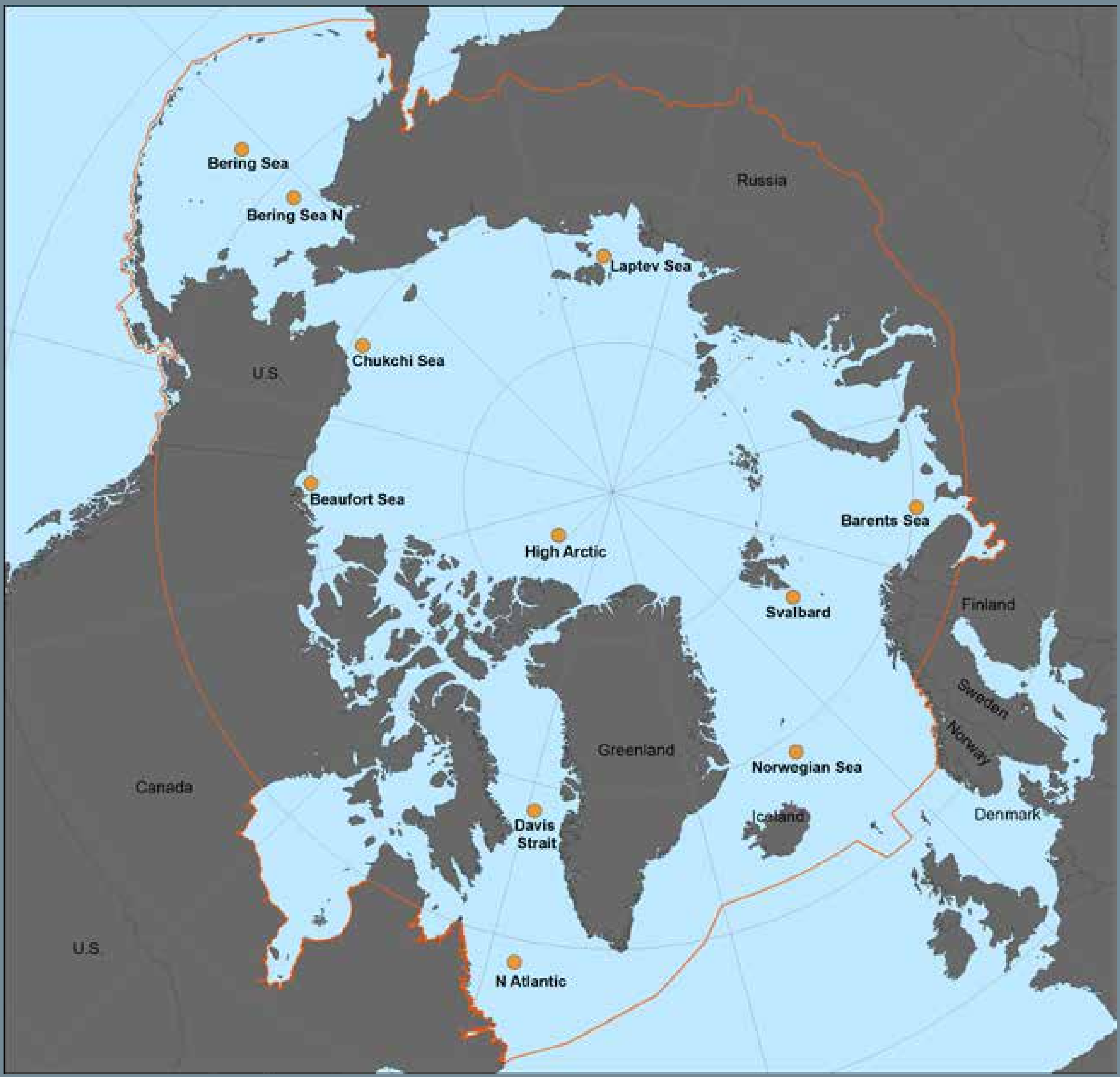



Figure 3-2. Locations selected for location-specific analysis

## 3.3 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

The analysis comprises several levels and steps of input, analysis, and output. A structured scheme for QA/QC was implemented throughout the work. At each step of analysis, QA/QC was performed to ensure that the stated methodology was implemented as intended. Limits were defined and entered into code to enable a review by someone other than the primary programmer. For the majority of the analysis, code was used that had been previously replicated for limited test data through an independent analysis. Finally, DNV GL and Nuka Research independently developed analysis code that could be compared for certain analyses. The minor discrepancies identified related only to cases where gaps in metocean data required that the data be estimated by some interpolation or approximation (as described in Section 4).

## 3.4 LIMITATIONS OF THE APPROACH

A response viability analysis provides a useful tool for oil spill response planning, but it does not attempt to incorporate all aspects of a response. It is also subject to the inherent challenges or limitations of the inputs used. This section describes some of the limitations of the approach:

- *Focuses only on impacts of metocean conditions, not logistics or other practical constraints.* A response viability analysis does not guarantee that a response will be deployed and be successful, even when conditions are deemed "favourable" 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.*
- *Quality and availability of metocean data.* A response viability analysis relies on having metocean data available to hindcast the relevant metocean conditions at the sites considered. This study benefitted from a thorough vetting of available data sources, but any limitations to the quality of the dataset carry through to the results of the analysis. (See discussion in Section 4.) The authors note that the 25km x 25km resolution in the dataset does not provide micro-scale resolution near coastal areas.
- *Relies on historic conditions to inform future decisions.* This response viability analysis is based on a hindcast of 10 years' of conditions in the study area. Although much longer records are available, Arctic climate is changing quickly (e.g. Thomson et al., 2013), and using older data would bias our results. These results are becoming out of date even as they are published due to the continued effects of global climate change on the Arctic.
- *Uneven documentation of response limits.* While some response limits are well documented or widely accepted for specific components of the response system, such as the wave heights used to characterize different types of containment boom (ASTM, 2000), other overall system response limits are not

as well documented. The response viability analysis approach – and pragmatic spill response planning in general – will benefit from further documentation of operating limits for the entire system 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.
- *Analysis does not consider how much time is needed for system deployment.* The analysis estimates the overall percentage of time conditions would be favourable, marginal, or not favourable for a given system. It does not seek to determine how long sustained favourable or marginal conditions would be needed for each system to deploy (which would be highly variable across not only the systems studied but also depending on the circumstances of the response).
- *Analysis does not consider response effectiveness, which would require assumptions regarding oil type and other factors.* This analysis focuses on the ability to safely <u>deploy</u> 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 type of spill, spilled volume, the oil, temperature and salinity of the water, and wind and wave conditions, and will have a significant effect on the utility of various responses 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.
- *Not all systems and potential configurations are included.* This study selected a set of baseline systems that generally represent well known marine oil spill response systems. Alternative combinations of vessels, components and configurations are possible, including some that are well known and proven. Other options are at various stages of the development process. The baseline systems and associated limitations used are benchmarks by which the metocean conditions are assessed and categorized. Other baseline systems may have given other results if their operating limits are different. Section 6.3 explores the impact of changes to wind and wave limits in a limited sensitivity analysis.

# 4 METOCEAN DATASET

The goal in compiling the metocean dataset was to achieve the highest quality input possible for the analysis within the available time and cost frame for the analysis. This proved challenging in a region as remote and diverse as the Arctic, with limited long-term observational data applicable for this area of study. The dataset also needed to cover a large area, but be granular enough to portray local and regional patterns. Data for a long time series was considered desirable.

This section discusses the data sources considered, identifies the two data sources selected, and describes the processing applied to build a single, cohesive dataset for use in the analysis.

## 4.1 REVIEW OF POTENTIAL DATA SOURCES

A thorough screening of possible data sources was performed. The assessment compared 11 data sources against the following criteria:

- **Geographical area to cover and spatial resolution**
  - Dataset should cover the whole AMAP area
  - Spatial resolution of 50-km grid or less
- **Temporal resolution**
  - Consistent time-series spanning a time frame of minimum 10 years
  - 6-hour time step or less
- **Dataset quality**
  - Sources that provide multiple parameters under a common scheme should be favored
  - Reliability in terms of being publicly accessible, updated regularly, and from a credible source
  - Quality in service, well documented, applicable and referenced by other sources
  - Low cost to reprocess and prepare data

Table 4-1 identifies the data sources reviewed and the results of the screening process. It should be emphasized that this evaluation of data sources pertained specifically to the purpose and scope of this study, and by no means represents a more general assessment of data quality or value in other contexts.

Table 4-1. Summary of data sources assessed for metocean conditions and sea ice (selected sources are highlighted in red)

METOCEAN PARAMETERS

| Data sources/suppliers | Type of data | Area Covered | Resolution | | | General comments | Reliability assessment (qualitative) | Data processing - time/cost |
|---|---|---|---|---|---|---|---|---|
| | | | Time resolution | Space resolution | Period | | | |
| **International Comprehensive Ocean-Atmosphere Data Set (ICOADS)** | Visual observations | Global | Daily | Latitude /Longitude | "1800"-present | In-situ observations, lack of data. Possibility for visibility. | Poor | Good |
| **NOMADS (NOAA)** | Modelled/ Reanalysis | Not complete Arctic | Hourly | 0.5 ° resolution | from 1979 | No wave parameters | Good | Poor |
| **National Oceanic and Atmospheric Administration (NOAA) Federal** | Modelled | Not defined | | 0.5 ° resolution | from 1979 | No wave parameters | Good | Poor |
| **Norwegian Meteorological Institute (MET Norway) (NORA10)** | Modelled/ Reanalysis | Regional (Norwegian waters) | 3 hours | 10 km X 10 km | > 10 years of data | Complete dataset (except ice) | Very good (regional) | Good |
| **MET Norway (ECMWF)** | Modelled/ Reanalysis | Global | 3-6 hours | 50 km x 50 km | from 1979 | Complete dataset (except ice) | Very good | Good |
| **Danish Meteorological Institute (DMI)** | Modelled | Regional | | 15 km x 15 km | 10-year-period | Complete dataset | Very good | Good |
| **European Center for Medium-Range Weather Forecasts (ECMWF)- ERA Interim** | Modelled | Arctic | | | | DMI and MET Norway use their data | Very good | Poor |
| **Bureau of Ocean Energy Management (BOEM)** | Modelled | Local | 1 hour | 10 km x 10 km | 1979-2009 | Only for the Beaufort and Chukchi Seas | Very good (regional) | Poor |

Table 4-1 continued. Summary of data sources assessed for metocean conditions and sea ice (selected sources are highlighted in red)

SEA ICE PARAMETER

| Data sources/suppliers | Type of data | Area Covered | Resolution | | | General comments | Reliability assessment (qualitative) | Data processing - time/cost |
|---|---|---|---|---|---|---|---|---|
| | | | Time resolution | Space resolution | Period | | | |
| **National Snow and Ice Data Center (NSIDC)** | Satellite | Arctic | Daily | 25 km x 25 km | 1978 - 2015 | Complete dataset used by Norwegian Authorities (i.e. Norwegian Polar Institute). Consistent time-series and coverage. Sufficient calibration and coastal correction | Very Good | Binary data, requires conversion |
| **Ocean and Sea Ice Satellite Application Facility (OSI SAF)** | Satellite | Arctic | Daily | 10 km x 10 km | 1978 - 2015 | Reprocessed sea ice concentration dataset of the EUMETSAT OSI SAF. Uses passive microwave data (PMW) from the SMMR, SSM/I and SSMIS sensors | Good | NetCDF |
| **University of Bremen** | Satellite | Arctic | Daily | 6.25 km x 6.25 km | 2002 - | High resolution, state-of-the-art algorithm. Inconsistency/ discontinuity in 2012 due to new satellite carrying new sensor. Sensor calibration not finalized. Lacking coastal correction | Medium | GeoTIFF |

## 4.2 DATASETS SELECTED

Based on the screening process the ERA-Interim dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the sea ice dataset prepared by the U.S. National Snow and Ice Data Center (NSIDC) were selected for the study.

### 4.2.1 ERA-Interim

ERA-Interim data were used for wind, sea state, air temperature, and water temperature data. It is a global atmospheric reanalysis produced by the ECMWF. The dataset includes a variety of parameters, including weather, ocean-wave, land-surface conditions and upper-air parameters covering the troposphere and stratosphere. Berrisford et al. (2009) and Dee et al. (2011) describe the development of the dataset and parameters. The data assimilation system used to produce ERA-Interim data is based on a 2006 release of the model system at ECMWF. The spatial resolution of the ERA interim dataset is 80 km. The atmospheric model is coupled to an ocean wave model in a 1.0 ° x 1.0 ° latitude/longitude grid.

MET Norway prepared the data for use in this project. The data were extracted from ECMWF for every 6 hours in a 0.5 ° x 0.5 ° grid. MET Norway applied a two-step-interpolation process resulting in a 25-km x 25-km resolution for the relevant parameters. A total of 29,443 grid cells were generated for the marine areas within the AMAP study area.

The relatively coarse resolution of the original ERA-Interim data means that small-scale variations are not captured well. This is particularly notable near polar lows or other small-scale phenomena, close to complicated coastlines, or among small islands. Grid cells near the coast were therefore excluded from the viability analysis. See Figure 4-1

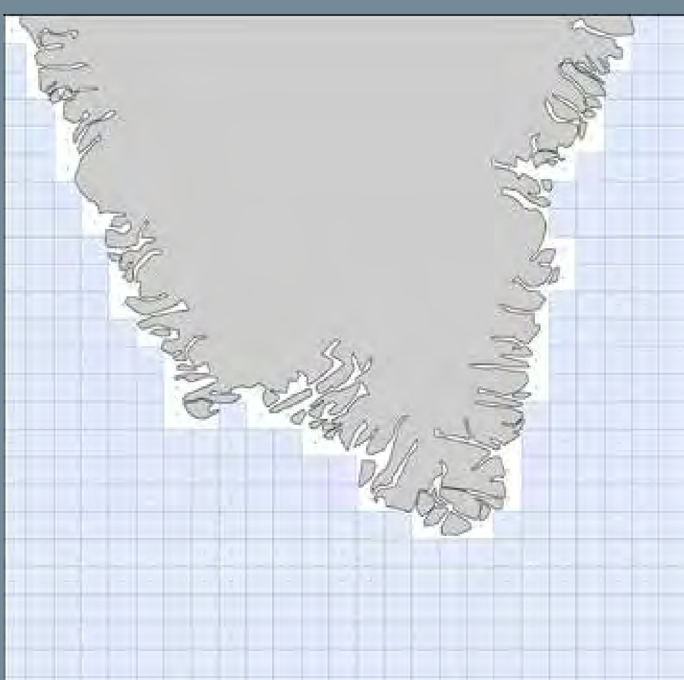


Figure 4-1 Example of 25-km x 25-km grid cells used (grid cells centered less than 10 km from shore were excluded)

for an example of how grid cells near the coast (centered 10-km or less from shore) were excluded to account for the uncertainties in the dataset. The data grid thus covers 93.1 % of the study area.

Quality assurance processes were carried out to ensure that the input as well as the output from the analysis are representative and valid within the study area. ECMWF verified the original ERA-Interim data. MET Norway and DNV GL controlled additional adaptations of the dataset. In general, wind speed and significant wave height correlate well with observations; however, ERA-Interim tends to underestimate strong winds and high waves.

After downloading the ERA-Interim data, it was found that there were no wave data north of 81°N.[5] There were also no data regarding wave height when the ice concentration exceeded 30%. For the viability analysis, this was resolved by calculating missing wave data using the following wave height formula:

$$Hs = 0.0212 * Ws * Ws$$

Where:
Hs = significant wave height in meters
Ws = Wind speed in m/s

### 4.2.2 National Snow and Ice Data Center

The U.S. National Snow and Ice Data Center's (NSIDC) sea ice product NSIDC-0051 dataset fulfilled requirements identified during the initial screening process for the ice concentration parameter. The NSIDC dataset is well documented and used internationally, including by Norwegian authorities when referring to the sea ice edge in the Barents Sea.

The NSIDC product uses a spatial resolution of 25 km and a temporal resolution of 24 hours (averaged daily means). The product has a mean accuracy of +/- 0.2% (area fraction of sea ice in cell) which corresponds to a cell value in the range 0 to 250. Key processes in preparation of the sea ice data were:

- Organize data into consistent monthly time series for the period 2006 – 2015.
- Process ice frequency maps for all months based on a 90% concentration threshold.
- Process ice cap maps for every month accordingly given a cut-off of 90% ice concentration. The ice cap is the natural limitation to marine oil spill response activity.

The viability analysis requires data for all parameters to be aligned and adapted to a common interface. To achieve this, the NSIDC original binary data were converted to ArcGIS raster datasets, spatially referenced, and converted to regular ASCII files to align with the same grid developed for the ERA-Interim dataset.

A quality check was completed to ensure that all cells in the study area represent valid ice concentration values.

5 ECMWF has started a new reanalysis project, ERA5. This project will improve wave data north of 81 degrees and should be ready in 2017.

## 4.3 OTHER PARAMETERS

### 4.3.1 Horizontal visibility

Horizontal visibility was one of the parameters required by the project, but was not available in the datasets selected, nor from any other sources that met the assessment criteria. Horizontal visibility was estimated based on relative humidity.

The actual vapor pressure (e) and the saturation vapor pressure ($e_s$) are calculated as:

$$e = 6.11 \cdot 10^{\frac{7.5 \cdot T_d}{237.3+T_d}}$$

$$e_s = 6.11 \cdot 10^{\frac{7.5 \cdot T}{237.3+T}}$$

Where:
T = air temperature
$T_d$ = dew point temperature

The visibility (v) in kilometers is calculated from relative humidity by a slightly modified version of a formula proposed by Gultepe and Milbrandt (2010).

### 4.3.2 Light conditions

Daylight and darkness are calculated based on geographical position, with daylight including civil twilight. Each twilight phase is defined by the solar elevation angle, which is the position of the sun in relation to the horizon. During civil twilight, the geometric center of the sun's disk is at most 6 degrees below the horizon. In the morning, this twilight phase ends at sunrise; in the evening it begins at sunset. (Sunrise and sunset are the moments when the sun's upper edge touches the horizon.) As the Earth's atmosphere scatters and reflects much of the sun's light, coloring the sky bright yellow and orange, artificial lighting is generally not required in clear weather conditions to carry out most outdoor activities during twilight hours.

The solar calculator developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) was applied to determine hours of daylight and darkness for each grid cell (NOAA, n.d.).

### 4.3.3 Structural Icing

For calculating superstructure icing, the NOAA-approved algorithm by Overland et al. (1990) was used, with inputs based on wind speed, air temperature, and water temperature from the ERA-Interim dataset.

**PR = (W_s * (T_f - T_a)) / (1 + 0.3 (T_s – T_f))**

Where:
W_s is wind speed 10 m above sea surface (m/s)
T_f is freezing temperature of sea water (set to -1.7 °C)
T_a is air temperature (°C)
T_s is water temperature at sea surface (°C)

### 4.3.4 Wind chill

Wind chill was calculated according to Woodson *et al*. (1992), using wind speed and air temperature data from the ERA-Interim dataset.

$$T_{wc} = 13.12 + 0.6215 * T\_a - 11.37 * (W\_s*3.6)^{0,16} + 0.3965 * T\_a * (W\_s*3.6)^{0,16}$$

Where:
W_s is wind speed 10 m above sea surface (m/s)
T_a is air temperature (°C)

Note that for very low wind speeds it can return a value greater than the actual temperature, which is presumably wrong. To eliminate this, a calculation was included in the code so that the dataset will not show wind chill as higher than air temperature for any given location.

## 4.4 SUMMARY OF PARAMETERS AND DATA SOURCES

Table 4-2 summarizes the parameters used in the response viability analysis and sources for each.

**Table 4-2.** Parameters and data sources used in viability analysis

| SOURCE | PARAMETER | UNIT | SPACE RESOLUTION | TIME RESOLUTION | TYPE OF DATA |
|---|---|---|---|---|---|
| **MET Norway (ERA-Interim)** | Wind speed at 10 meters above sea surface | m/s | Approximately 0.5 ° x 0.5 ° (ERA Interim) | | Modelled/ hindcast |
| | Significant wave height | m | Interpolated to: | Every 6 hours 10 years of data (2006-2015) | |
| | Air temperature at 2 meters above sea surface | ˚C | 25 km x 25 km | | |
| | Water temperature at sea surface | ˚C | | | |
| | (There is no wave data when the ice concentration > 30 %) | | | | |
| **MET Norway** | Horizontal visibility | m | 25 x 25 km | Every 6 hours | Calculated based on air temperature and dew point temperature |
| **NSIDC** | Ice concentration | % | 25 x 25 km | Daily 10 years of data (2006 – 2015) | Satellite Imagery Processed by DNV GL |
| **DNV GL** | Daylight (including civil twilight) and darkness | Yes/no | 25 x 25 km | Every 6 hours | Calculated based on position as described in Section 4.3.2 |
| **DNV GL** | Structural icing | cm/hr | 25 x 25 km | Every 6 hours | Calculated based on wind speed, air temperature, and water temperature as described 4.3.3 |
| **DNV GL** | Wind chill | ˚C | 25 x 25 km | Every 6 hours | Calculated based on wind speed and air temperature as described 4.3.4 |

# 5 RESPONSE SYSTEMS AND LIMITS

This section presents the 10 response systems analyzed, including the primary equipment and other resources that comprise each system and the limits used in the analysis. They are listed again in Table 5-1.

**Table 5-1.** Response systems studied

| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
|---|---|---|
| Two vessels with boom | Vessel application | Vessels with fire boom |
| Single vessel with outrigger | FIxed-wing aircraft application | Helicopter with ice containment |
| Three vessels of opportunity (VOO) with boom | Helicopter application | Helicopter with herders |
| Single vessel in ice | | |

The visibility-related limits do not include detecting slick location, but do include aerial observation to direct the response system to the thickest oil either by observation from an aircraft or use of an observing technology such as an aerostat or unmanned aircraft.

Not all factors will affect all tactics; for example, vessel superstructure icing from sea spray does not affect aerial platforms and cloud ceiling does not affect vessel platforms. Response may also be affected by conditions that are not available in the dataset and therefore will not be quantified in this analysis, such as currents or icebergs. The dataset does not include vertical visibility, but limits are presented for potential future analyses if the necessary data become available.

Finally, all systems require some type of operating platform. Platform limits refer to the ability to safely operate the vessel or aircraft, and, in the case of vessels, to maneuver on deck. We assume that the limitations on helicopter operation are the same whether that helicopter is deploying dispersants or igniting an in-situ burn. Likewise, vessel limits may vary by size or type but these limits will be the same whether the vessel is deploying boom for mechanical recovery or containment for an in-situ burn.

Supporting references are provided in Appendix D.

## 5.1 BASELINE RESPONSE SYSTEMS AND LIMITS

This section describes the baseline response systems and limits used for each of the 10 systems analyzed.

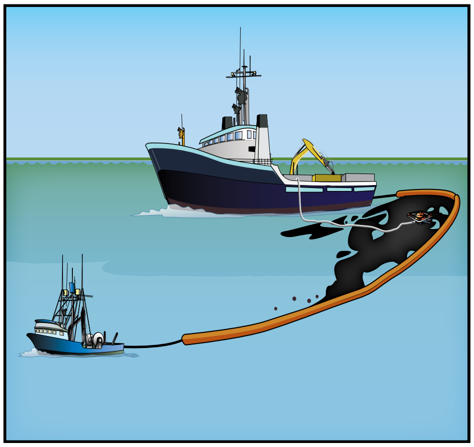
WMO terminology is used to describe the ice concentration to which each system is suited. The following general terms are also used. These are intended to convey a general understanding of two common types of operating environments in which marine oil spill response may be conducted. They are not tied to any particular regulation or categorization scheme.

***Offshore*** refers to the open ocean area where spill response systems operate in an environment that has little or no influence from shallow-water or land masses. Offshore waters are the most severe operating environments for spill response systems in the Arctic. Systems operating in the offshore environment must be self-sufficient and able to cope with the full range of metocean conditions that may occur at that location.

***Nearshore*** waters are generally closer to shore and may be influenced by either shallow water depths or protection from winds by land. Nearshore waters are generally more protected and thus less severe than offshore waters. Systems intended for the nearshore operating environment are generally less tolerant of high sea states than systems operating in offshore waters. They are also able to move to a safe harbor during storm events.

### 5.1.1 Mechanical recovery: Two vessels with boom

The Two Vessels with Boom system uses one vessel to deploy the skimmer, hold recovered fluids, and support one side of the containment boom. A second, smaller vessel tows the other end of the boom to provide a configuration that contains the oil for skimming. The system is intended to contain and recover oil in an offshore environment; it can also be used in nearshore environments if there is sufficient water depth. It is primarily a tactic to be used in open-water conditions or very open pack ice.



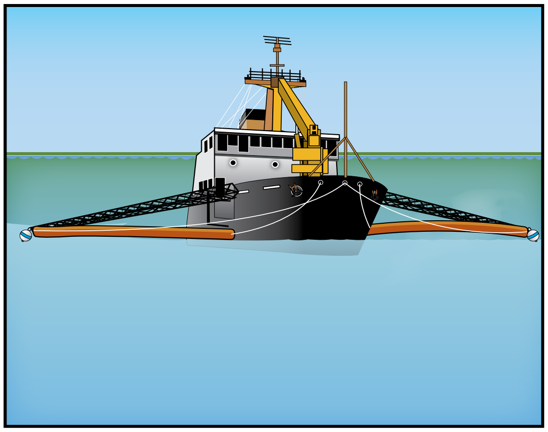
| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| Vessel platform | 1 ea. 75 m offshore response vessel<br>1 ea. 20 m vessel of opportunity to tow boom |
| Containment system | Boom suited for > 2 m rough seas |
| Skimming system | High volume oleophilic skimmer suited for > 2 m rough seas |
| Primary storage | Onboard response vessel |
| Other components | Detection technology (such as aerial observation or FLIR) to detect and track oil |

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| Wind m/s | ≤ 11 | 11 | 18 | ≥ 18 |
| Wind wave height m | ≤ 1.8 | 1.8 | 3.0 | ≥ 3.0 |
| Sea ice coverage % | ≤ 10 | 10 | 30 | ≥ 30 |
| Air temperature °C | ≥ -5 | -5 | -18 | ≤ -18 |
| Wind chill temp. °C | ≥ -31.7 | -31.7 | -37.2 | ≤ -37.2 |
| Structural icing cm/hr | < 0.7 | 0.7 | 2.0 | > 2.0 |
| Light conditions (day/dark) | Daylight | Darkness | | |
| Horizontal visibility km | ≥ 0.9 | 0.9 | 0.2 | ≤ 0.2 |
| Vertical visibility m | ≥ 152 | 152 | 10 | ≤10 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| Wind kts | ≤ 21 | 21 | 35 | ≥ 35 |
| Wind wave height ft | ≤ 6 | 6 | 10 | ≥ 10 |
| Sea ice coverage % | ≤ 10 | 10 | 30 | ≥ 30 |
| Air temperature °F | ≥ 23 | 23 | 0 | ≤ 0 |
| Wind chill temp. °F | ≥ -25 | -25 | -35 | ≤ -35 |
| Structural icing in/hr | < 0.3 | 0.3 | 0.8 | > 0.8 |
| Light conditions (day/dark) | Daylight | Darkness | | |
| Horizontal visibility nm | ≥ 0.5 | 0.5 | 0.1 | ≤ 0.1 |
| Vertical visibility ft | ≥ 500 | 500 | 33 | ≤ 33 |

### 5.1.2 Mechanical recovery: Single vessel with outrigger

The Single Vessel with Outrigger relies on a large vessel to support the skimmer, storage, and one end of the containment boom. An outrigger affixed to the vessel supports the boom. This system is intended to contain and recover oil in an offshore environment, or in nearshore environments if there is sufficient water depth. It is primarily a tactic to be used in open-water conditions or very open pack ice.



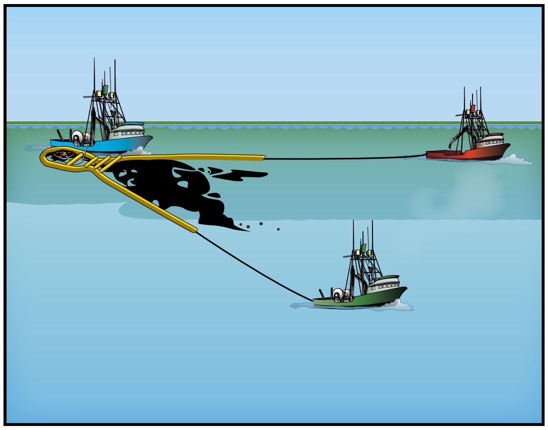
| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| Vessel platform | 1 ea. 65 m offshore response vessel |
| Containment system | 2 ea. 14 m spars with active containment system suited to waves up to 1 m |
| Skimming system | Weir skimmer suited to operating in waves up to 1 m |
| Primary storage | Towed storage |
| Other components | Detection technology (such as aerial observation or FLIR) to detect and track oil |

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| Wind m/s | ≤ 11 | 11 | 17 | ≥ 17 |
| Wind wave height m | ≤ 0.9 | 0.9 | 2.0 | ≥ 2.0 |
| Sea ice coverage % | ≤ 10 | 10 | 30 | ≥ 30 |
| Air temperature °C | ≥ -5 | -5 | -18 | ≤ -18 |
| Wind chill temp. °C | ≥ -31.7 | -31.7 | -37.2 | ≤ -37.2 |
| Structural icing cm/hr | < 0.7 | 0.7 | 2.0 | > 2.0 |
| Light conditions (day/dark) | Daylight | Darkness | | |
| Horizontal visibility km | ≥ 0.9 | 0.9 | 0.2 | ≤ 0.2 |
| Vertical visibility m | ≥ 152 | 152 | 10 | ≤10 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| Wind kts | ≤ 21 | 21 | 33 | ≥ 33 |
| Wind wave height ft | ≤ 3.0 | 3.0 | 6.5 | ≥ 6.5 |
| Sea ice coverage % | ≤ 10 | 10 | 30 | ≥ 30 |
| Air temperature °F | ≥ 23 | 23 | 0 | ≤ 0 |
| Wind chill temp. °F | ≥ -25 | -25 | -35 | ≤ -35 |
| Structural icing in/hr | < 0.3 | 0.3 | 0.8 | > 0.8 |
| Light conditions (day/dark) | Daylight | Darkness | | |
| Horizontal visibility nm | ≥ 0.5 | 0.5 | 0.1 | ≤ 0.1 |
| Vertical visibility ft | ≥ 500 | 500 | 33 | ≤ 33 |

### 5.1.3 Mechanical recovery: Three vessels-of-opportunity with Boom

This system uses three vessels-of-opportunity (which may be fishing or other vessels not dedicated to oil spill response). One vessel deploys the skimmer and associated storage device, while the other two move the ends of the active booming system. It is primarily intended for a nearshore environment with open-water conditions (no ice or very low concentrations of pack ice). The limits for this system are based on the use of equipment and vessels suited to more protected waters than the previous two systems described.



| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| **Vessel platform** | 3 ea. 15 – 20 m vessels of opportunity |
| **Containment system** | Active booming system suited to waves up to 1 m |
| **Skimming system** | Oleophilic skimmer suited to waves up to 1 m |
| **Primary storage** | Towed storage |
| **Other components** | Detection technology (such as aerial observation or FLIR) to detect and track oil |

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind m/s** | ≤ 11 | 11 | 15 | ≥ 15 |
| **Wind wave height m** | ≤ 0.6 | 0.6 | 1.0 | ≥ 1.0 |
| **Sea ice coverage %** | ≤ 10 | 10 | 20 | ≥ 20 |
| **Air temperature °C** | ≥ -5 | -5 | -18 | ≤ -18 |
| **Wind chill temp. °C** | ≥ -31.7 | -31.7 | -37.2 | ≤ -37.2 |
| **Structural icing cm/hr** | < 0.7 | 0.7 | 2.0 | > 2.0 |
| **Light conditions (day/dark)** | Daylight | Darkness | | |
| **Horizontal visibility km** | ≥ 0.9 | 0.9 | 0.2 | ≤ 0.2 |
| **Vertical visibility m** | ≥ 152 | 152 | 10 | ≤10 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind kts** | ≤ 21 | 21 | 30 | ≥ 30 |
| **Wind wave height ft** | ≤ 2.0 | 2.0 | 3.3 | ≥ 3.3 |
| **Sea ice coverage %** | ≤ 10 | 10 | 20 | ≥ 20 |
| **Air temperature °F** | ≥ 23 | 23 | 0 | ≤ 0 |
| **Wind chill temp. °F** | ≥ -25 | -25 | -35 | ≤ -35 |
| **Structural icing in/hr** | < 0.3 | 0.3 | 0.8 | > 0.8 |
| **Light conditions (day/dark)** | Daylight | Darkness | | |
| **Horizontal visibility nm** | ≥ 0.5 | 0.5 | 0.1 | ≤ 0.1 |
| **Vertical visibility ft** | ≥ 500 | 500 | 33 | ≤ 33 |

### 5.1.4 Mechanical recovery: Single vessel in ice

The Single Vessel in Ice system does not use containment boom and is intended to contain and recover oil in high concentrations of ice (from close or very close pack ice to compact pack ice). Because it relies on sea ice flows to contain the spreading of oil, it is not useful in lower ice concentrations. This is a highly specialized system requiring an ice-class vessel.

| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| Vessel platform | 1 ea. 90 m ice-class, offshore response vessel |
| Containment system | None |
| Skimming system | Skimming system suited for high ice concentrations or compact pack ice |
| Primary storage | Onboard response vessel |
| Other components | Detection technology (such as aerial observation or FLIR) to detect and track oil |

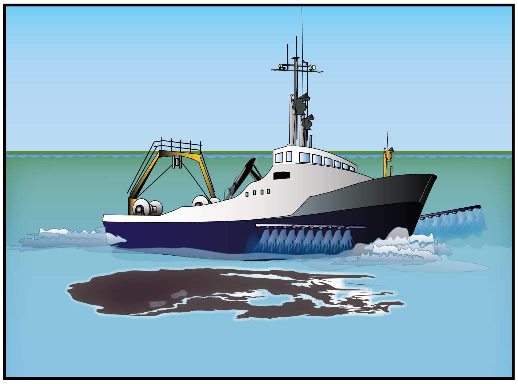
| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| Wind m/s | ≤ 15 | 15 | 25 | ≥ 25 |
| Wind wave height m | Assumed not limiting for this system. | | | |
| Sea ice coverage % | ≥ 90 | 90 | 70 | < 70 |
| Air temperature °C | Assumed not limiting for this system. | | | |
| Wind chill temp. °C | Assumed not limiting for this system. | | | |
| Structural icing cm/hr | < 0.7 | 0.7 | 2.0 | > 2.0 |
| Light conditions (day/dark) | Daylight | Darkness | | |
| Horizontal visibility km | ≥ 0.9 | 0.9 | 0.2 | ≤ 0.2 |
| Vertical visibility m | ≥ 152 | 152 | 10 | ≤10 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| Wind kts | ≤ 29 | 29 | 48 | ≥ 48 |
| Wind wave height ft | Assumed not limiting for this system. | | | |
| Sea ice coverage % | ≥ 90 | 90 | 70 | < 70 |
| Air temperature °F | Assumed not limiting for this system. | | | |
| Wind chill temp. °F | Assumed not limiting for this system. | | | |
| Structural icing in/hr | < 0.3 | 0.3 | 0.8 | > 0.8 |
| Light conditions (day/dark) | Daylight | Darkness | | |
| Horizontal visibility nm | ≥ 0.5 | 0.5 | 0.1 | ≤ 0.1 |
| Vertical visibility ft | ≥ 500 | 500 | 33 | ≤ 33 |

## 5.2 DISPERSANTS

### 5.2.1 Dispersants: Vessel application

This system is intended to disperse oil floating on the surface by delivering a measured dose of dispersants in fine droplets from a vessel and mechanically agitating the slick and water column. It may be used in offshore or nearshore environments. It may be used in a range of ice concentrations as long as the vessel is appropriately equipped.



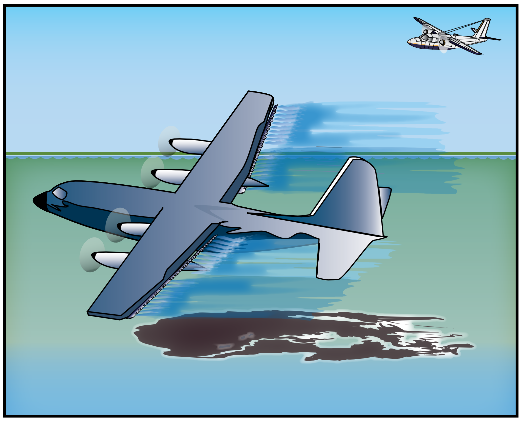
| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| **Vessel platform** | 1 ea. 50 – 100 m response vessel |
| **Dispersant application system** | 10 m dispersant spray arms |
| **Other components** | Detection technology (such as aerial observation or FLIR) to detect and track oil |

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind m/s** | ≤ 11 | 11 | 20 | ≥ 20 |
| **Wind wave height m** | ≤ 2.7 | 2.7 | 5.0 | ≥ 5.0 |
| **Sea ice coverage %** | ≤ 10 | 10 | 70 | ≥ 70 |
| **Air temperature °C** | Assumed not limiting for this system. | | | |
| **Wind chill temp. °C** | ≥ -31.7 | -31.7 | -37.2 | ≤ -37.2 |
| **Structural icing cm/hr** | < 0.7 | 0.7 | 2.0 | > 2.0 |
| **Light conditions (day/dark)** | Daylight | Darkness | | |
| **Horizontal visibility km** | ≥ 0.9 | 0.9 | 0.2 | ≤ 0.2 |
| **Vertical visibility m** | ≥ 152 | 152 | 10 | ≤10 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind kts** | ≤ 21 | 21 | 39 | ≥ 39 |
| **Wind wave height ft** | ≤ 9.0 | 9.0 | 16.3 | ≥ 16.3 |
| **Sea ice coverage %** | ≤ 10 | 10 | 70 | ≥ 70 |
| **Air temperature °F** | Assumed not limiting for this system. | | | |
| **Wind chill temp. °F** | ≥ -25 | -25 | -35 | ≤ -35 |
| **Structural icing in/hr** | < 0.3 | 0.3 | 0.8 | > 0.8 |
| **Light conditions (day/dark)** | Daylight | Darkness | | |
| **Horizontal visibility nm** | ≥ 0.5 | 0.5 | 0.1 | ≤ 0.1 |
| **Vertical visibility ft** | ≥ 500 | 500 | 33 | ≤ 33 |

### 5.2.2 Dispersants: Airplane Application

This system is intended to disperse oil floating on the surface by delivering a measured dose of dispersants in fine droplets from a fixed-wing aircraft. It may be used in offshore or nearshore environments. It is primarily intended for open-water conditions (little to no ice). The system is comprised of an aerial spray aircraft and a spotter aircraft.



| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| **Aircraft platform** | 2 ea. multi-engine fixed-wing aircraft, one for dispersant application, one for aerial spotting |
| **Dispersant application system** | Aerial high volume dispersant application system |
| **Other components** | Detection technology (such as aerial observation or FLIR) to detect and track oil |

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind m/s** | ≤ 13 | 13 | 15 | ≥ 15 |
| **Wind wave height m** | < 3 | 3 | 5 | > 5 |
| **Sea ice coverage %** | ≤ 10 | 10 | 30 | ≥ 30 |
| **Air temperature °C** | *Assumed not limiting for this system.* | | | |
| **Wind chill temp. °C** | *Assumed not limiting for aerial systems.* | | | |
| **Structural icing cm/hr** | *Assumed not limiting for aerial systems.* | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility km** | ≥ 5.6 | 5.6 | 1.9 | < 1.9 |
| **Vertical visibility m** | ≥ 1524 | 1524 | 305 | ≤ 305 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind kts** | ≤ 26 | 26 | 30 | ≥ 30 |
| **Wind wave height ft** | < 9.9 | 9.9 | 16.3 | > 16.3 |
| **Sea ice coverage %** | ≤ 10 | 10 | 30 | ≥ 30 |
| **Air temperature °F** | Assumed not limiting for this system. | | | |
| **Wind chill temp. °F** | Assumed not limiting for aerial systems. | | | |
| **Structural icing in/hr** | Assumed not limiting for aerial systems. | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility nm** | ≥ 3.0 | 3.0 | 1.0 | < 1.0 |
| **Vertical visibility ft** | ≥ 5000 | 5000 | 1000 | ≤ 1000 |

### 5.2.3 Dispersants: Helicopter Application

This system is intended to disperse oil floating on the surface by delivering a measured dose of dispersants in fine droplets from a device slung under a helicopter. It is usually employed in nearshore environments (within helicopter range from shore). It may be used in a range of ice conditions.

| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| **Aircraft platform** | Twin engine jet helicopter |
| **Dispersant application system** | Aerial dispersant application system |
| **Other components** | Detection technology (such as aerial observation, FLIR, or ice-penetrating radar) to detect and track oil |

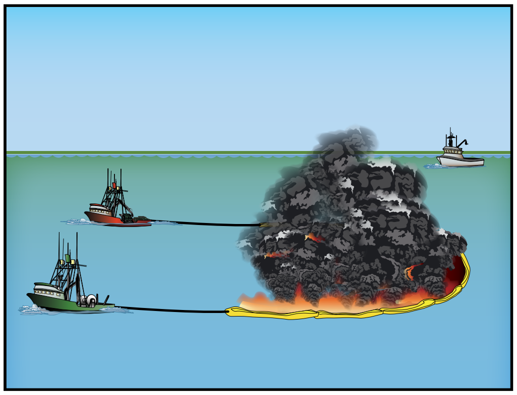
| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind m/s** | ≤ 11 | 11 | 15 | ≥ 15 |
| **Wind wave height m** | < 3 | 3 | 5 | > 5 |
| **Sea ice coverage %** | ≤ 10 | 10 | 50 | ≥ 50 |
| **Air temperature ºC** | > -40 | -40 | -40 | ≤ -40 |
| **Wind chill temp. ºC** | Assumed not limiting for aerial systems. | | | |
| **Structural icing cm/hr** | Assumed not limiting for aerial systems. | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility km** | ≥ 1.9 | 1.9 | 0.7 | < 0.7 |
| **Vertical visibility m** | ≥ 305 | 305 | 152 | ≤ 152 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind kts** | ≤ 21 | 21 | 30 | ≥ 30 |
| **Wind wave height ft** | < 9.9 | 9.9 | 16.3 | > 16.3 |
| **Sea ice coverage %** | ≤ 10 | 10 | 50 | ≥ 50 |
| **Air temperature ºF** | > -40 | -40 | -40 | ≤ -40 |
| **Wind chill temp. ºF** | Assumed not limiting for aerial systems. | | | |
| **Structural icing in/hr** | Assumed not limiting for aerial systems. | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility nm** | ≥ 1.0 | 1.0 | 0.4 | < 0.4 |
| **Vertical visibility ft** | ≥ 1000 | 1000 | 500 | ≤ 500 |

## 5.3 IN-SITU BURNING

### 5.3.1 In-situ burning: Vessels with fire boom

This system is intended to remove oil floating on the surface by concentrating it to a sufficient thickness with boom, so that it will ignite and burn. It may be used in offshore or nearshore environments. Two boom-towing vessels are utilized. It is primarily a tactic to be used in open-water conditions or very open pack ice.



| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| **Vessel platform** | 3 ea. vessels of opportunity |
| **Containment system** | Fire boom |
| **Ignition system** | Handheld gelled-fuel igniter |
| **Other components** | Detection technology (such as aerial observation or FLIR) to detect and track oil |

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind m/s** | ≤ 5 | 5 | 10 | ≥ 10 |
| **Wind wave height m** | ≤ 1.0 | 1.0 | 2.0 | ≥ 2.0 |
| **Sea ice coverage %** | ≤ 10 | 10 | 30 | ≥ 30 |
| **Air temperature ºC** | Assumed not limiting for this system. | | | |
| **Wind chill temp. ºC** | ≥ -31.7 | -31.7 | -37.2 | ≤ -37.2 |
| **Structural icing cm/hr** | < 0.7 | 0.7 | 2.0 | > 2.0 |
| **Light conditions (day/dark)** | Daylight | Darkness | | |
| **Horizontal visibility km** | ≥ 0.9 | 0.9 | 0.2 | ≤ 0.2 |
| **Vertical visibility m** | ≥ 152 | 152 | 10 | ≤10 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind kts** | ≤ 10 | 10 | 20 | ≥ 20 |
| **Wind wave height ft** | ≤ 3.3 | 3.3 | 6.6 | ≥ 6.6 |
| **Sea ice coverage %** | ≤ 10 | 10 | 30 | ≥ 30 |
| **Air temperature ºF** | Assumed not limiting for this system. | | | |
| **Wind chill temp. ºF** | ≥ -25 | -25 | -35 | ≤ -35 |
| **Structural icing in/hr** | < 0.3 | 0.3 | 0.8 | > 0.8 |
| **Light conditions (day/dark)** | Daylight | Darkness | | |
| **Horizontal visibility nm** | ≥ 0.5 | 0.5 | 0.1 | ≤ 0.1 |
| **Vertical visibility ft** | ≥ 500 | 500 | 33 | ≤ 33 |

### 5.3.2 In-situ burning: Helicopter with ice containment

This system is intended to remove oil floating on the surface that has been naturally contained among floating pack ice so that it will ignite and burn. The burn is ignited by dropping burning fluid from a device slung under a helicopter. It may be used offshore, though requires sufficient ice coverage to contain the slick but not so much that the slick is submerged or entirely encapsulated in the ice.

| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| **Vessel platform** | Twin engine jet helicopter |
| **Ignition system** | Aerial ignition system |
| **Other components** | Detection technology (such as aerial observation, FLIR, or ice-penetrating radar) to detect and track oil |

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind m/s** | ≤ 5 | 5 | 10 | ≥ 10 |
| **Wind wave height m** | ≤ 0.9 | 0.9 | 2.0 | ≥ 2.0 |
| **Sea ice coverage %** | 70 ≤ G ≤ 90 | 60 ≤ Y < 70 | 90 < Y ≤ 95 | 60 > R > 95 |
| **Air temperature °C** | > -40 | -40 | -40 | ≤ -40 |
| **Wind chill temp. °C** | Assumed not limiting for aerial systems. | | | |
| **Structural icing cm/hr** | Assumed not limiting for aerial systems. | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility km** | ≥ 1.9 | 1.9 | 0.7 | < 0.7 |
| **Vertical visibility m** | ≥ 305 | 305 | 152 | ≤ 152 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind kts** | ≤ 10 | 10 | 20 | ≥ 20 |
| **Wind wave height ft** | ≤ 3.1 | 3.1 | 6.6 | ≥ 6.6 |
| **Sea ice coverage %** | 70 ≤ G ≤ 90 | 60 ≤ Y < 70 | 90 < Y ≤ 95 | 60 > R > 95 |
| **Air temperature °F** | > -40 | -40 | -40 | ≤ -40 |
| **Wind chill temp. °F** | Assumed not limiting for aerial systems. | | | |
| **Structural icing in/hr** | Assumed not limiting for aerial systems. | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility nm** | ≥ 1.0 | 1.0 | 0.4 | < 0.4 |
| **Vertical visibility ft** | ≥ 1000 | 1000 | 500 | ≤ 500 |

### 5.3.3 In-situ burning: Helicopter with herders

This system is intended to remove oil floating on the surface by concentrating it with chemical herders to a sufficient thickness that it will volatize and burn. It may be used in offshore or nearshore environments. The chemical herder and ignition fluid are delivered from a device slung under a helicopter. It is primarily intended for conditions where the ice precludes effective containment by boom, but ice concentration is not sufficient to provide natural containment. *This is the only system in this analysis that is considered to be still under development.*

| SYSTEM COMPONENTS | BASELINE SPECIFICATIONS |
|---|---|
| **Vessel platform** | Twin engine jet helicopter |
| **Herder system** | Aerial chemical herder application system |
| **Ignition system** | Aerial ignition system |
| **Other components** | Detection technology (such as aerial observation, FLIR, or ice-penetrating radar) to detect and track oil |

*The International Oil and Gas Producers provided limits for wind, sea ice, and air temperature. There was insufficient information to establish wave height limits for this system when limits were developed.*

| SYSTEM LIMITS – METRIC | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind m/s** | ≤ 4 | 4 | 6 | ≥ 6 |
| **Wind wave height m** | No limit applied; information not yet available for this developing system. | | | |
| **Sea ice coverage %** | ≤ 30 | 30 | 60 | ≥ 60 |
| **Air temperature ºC** | > -20 | | | ≤ -20 |
| **Wind chill temp. ºC** | Assumed not limiting for aerial systems. | | | |
| **Structural icing cm/hr** | Assumed not limiting for aerial systems. | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility km** | ≥ 1.9 | 1.9 | 0.7 | < 0.7 |
| **Vertical visibility m** | ≥ 305 | 305 | 152 | ≤ 152 |

| SYSTEM LIMITS – ENGLISH | FAVOURABLE | MARGINAL | | NOT FAVOURABLE |
|---|---|---|---|---|
| | Upper Boundary | Lower Boundary | Upper Boundary | Lower Boundary |
| **Wind kts** | ≤ 8 | 8 | 12 | ≥ 12 |
| **Wind wave height ft** | No limit applied; information not yet available for this developing system. | | | |
| **Sea ice coverage %** | ≤ 30 | 30 | 60 | ≥ 60 |
| **Air temperature ºF** | > -4 | | | ≤-4 |
| **Wind chill temp. ºF** | Assumed not limiting for aerial systems. | | | |
| **Structural icing in/hr** | Assumed not limiting for aerial systems. | | | |
| **Light conditions (day/dark)** | Daylight | | | Darkness |
| **Horizontal visibility nm** | ≥ 1.0 | 1.0 | 0.4 | < 0.4 |
| **Vertical visibility ft** | ≥ 1000 | 1000 | 500 | ≤ 500 |

## 5.4 COMPARISON OF RESPONSE LIMITS

Figure 5-1 presents the response limits in a set of green, yellow, and red bars, showing the limits organized by response system (in metric only). For another view, Figure 5-2 presents the same limits, but organized by metocean parameter. In the grid to the left of the bars, a black dot indicates which response system – or systems – relates to which limit bar. In this view, the similarities among systems that use the same platform are evident.

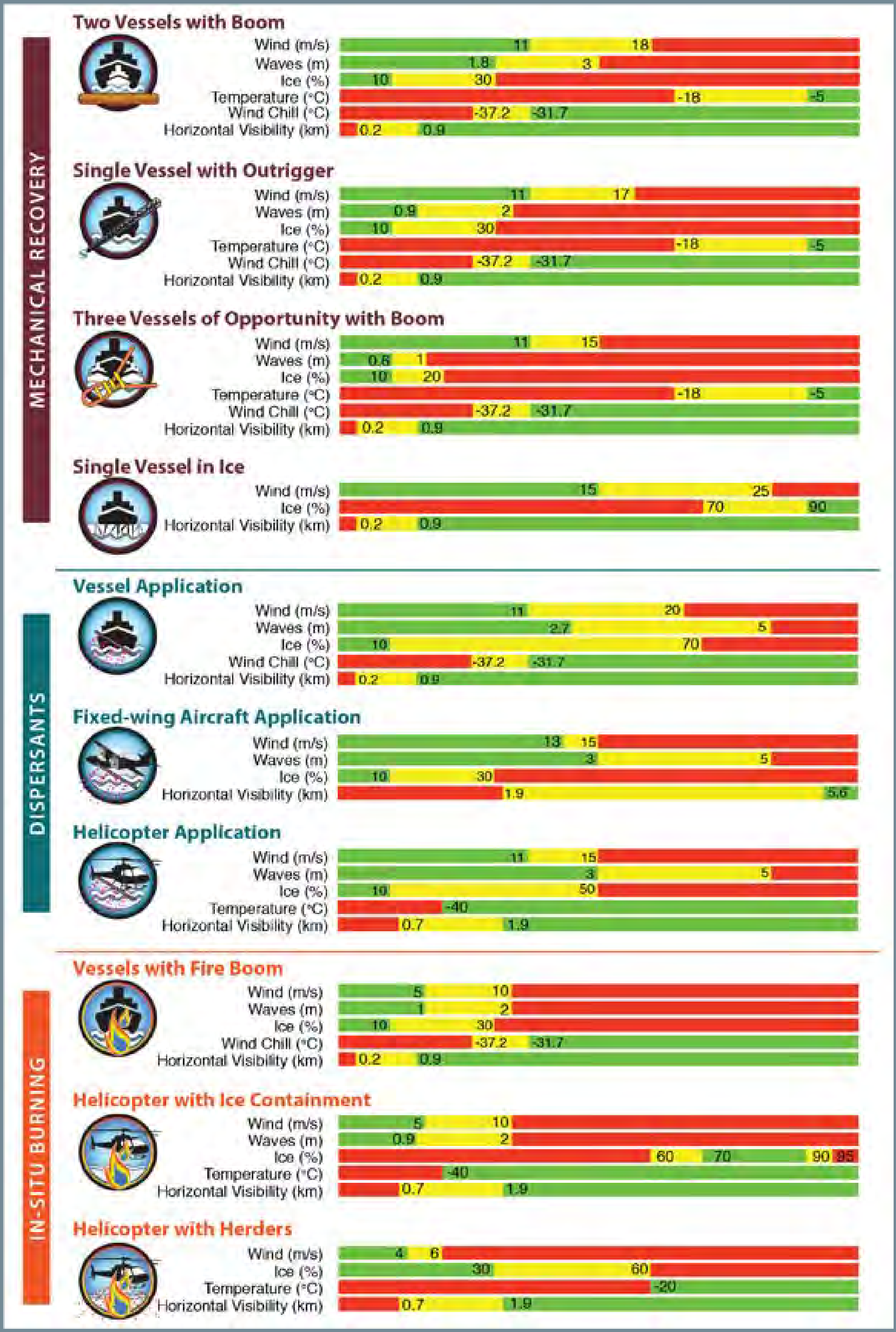



Figure 5-1. Comparison of response limits used for each system studied – organized by system (metric only); structural icing and daylight/darkness not included

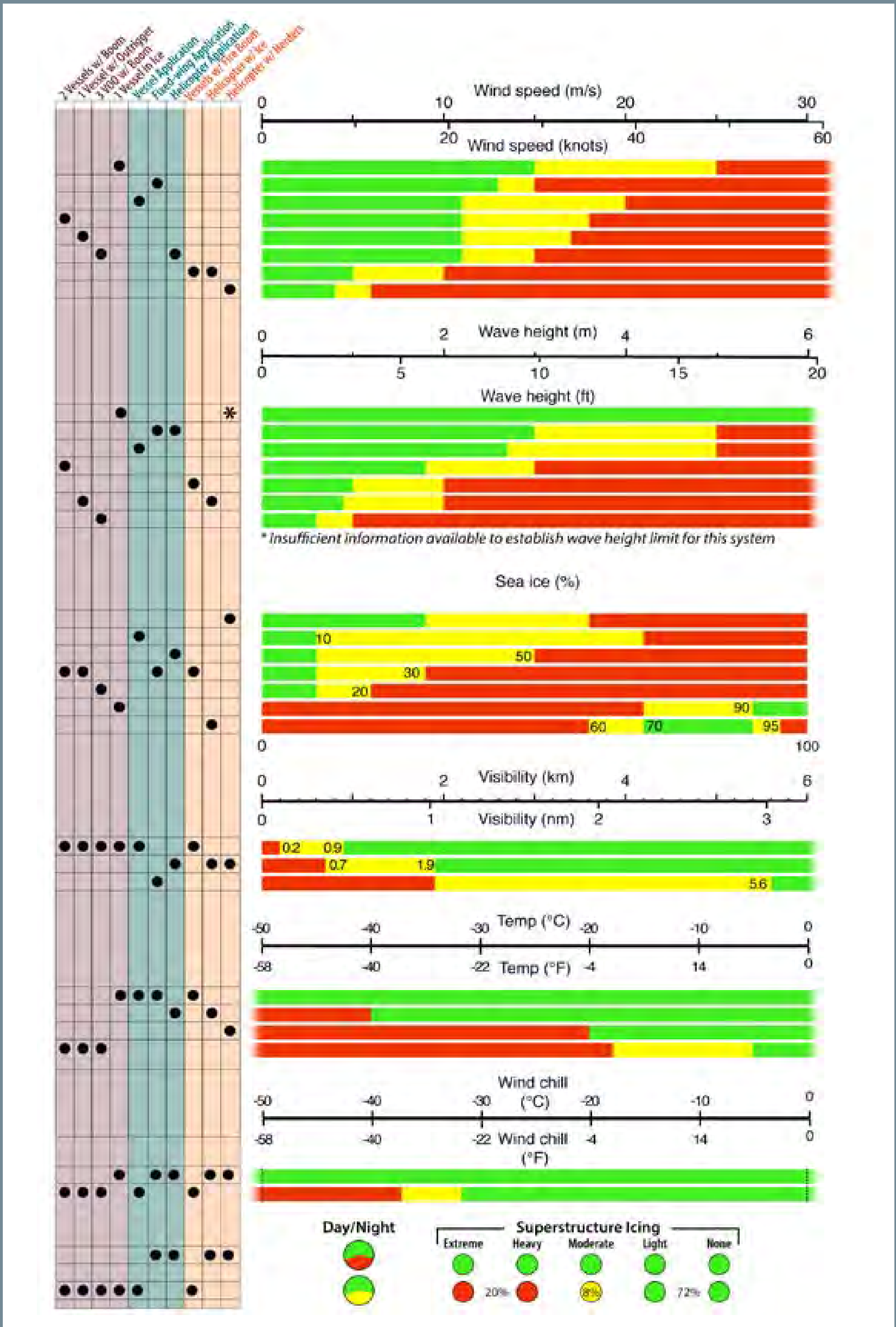



Figure 5-2. Comparison of response limits - organized by metocean condition (metric and English units)

# 6 RESULTS

This section presents the results of the analysis by addressing the following research questions:

1. **For each response strategy and baseline system, what is the overall response viability? How does viability vary geographically and seasonally? What metocean condition(s) have the greatest impact?**
2. **What is the overall viability of marine oil spill response in the Arctic?**
3. **How would system improvements that result in incremental adjustments to the response limits affect response viability?**

## 6.1 VIABILITY BY RESPONSE STRATEGY

**For each response strategy and baseline system, what is the overall response viability? How does viability vary geographically and seasonally? What metocean condition(s) have the greatest impact?** This section explores the viability of each response strategy based on comparing the response systems within that strategy and considering which metocean conditions appear to have the greatest impact on the results of the analysis.

For this question, we use a combination of the gridded map-based results with results from the 11 location-specific analyses to provide a more detailed exploration of viability at select locations.

Appendix A provides the map-based results for each system for the months of January, April, July, and October.

### 6.1.1 Mechanical Recovery

Table 6-1 provides the percentage of time that conditions were favourable, marginal, or not favourable for each of the mechanical recovery systems studied in average for the total area. Conditions are generally more likely to be favourable for mechanical recovery systems – all of which are based on vessels – in the summer than winter. As presented in both the table and maps (Figure 6-1), when conditions are not red, they are more likely to be yellow than green.

Table 6-1. Percentage of time conditions are favourable, marginal, or not favourable for response for mechanical recovery tactics (averaged for whole study area)

| Baseline system | Response condition | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Whole Arctic - average % | | | | | | | | | | | | |
| Two vessels with boom | Fav | 1 | 1 | 3 | 8 | 16 | 22 | 26 | 30 | 28 | 12 | 3 | 1 | **13** |
| | Marg | 16 | 15 | 15 | 17 | 18 | 18 | 20 | 24 | 34 | 37 | 29 | 19 | **22** |
| | Not fav. | 83 | 82 | 82 | 75 | 66 | 60 | 56 | 46 | 38 | 49 | 68 | 79 | **65** |
| Single vessel with out-rigger | Fav | 0 | 0 | 0 | 1 | 5 | 9 | 12 | 13 | 10 | 4 | 1 | 0 | **5** |
| | Marg | 7 | 7 | 8 | 13 | 22 | 26 | 29 | 34 | 37 | 29 | 17 | 9 | **20** |
| | Not fav. | 93 | 93 | 92 | 86 | 73 | 65 | 59 | 53 | 53 | 67 | 82 | 91 | **75** |
| Three VOO with boom | Fav | 0 | 0 | 0 | 0 | 2 | 3 | 6 | 6 | 4 | 1 | 0 | 0 | **2** |
| | Marg | 1 | 1 | 1 | 2 | 6 | 11 | 13 | 14 | 12 | 8 | 3 | 1 | **6** |
| | Not fav. | 99 | 99 | 99 | 98 | 92 | 86 | 81 | 80 | 84 | 91 | 97 | 99 | **92** |
| Single vessel in ice | Fav | 0 | 0 | 1 | 3 | 13 | 12 | 2 | 1 | 1 | 0 | 0 | 0 | **3** |
| | Marg | 5 | 5 | 6 | 15 | 26 | 16 | 7 | 4 | 9 | 9 | 6 | 5 | **9** |
| | Not fav. | 95 | 95 | 93 | 82 | 61 | 72 | 91 | 95 | 90 | 91 | 94 | 95 | **88** |

The limits for the three mechanical recovery systems designed primarily for response in open-water or low ice concentrations (all but the Single Vessel in Ice) are similar *except* for wave height and sea ice coverage as was presented in Figure 5-2. For both parameters, the limits for Three Vessels of Opportunity (VOO) with Boom are lower than for the other two open-water systems. This results in conditions being not favourable for Three VOO with Boom more than for the other two open-water mechanical systems. This aligns with its application in the nearshore environment.

Conditions would be favourable or marginal for Two Vessels with Boom more often than the other mechanical recovery systems studied, based on the averaged results. Figure 6-1 shows the geographic variability of the results across the study area[6]. The maps show whether conditions in a particular area are more likely to be favourable (green), marginal (yellow), or not favourable (red) during the contrasting months of January and October. Of the four focus months (January, April, July, and October), January and October represent the worst (highest percentage of red conditions) and best (lowest percentage of red conditions) for that system.[7]

6 Note that the results on the maps are shown in 20% increments but describe geographic variability, while the tablular format provides more precision in the presentation of the results but represents numeric results for the entire area.

7 September is actually the month in which this system would be most likely to be viable across the region.

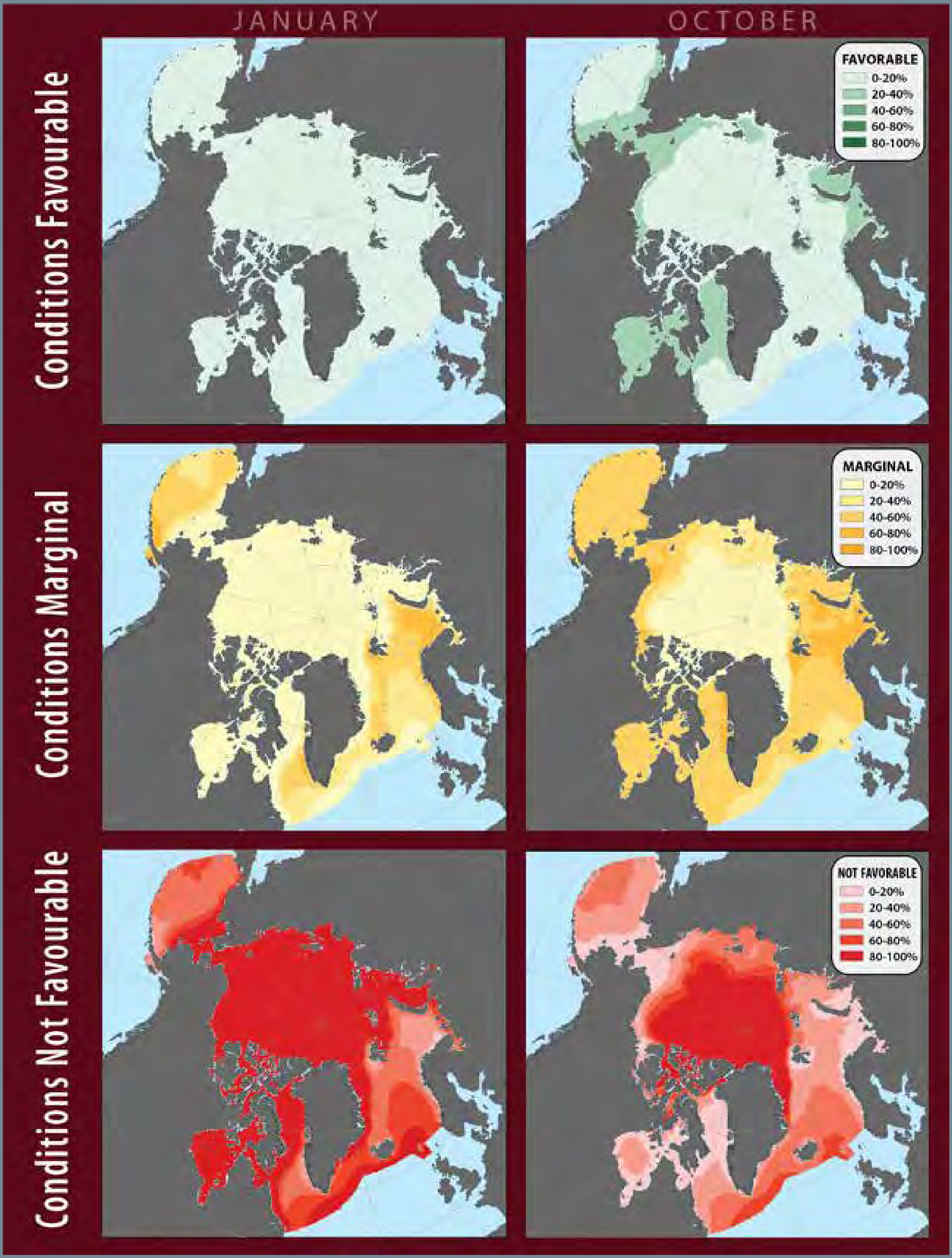



**Figure 6-1**. Selection of the results maps for Two Vessels with Boom for January and October (darker shades indicate more time periods of each color). For the full map series and associated legends, see Appendix A.

The presence of sea ice is clearly evident in the maps, but these do not indicate which of the other parameters are impacting response viability. For this perspective, we look at the results from the analysis of specific locations.

Figure 6-2 shows the results at each single location[8] presented in a series of annual cycles of data compiled from January – December for each. The overall results for that location, with all parameters combined, are shown in the left column. Results throughout the year vary greatly: conditions are not favourable at all at the High Arctic location, but are favourable or marginal at least some of each month at the Bering Sea location, the North Atlantic (between Greenland and Canada), and western Europe locations (Barents Sea, Svalbard, and Norwegian Sea).

The columns to the right show the results for a single parameter (wind speed, wave height, and sea ice coverage) or combined parameters, as with "cold" which shows vessel icing, wind chill, and air temperature; and horizontal visibility. From this, we can see that during the summer months when sea ice is absent from many – though not all – of the locations, visibility and waves emerge as limitations. The western European locations have relatively greater response viability (as also seen in the maps). Sea ice conditions are almost always favourable in these locations, but where response is compromised it is due to marginal wind and cold, and marginal or not favourable waves.

While response conditions are least viable at the High Arctic location, they are similarly dominated by sea ice during the winter at the Chukchi and Beaufort Sea locations off the U.S. and the Laptev Sea off Russia. The effect is also visible, though not for as much of the year, at the Bering Sea North and East Davis Strait locations. In these locations, if sea ice conditions are favourable or marginal, visibility is more likely than any other metocean condition to be not favourable. (There are times when sea ice conditions are favourable but visibility conditions are not favourable. However, visibility will vary and is never "not favourable" for an entire month the way sea ice can be.)

In contrast to the three open-water-based systems, the Single Vessel in Ice is designed for much higher concentrations of sea ice. Therefore, it is worth considering its viability during times when the other tactics would not be viable due to high ice concentrations. For this perspective, we focus on the results at the locations analyzed where sea ice is most likely to be present. In all cases, sea ice conditions are favourable except during the summer months (except at the High Arctic ice conditions are always favourable for this system). With the large vessel used, wave and wind conditions do not pose a challenge to this system. Visibility conditions are typically worse in the summer than winter, so while poor visibility may impede this vessel-based tactic somewhat, it is generally worse when there is no ice anyway. There is no cold/wind chill limit for this system, as personnel are not required to spend long periods on deck. This leaves the effect of superstructure icing, which is assumed to be the same for this system as the other vessel-based systems, and is potentially significant during the winter months. Figure 6-3 shows the annual cycle for the Single Vessel in Ice at locations dominated by sea ice. While the system does better at these locations than others, superstructure icing may still be a problem.

8 Single grid cells used are shown in Figure 3-2.

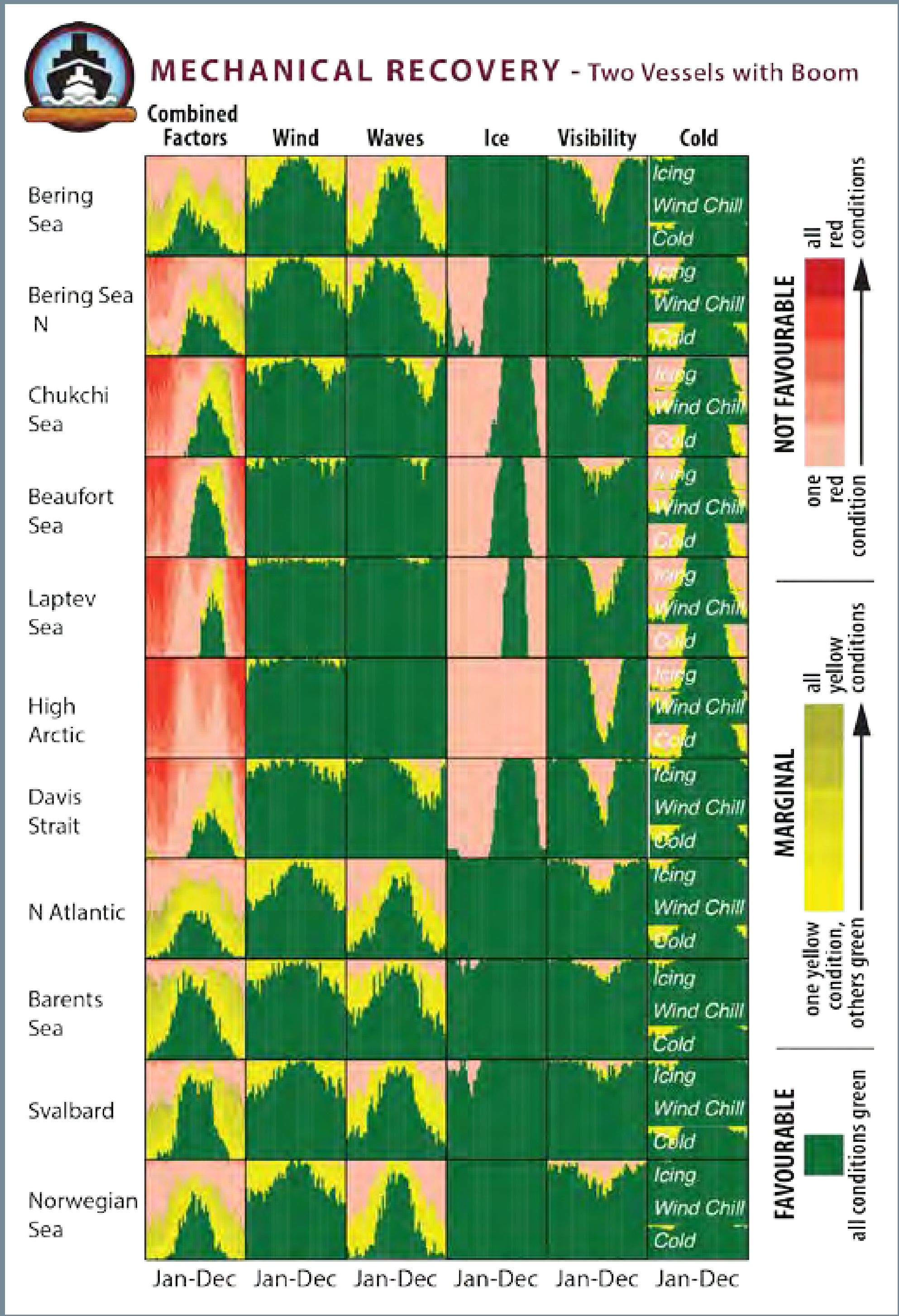



**Figure 6-2.** Results of single location analyses, compiled into a single annual cycle (January - December) for Two Vessels with Boom

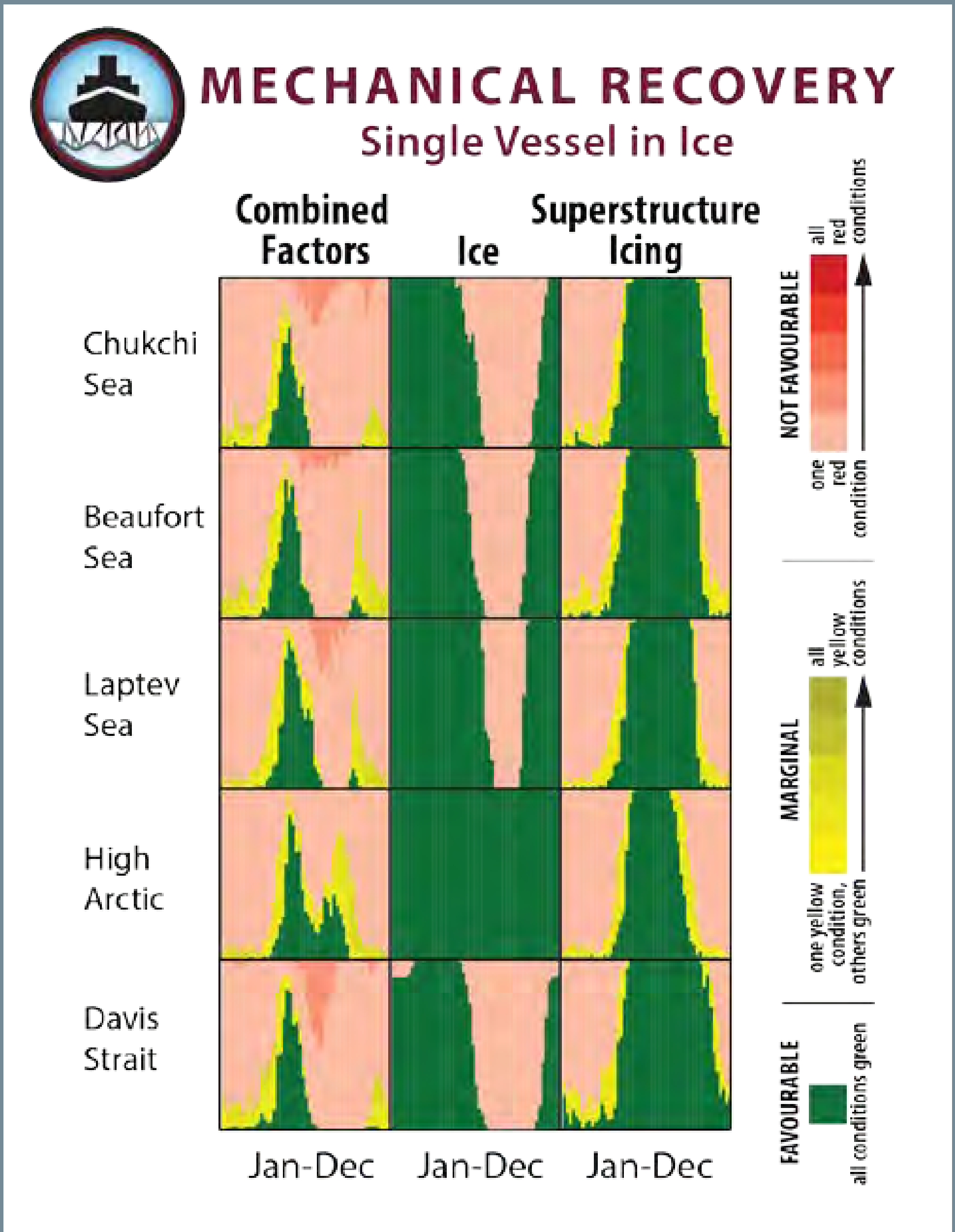



**Figure 6-3.** Annual cycles for Single Vessel in Ice at selected locations where sea ice is most likely present (showing results with all parameters combined, in the left column, as well as for sea ice and vessel icing independently)

### 6.1.2 Dispersants

Table 6-2 shows the percentage of time that conditions would be favourable, marginal, or not favourable for each of the three dispersants systems during each month and combined for the year. The percentages are based on averages for the whole study area. Conditions are more likely to be favourable or marginal for the application of dispersants than any of the mechanical recovery or in-situ burning systems studied. The two aircraft-based systems were similar, with the helicopter-based application slightly more viable than the fixed-wing system. Conditions for all three dispersants systems studied are more likely to be favourable or marginal in summer (ice-free months) than winter.

**Table 6-2. Percentage of time conditions are favourable, marginal, or not favourable for the dispersant systems analyzed (averaged for whole study area)**

| Baseline system | Response condition | Whole Arctic - average % | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
| Vessel | Fav | 3 | 4 | 8 | 14 | 21 | 25 | 28 | 34 | 35 | 19 | 7 | 3 | **17** |
| | Marg | 29 | 27 | 23 | 22 | 22 | 24 | 24 | 26 | 37 | 47 | 41 | 33 | **30** |
| | Not fav | 68 | 69 | 69 | 64 | 57 | 51 | 48 | 40 | 28 | 34 | 52 | 64 | **53** |
| Fixed-wing Aircraft | Fav | 3 | 5 | 10 | 14 | 16 | 13 | 11 | 16 | 23 | 18 | 8 | 4 | **12** |
| | Marg | 4 | 5 | 8 | 9 | 9 | 13 | 15 | 17 | 17 | 10 | 6 | 4 | **10** |
| | Not fav | 93 | 90 | 82 | 77 | 75 | 74 | 74 | 67 | 60 | 72 | 86 | 92 | **78** |
| Helicopter | Fav | 3 | 5 | 10 | 16 | 21 | 22 | 24 | 29 | 33 | 20 | 8 | 4 | **16** |
| | Marg | 4 | 6 | 9 | 10 | 8 | 10 | 11 | 11 | 12 | 10 | 6 | 4 | **8** |
| | Not fav | 93 | 89 | 81 | 74 | 71 | 68 | 65 | 60 | 55 | 70 | 86 | 92 | **76** |

The results maps for the vessel application of dispersants (Figure 6-4) have some similarities to those in Figure 6-1 for Two Vessels with Boom: both systems rely on the safe operation of vessels and are impeded by the presence of sea ice. However, based on the limits identified for this study, Dispersants - Vessel Application has a higher ice tolerance than Mechanical Recovery - Two Vessels with Boom.

Figure 6-5 shows the annual cycles for each of the 11 locations analyzed, with the cycles for specific parameters to the right. This shows that while wind and wave conditions may be marginal for this system, sea ice, cold (wind chill or icing), and visibility conditions are more likely to be not favourable. As the system is vessel-based and requires crew to maneuver on deck, it is subject to the same limitations as most of the mechanical recovery systems for visibility, wind chill, and structural icing.

Because dispersants may be applied from a vessel or aircraft, it is informative to consider the results for the aircraft-based systems in contrast to the vessel-based system. For this purpose, we compare the effects of different metocean conditions on the Vessel Application system and the Fixed-wing Aircraft Application system (which has a slightly greater viability than the helicopter-based system based on the numeric results for the study area in Table 6-2). The effects of sea ice and waves are similar, but cold, wind, and visibility conditions affect the systems differently. Figure 6-6 shows the relative impact of these parameters on the two platforms at the 11 single locations studied. Wind and, especially, visibility conditions are more likely to be not favourable for Fixed-wing Aircraft Application, while cold is more likely to affect Vessel Application.

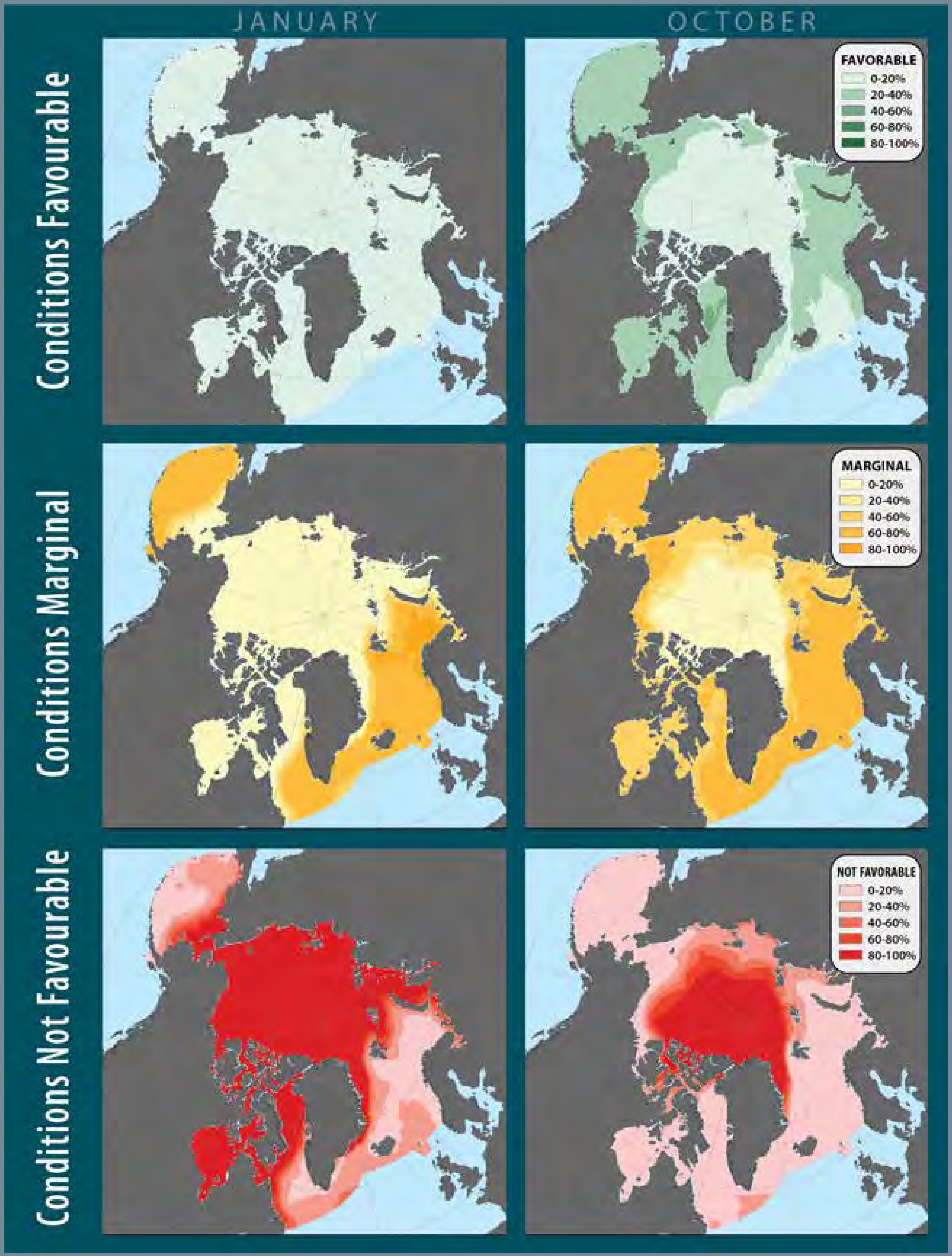



**Figure 6-4.** Selection of results maps for Dispersants - Vessel Application for January and October (darker shades indicate more time periods of each color)

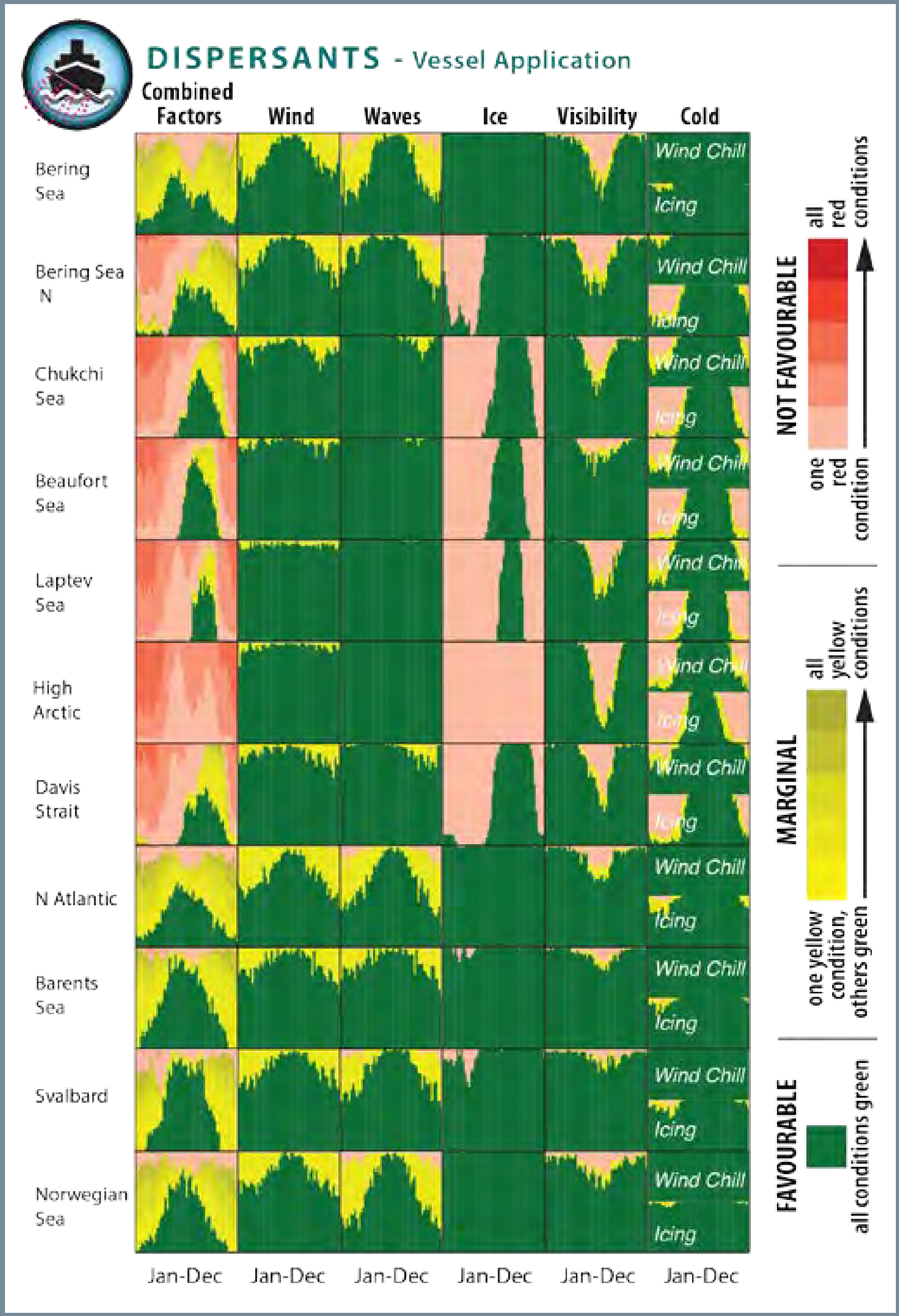



**Figure 6-5.** Results of single location analyses, compiled into a single annual cycle (January - December) for Dispersants – Vessel Application

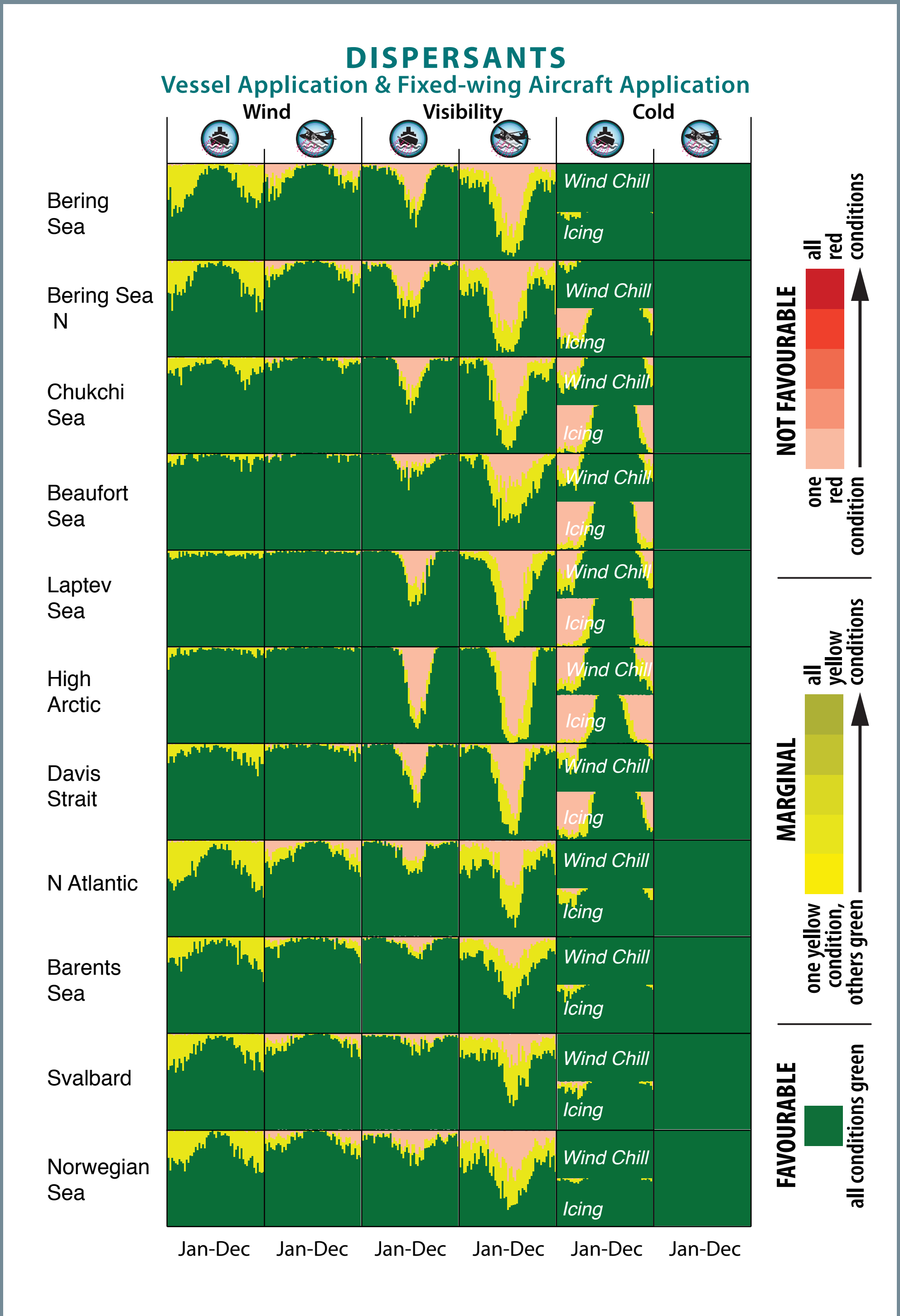



**Figure 6-6.** Annual cycles at 11 locations for wind, visibility, and cold only, comparing effect on dispersant application platforms

### 6.1.3 In-situ burning

Table 6-3 shows the percentage of time that conditions would be favourable, marginal, or not favourable for the three in-situ burning systems studied. Average results for the whole study area are shown for each month and for the whole year. In-situ burning requires a certain slick thickness, which is accomplished in three ways in the systems studied: containment with fire boom deployed from vessels, natural containment by sea ice, and the application of chemical herders.

**Table 6-3. Percentage of time conditions are favourable, marginal, or not favourable for in-situ burning systems (averaged for whole study area)**

| Baseline system | Response condition | Whole Arctic - average % | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
| Vessels with Fire Boom | Fav | 0 | 0 | 0 | 1 | 4 | 7 | 9 | 10 | 7 | 3 | 1 | 0 | **4** |
| | Marg | 7 | 6 | 7 | 12 | 21 | 27 | 31 | 36 | 37 | 28 | 16 | 9 | **20** |
| | Not fav | 93 | 94 | 93 | 87 | 75 | 66 | 60 | 54 | 56 | 69 | 83 | 91 | **76** |
| Helicopter with Ice | Fav | 0 | 1 | 1 | 2 | 3 | 3 | 1 | 1 | 2 | 2 | 1 | 0 | **1** |
| | Marg | 2 | 3 | 7 | 9 | 10 | 9 | 4 | 3 | 5 | 5 | 2 | 2 | **5** |
| | Not fav | 98 | 96 | 92 | 89 | 87 | 88 | 95 | 96 | 93 | 93 | 97 | 98 | **94** |
| Helicopter with Herders | Fav | 1 | 1 | 2 | 3 | 5 | 7 | 8 | 8 | 8 | 4 | 2 | 1 | **4** |
| | Marg | 1 | 2 | 3 | 5 | 8 | 11 | 12 | 12 | 11 | 6 | 2 | 1 | **6** |
| | Not fav | 98 | 97 | 95 | 92 | 87 | 82 | 80 | 80 | 81 | 90 | 96 | 98 | **90** |

Conditions are more likely to be favourable or marginal for the Vessels with Fire Boom system than the two other in-situ burning systems, based on the results averaged across the study area (4% favourable and 20% marginal of the year). As with other vessel-based systems, conditions are more likely favourable or marginal during the summer or ice-free months than in the winter. The two helicopter-based systems have similar results for the year overall (90% and 94% not favourable conditions), but viability by month is more variable. Conditions for the "under development" system of Helicopter with Herders are favourable or marginal for about 20% of the months of June, July, August, and September. The results maps for January and July are presented for Vessels with Fire Boom as examples of the worst and best of the focus months for this in-situ burning system. As shown in Figure 6-7, in locations where the conditions for the Vessels with Fire Boom system are favourable or marginal, they appear in most places to be more likely to be marginal than favourable. To understand what conditions are affecting this system, we can look at the annual cycles for the 11 locations studied as done in previous sections (Figure 6-8). The effects of cold, ice, and visibility are similar to those seen for the other vessel-based systems used for open-water mechanical recovery and the application of dispersants from a vessel. However, wind has a much greater effect on this system due to its impact on igniting and sustaining a burn.

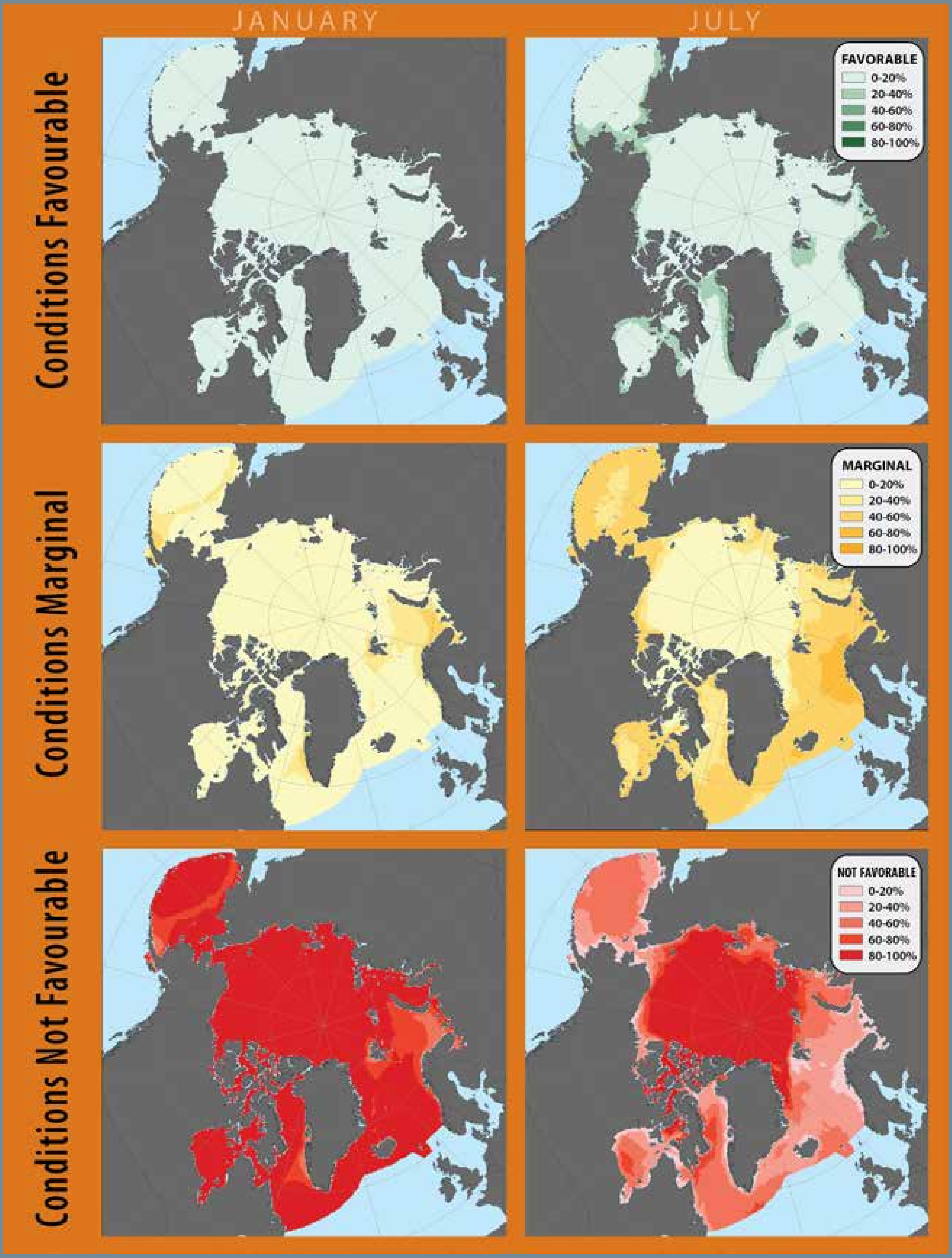



Figure 6-7. Results maps for the Vessels with Fire Boom in-situ burning system for January and July (darker shades indicate more time periods of each color)

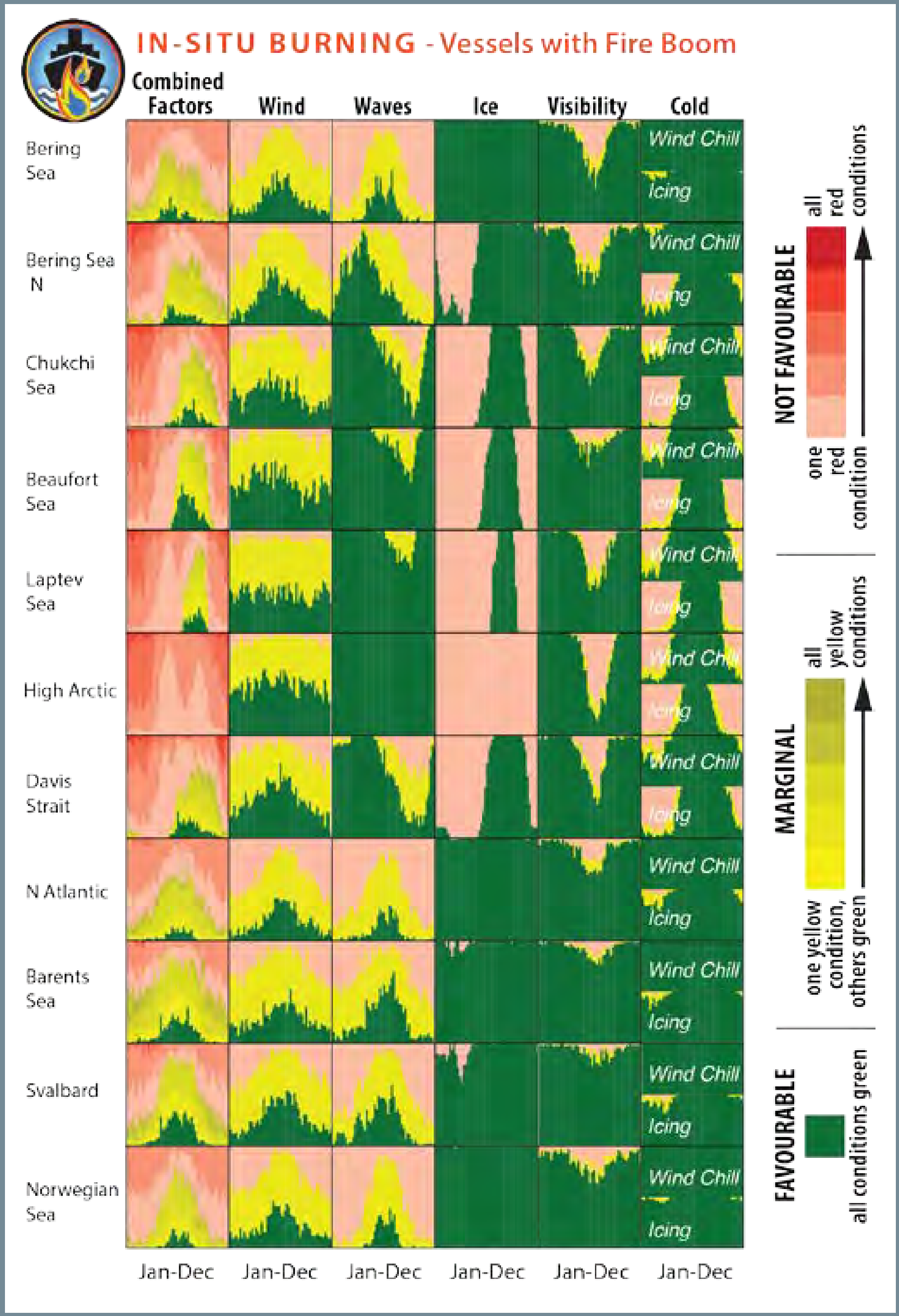



**Figure 6**-8. Results of single location analyses, compiled into a single annual cycle (January - December) for in-situ burning with the slick contained with fire boom

Similar to dispersants, in-situ burning may be based off a vessel or aircraft (in this case, helicopters only). However, without vessels in the water maneuvering fire boom, alternatives are needed to achieve the necessary slick thickness. For Helicopter in Ice, this requires enough ice to contain the oil but not enough to obstruct access to it. For the 11 locations studied, this system is never viable due to the fact that sea ice is always either absent or present at 100% concentration. Thus, the middle-range ice conditions where this system would be viable do not occur and the effects of other conditions are irrelevant.

In-situ Burning – Helicopter with Herders would be viable at least some of the time in almost all months at all locations except the High Arctic. Because a wave limit was not available at the time the limits were established, it is important to acknowledge that these results assume that waves are never limiting though in fact they could be. There are times when cold, ice, and visibility conditions are not favourable for this system, however. The three conditions that have the greatest impact on this system are dominant in different seasons, meaning that when ice conditions are most likely to be favourable, visibility conditions are most likely not favourable. (See Figure 6-9.) There are also times throughout the year when wind conditions are marginal or not favourable.

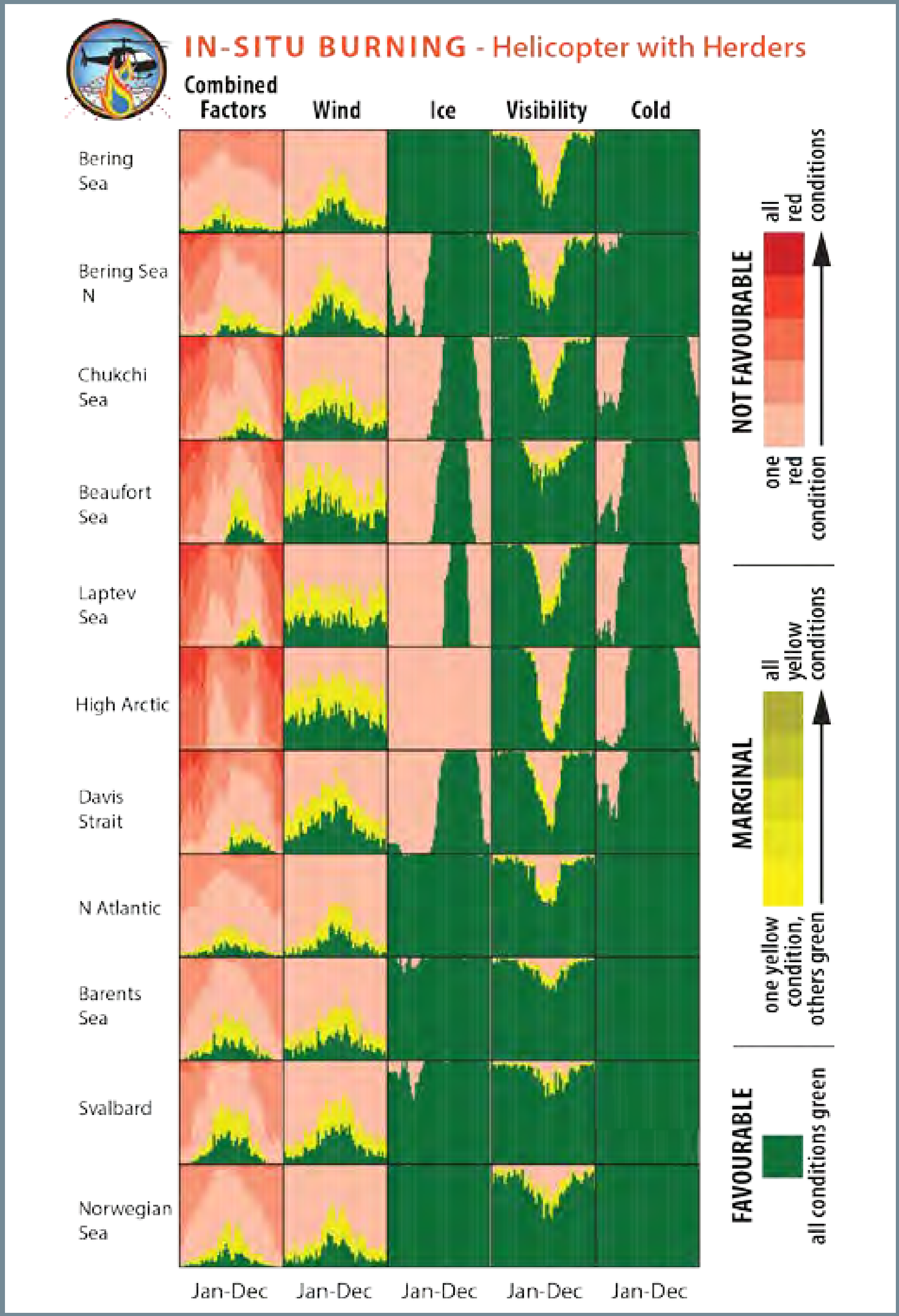



**Figure 6-9.** Results of single location analyses, compiled into a single annual cycle (January - December) for the application of herders and ignition from a helicopter (waves excluded because there is no wave limit used in the analysis; thus, it is always "green")

## 6.2 OVERALL VIABILITY

***What is the overall viability of marine oil spill response in the Arctic?*** This question is answered first based on the total percentage of time that response conditions are favourable, marginal, or not favourable during the study period) for any one of the systems studied in Figure 6-10. The percentages represent an average across the entire study area for the 10 years of metocean data compiled. All systems are likely to face "not favorable" (red) conditions more than 50% of the time over the whole area, some of them more than 75% of the time. For the times when response is either favourable or marginal, it is more likely marginal than favourable *except* for the two aircraft-based dispersant applications. These averages are presented to summarize the results and provide a holistic picture of the study area, regardless of the degree of spill hazard due to current activities. However, we note that lower latitudes will have a higher percentage of time when response is favourable or marginal than in the High Arctic based on the mapped results at 11 individual locations as presented in the preceding sections and Appendix A and B.

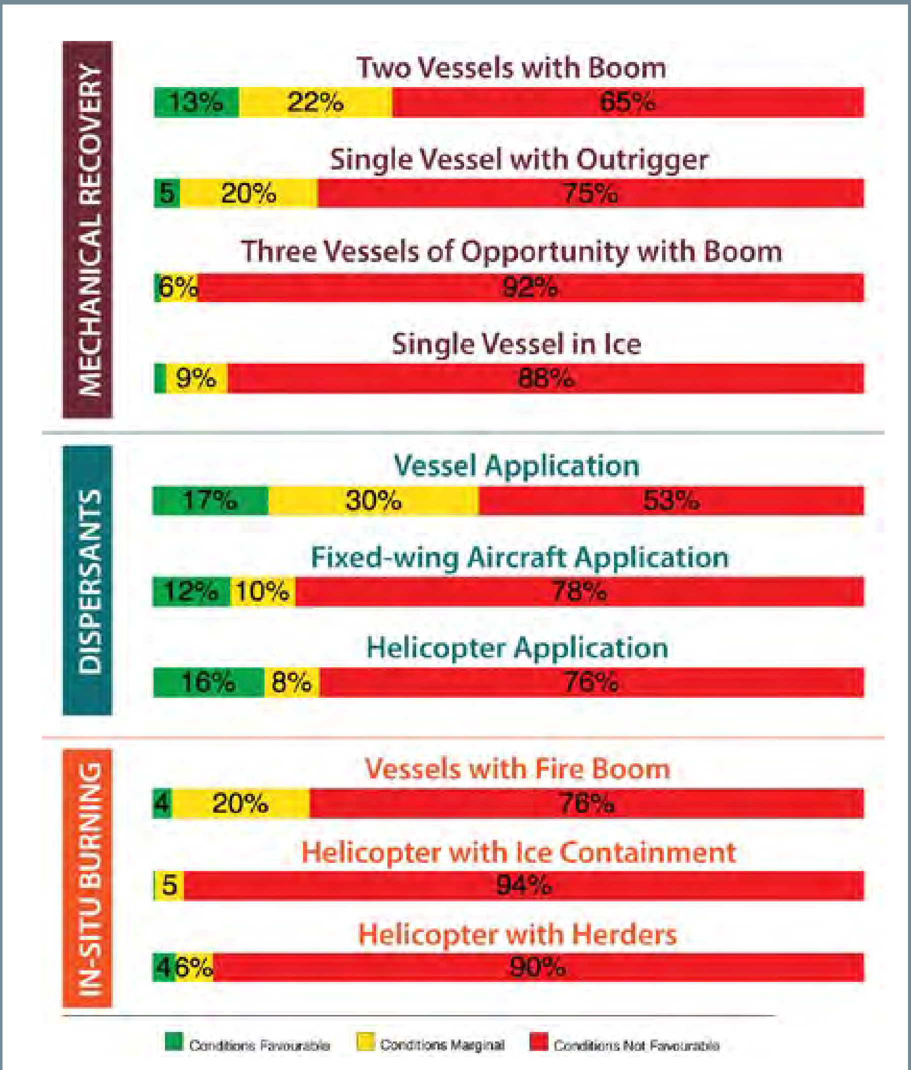



**Figure 6-10.** Annual percentage of time that conditions are favourable, marginal, or not favourable for response systems studied (averaged for entire study area)

Figure 6-11 shows the distribution of the response viability index (RVI) across the study area for the months of January, April, July, and October. The figure uses a single index ranging from zero (lowest possible viability) to two (highest possible viability) to show the calculated viability when comparing all 10 systems in the study. The maximum RVI value speaks to the concept of a "response toolbox" in which planners and responders have more than one option available to them for any given location. The RVI is generally lowest in the high Arctic. It is highest in July in the Barents Sea and some areas along the coasts of eastern Greenland, Hudson Bay (Canada), Alaska (U.S.), and far eastern Russia.

Appendix C contains the results for each of the 11 locations studied, presented in the "annual cycle" format.

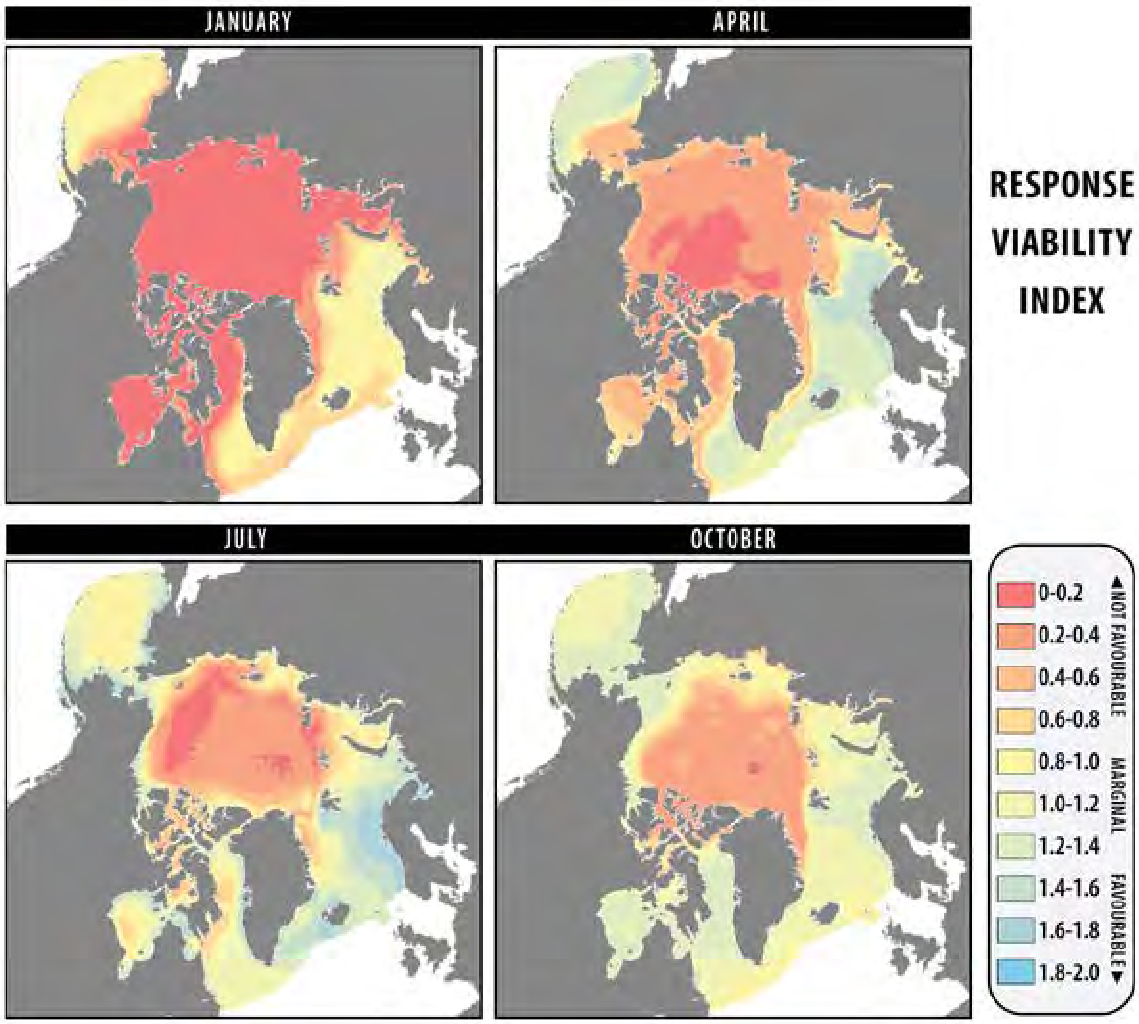



**Figure 6-11.** Response Viability Index for January, April, July, and October based on highest calculated viability when comparing all 10 systems in the study for each grid cell and timestep (month)

## 6.3 POTENTIAL IMPACT OF SYSTEM IMPROVEMENTS

**How would system improvements that result in incremental adjustments to the response limits affect response viability?**

Response operating limits may change as technology advances, new practices are developed, or better information is obtained about the limits of current systems. For the purpose of this study, incremental changes to the limits for two different parameters (wind and waves) were analyzed for their impact on the overall viability of the response systems.

The parameters and magnitude of the limit modifications analyzed were not selected based on an in-depth review of the potential for any particular system improvements, nor based on any judgment regarding emerging developments in the field. They were chosen, instead, to illustrate the potential significance of system changes resulting in incremental adjustments to the limits. Those parameters that tend to relate most closely to safety (vessel icing, wind chill, visibility, etc.) were not modified in this analysis. The purpose of the analysis was to assess the rate of change in response viability based on incremental changes in selected individual limits. Sea ice was excluded from the sensitivity analysis because the in the metocean data compiled, conditions were almost always at the extremes of the 0-100% ice concentration scale. (Appendix C illustrates this and shows how aggregated conditions for all parameters at the 11 locations studied compared to the response limits for the different systems.)

The sensitivity analysis was conducted by incrementally increasing the wind speed and wave height limits for each strategy to reflect a hypothetical increased tolerance for wind and waves. The limits between the favourable/marginal and marginal/not favourable boundaries were increased by the same increment in each case. Results were recorded as percent changes in the amount of time conditions would be favourable or marginal for a particular system. Generally, the percentage of time conditions were favourable or marginal *increased* while the percentage of time they were not favourable *decreased*.

With few exceptions, the changes in wind and wave limits resulted in a linear *increase* in the percentage of time conditions were favourable or marginal (with a corresponding linear *decrease* in the time conditions were not favourable). The rate of change is expressed as the increase of favourable and marginal conditions and the corresponding decrease in the amount of time identified with conditions that were not favourable.

### 6.3.1 Results of change to wind limits

Wind speed limits were increased in 1-m/s (2-kt) increments from 1 to 4 m/s (2 to 7.8 kts) for each strategy while holding all other limits constant. Table 6-4 presents the results of the average rate of change for each tactic expressed as percentage change in the combined favourable/marginal conditions per 1 m/s increase in wind tolerance. The results reported are based on all months of the year when applied to the entire gridded dataset.

Table 6-4. Rate of change in favourable/marginal conditions per 1 m/s increase in wind speed limit (averaged across study area over entire year)

| STRATEGY | | RATE OF CHANGE (increase in total green/yellow per 0.1 m increase) |
|---|---|---|
| Mechanical Recovery | Two Vessels with Boom | 0% |
| | Single Vessel with Outrigger | 0% |
| | Three VOO with Boom | 0% |
| | Single Vessel in Ice | 0% |
| Dispersants | Vessel Application | 0% |
| | Fixed-wing Aircraft Application | 0.1% |
| | Helicopter Application | 0.1% |
| In-situ Burning | Vessels with Fire Boom | 0.1% |
| | Helicopter with Ice | 0.1% |
| | Helicopter with Herders[2] | 2.4% |

Figure 6-12 presents the results of the sensitivity analysis of the In-situ Burning – Helicopter with Herders, which is the strategy that shows the greatest sensitivity to changes in wind speed limits.


**Figure 6-12.** Percentage change in results for In-Situ Burning – Helicopter with Herders achieved by increasing wind speed limits 1, 2, 3, and 4 m/s

With the exception of In-situ Burning – Helicopter with Herders, changes in wind speed tolerance for the strategies studied resulted in little or no change in response viability. This is because other metocean conditions were limiting these strategies. Increasing the wind speed limits for In-Situ Burning – Helicopter with Herders would increase the response viability of this tactic by about 2.4% per m/s of increase.

### 6.3.2 Results of change to wave height limits

Wave height limits were increased by 0.2 m increments from 0.2 to 0.8 m for each strategy while holding all other limits constant. Table 6-5 presents the results of the average rate of change for each tactic expressed as percentage change in the amount of time conditions would be favourable or marginal per 0.1 m increase in wave tolerance across all months of the year when applied to the entire gridded dataset.

**Table 6-5.** Rate of change in response viability per 0.1 m increase in wave limits (averaged across the study area over the entire year)

| STRATEGY | | RATE OF CHANGE (increase in total green/yellow per 0.1 m increase) |
|---|---|---|
| Mechanical Recovery | Two Vessels with Boom | 0.5% |
| | Single Vessel with Outrigger | 1.0% |
| | Three VOO with Boom | 1.6% |
| | Single Vessel in Ice | 0% |
| Dispersants | Vessel Application | 0.1% |
| | Fixed-wing Aircraft Application | 0% |
| | Helicopter Application | 0% |
| In-situ Burning | Vessels with Fire Boom | 0.6% |
| | Helicopter with Ice | 0% |
| | Helicopter with Herders[3] | 0% |

Figure 6-13 presents the results of the sensitivity analysis for Mechanical Recovery – Two Vessels of Opportunity with Boom, the strategy that shows the greatest sensitivity to changes in wave height limits.

Increasing the tolerance to wave height had a greater effect on response viability than increasing wind speed. As would be expected, the percentage of time when conditions would be favourable or marginal for vessel-based systems generally increased as the wave limits were increased.[9] On the other hand, there was no change for aircraft-based strategies. (Note that there is no wave limit associated with In-situ Burning – Helicopter with Herders.)

The greatest change in results was seen in Mechanical Recovery – Two Vessels of Opportunity with Boom, which showed a 1.6% change in response viability per 0.1 m increase in wave height tolerance. This nearshore system has the lowest wave height limit and therefore benefits most from increasing the limits.

A detailed examination of the data by month generally revealed higher rates of change during the ice-free months, as would be expected.

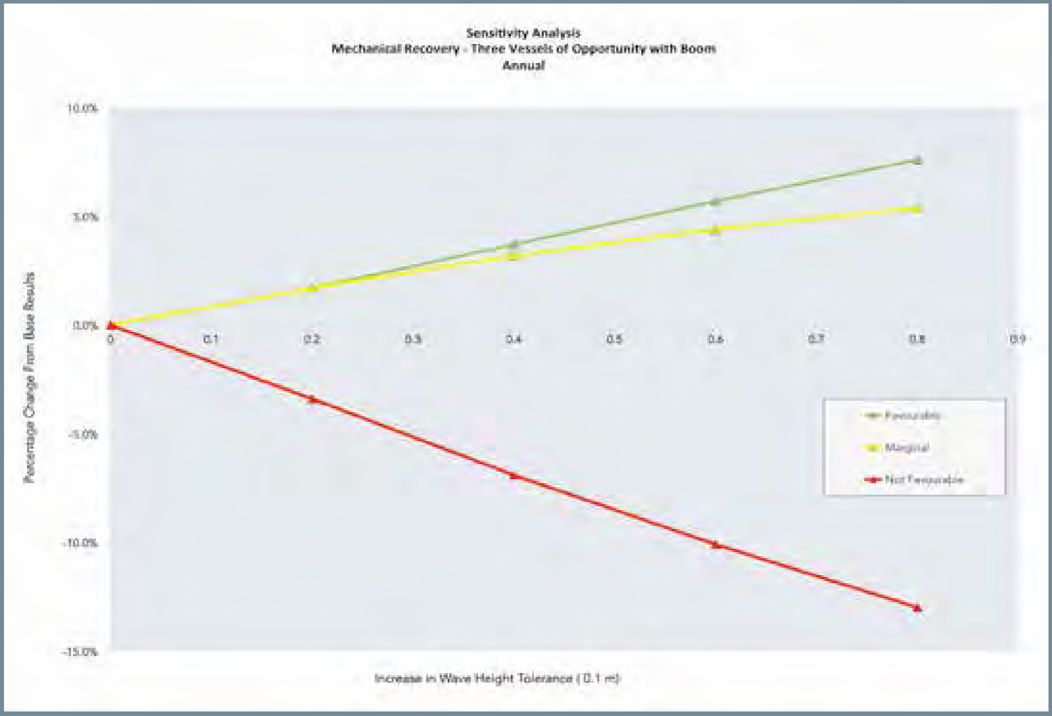



**Figure 6-13.** Percentage change in annual Response Viability for Mechanical Recovery - Three Vessels of Opportunity with Boom by increasing wave height limits 0.2, 0.4, 0.6, and 0.8 m

9 The results for Mechanical Recovery – Single Vessel in Ice were the exception. There is no wave limit for this system and thus no change in the results based on the sensitivity analysis for wave height limits.

# 7 OBSERVATIONS

This section summarizes some key findings and observations and considerations regarding the study results.

## 7.1 FINDINGS

Conditions in the metocean dataset prepared for this study were "not favourable" more than 50% of the time for all response systems studied when averaged across the entire study area and entire year. This averaging, however, reflects conditions across the entire study area, and does not reflect the many geographical and seasonal variations within it. The average is also influenced by the definition of the study area itself: this study considered the circumpolar Arctic holistically, based on the AMAP area. Dividing the area differently, or focusing in on specific sub-areas of interest, would lead to other results (as presented in the maps and other figures; refer to Appendices A and B for results).

- Based on these averaged, overall results, response systems vary in the extent to which the combined metocean parameters may result in favourable, marginal, or not favourable conditions.

  Conditions were **favourable** at least 10% of the time for the following systems:

  - Dispersant – Vessel Application (17%),
  - Dispersant – Helicopter Application (16%),
  - Mechanical Recovery – Two Vessels with Boom (13%), and
  - Dispersant – Fixed-wing Application (12%)

  Conditions were either **favourable *or* marginal** at least 25% of the time (combined) for the following systems:

  - Dispersant – Vessel Application (47%),
  - Mechanical Recovery – Two Vessels with Boom (35%), and
  - Mechanical Recovery – Single Vessel with Outrigger (25%)

  Finally, conditions were found to be **not favourable** at least 90% of the time for:

  - In-situ Burning – Helicopter with Ice Containment (94%),
  - Mechanical Recovery – Three Vessels of Opportunity with Boom (92%), and
  - In-situ Burning – Helicopter with Herder (90%)

- Looking across the study area, response viability varies significantly throughout the year and is generally much better during the months that are ice-free in most areas (July to October). In winter, conditions are generally not favourable to response with most systems. Response viability in the fall is generally better than in the spring.
- Response viability varies with location. Conditions in the Bering Sea, Barents Sea, Norwegian Sea, Baffin Bay, Hudson Bay, and North Atlantic are more likely to be favourable for a spill response than other areas within the Arctic region.
- During summer, conditions are also more likely to be favourable to response in the areas closer to shore (Beaufort Sea, Bering Strait, East Siberian Sea, Laptev Sea, and Kara Sea).
- Waves, sea ice concentration, and visibility are the metocean conditions that are most likely to limit deployment of response systems.
- Incremental changes to the response limits studied (wind and waves) result in relatively small improvements in the percentage of time that conditions were favourable or marginal for a given response system.

## 7.2 DISCUSSION

This section discusses some considerations and observations regarding the study results.

- The results of this response viability analysis do not estimate the amount of time that a response could be mounted, but rather the percentage of time that various metocean conditions may affect it.
- The overall results for the study area are influenced by the amount of that area that is in the High Arctic where there is currently little to no activity. Response viability is generally better at lower latitudes, which is where current shipping routes and other activity create greater oil spill probability.
- Even though an individual response system may not be viable frequently in this study, it could still be the best option for certain circumstances. A suite of approaches and response systems is typically considered in spill response planning. For instance, conditions for the Mechanical Recovery – Single Vessel in Ice system are only favourable 3% of the time, but this may be the only response option available in high ice concentrations when there is limited visibility. This study did not examine the combined viability of multiple response systems that could be available for the same area.
- The vast distance between logistical support bases in the region and the potentially brief window of opportunity to respond will favor response strategies that can be rapidly mobilized over long distances, such as aircraft-based strategies. A spill that becomes encapsulated in ice could theoretically be monitored until the ice melts, thus increasing the window of opportunity, though this is not proven.
- The results of the study did not favor response systems designed for ice concentrations in the mid-range because the data showed largely 0 or 100% ice concentration conditions. This could be an artefact of the data source used, and could be explored further with different data sources for more localized areas.

- The authors offer the following caveats for consideration when reviewing or applying the results:
    - The results of this study should be viewed as conservative because:
        - The metocean data do not include cloud ceiling, which could further limit aircraft operations, and
        - The study does not consider the consecutive timesteps that a favourable or marginal condition exists; some windows of opportunity will likely be too short to mobilize and mount a response.
    - This study is based on metocean conditions during the previous 10 years. If sea ice continues to retreat, response viability may change in the future.
    - There is high variation year-to-year within the dataset. Conditions at any given time or place could be different than those that result from the analysis.
    - Observations regarding viability are relative to this study only and do not relate to values in other similar studies.

## 7.3 RECOMMENDATIONS

The authors offer the following recommendations at the conclusion of the project:

- The metocean dataset assembled for this study could be improved by adding cloud ceiling data as this metocean condition is limiting to aircraft operations.
- Future analyses and practical response planning and decision-making would be strengthened by having better documentation (and quantification) of limits for the different response systems. Documenting limits from larger scale tests or actual exercises or deployments would be the best method to quantify response limits.
- An extensive volume of information has been compiled for, and generated by, this study. Only a subset of it is presented in this report. A web-based response viability tool is one option for maximizing the benefit of the effort undertaken here and could enable response planners, responders, and others to further assess response viability – and options for increasing response viability - in their locations of interest.

# 8 CONCLUSION

This study contributes to a growing body of knowledge regarding Arctic oil spill response, with a practical focus on the ability to deploy and operate a set of example response systems in the prevailing metocean conditions. The availability and effectiveness of those systems are also important to understand, but are outside the scope of this analysis. Instead, we applied a uniform approach across the region for a holistic understanding of the potential impact of Arctic conditions on response deployment. When examined for individual locations, this information can inform oil spill contingency planning, equipment and system selection, and potential system modifications for improved viability.

The study concludes that Arctic conditions are likely to challenge marine oil spill response in the Arctic based on the metocean conditions in the 10-year hindcast compiled for this project, though results vary considerably throughout the year. Particularly at the lower latitudes in the study area, there are times when conditions will be favourable to response. For most systems studied, this correlates to the ice-free months. Responders, planners, or decision-makers focused on a particular location or region can use these results to identify the approach that is most likely to be suitable at different times of the year. More in-depth studies could be applied to identify operational windows for different systems, or identify the system or systems that are most likely to be viable for a particular location.

This study also represents an advance in the response viability analytical approach, by combining a map-based analysis with a focus on select locations for more in-depth analysis of the seasonal changes and relative impact of different metocean conditions on the response. Input from international experts was applied to the method, selection of systems and limits, and presentation of results. This is also the largest geographic area to which a consistent approach has been applied.

The data compiled and technique applied in this study could be used or expanded to explore the impact of different limits based on system modifications, technological innovations, or new documentation of the operational limits for a particular system. Subsequent analyses could also explore changes to response viability as the Arctic environment changes, or inform technological development. Options for extending the response window by combining response systems could be explored. Additional individual grid cells can also be analyzed for locations of interest.

Finally, response viability based on metocean conditions is an important aspect of the overall risk profile for the Arctic, as response represents the last intervention between hazard and consequence.

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## About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil & gas and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our professionals are dedicated to helping our customers make the world safer, smarter and greener.

## About Nuka Research and Planning Group, LLC

Nuka Research and Planning Group, LLC is an environmental consulting firm offering a range of services to support policy development, planning, training, outreach and facilitation for international clients in industry, government, and non-profit sectors.

# Appendix A

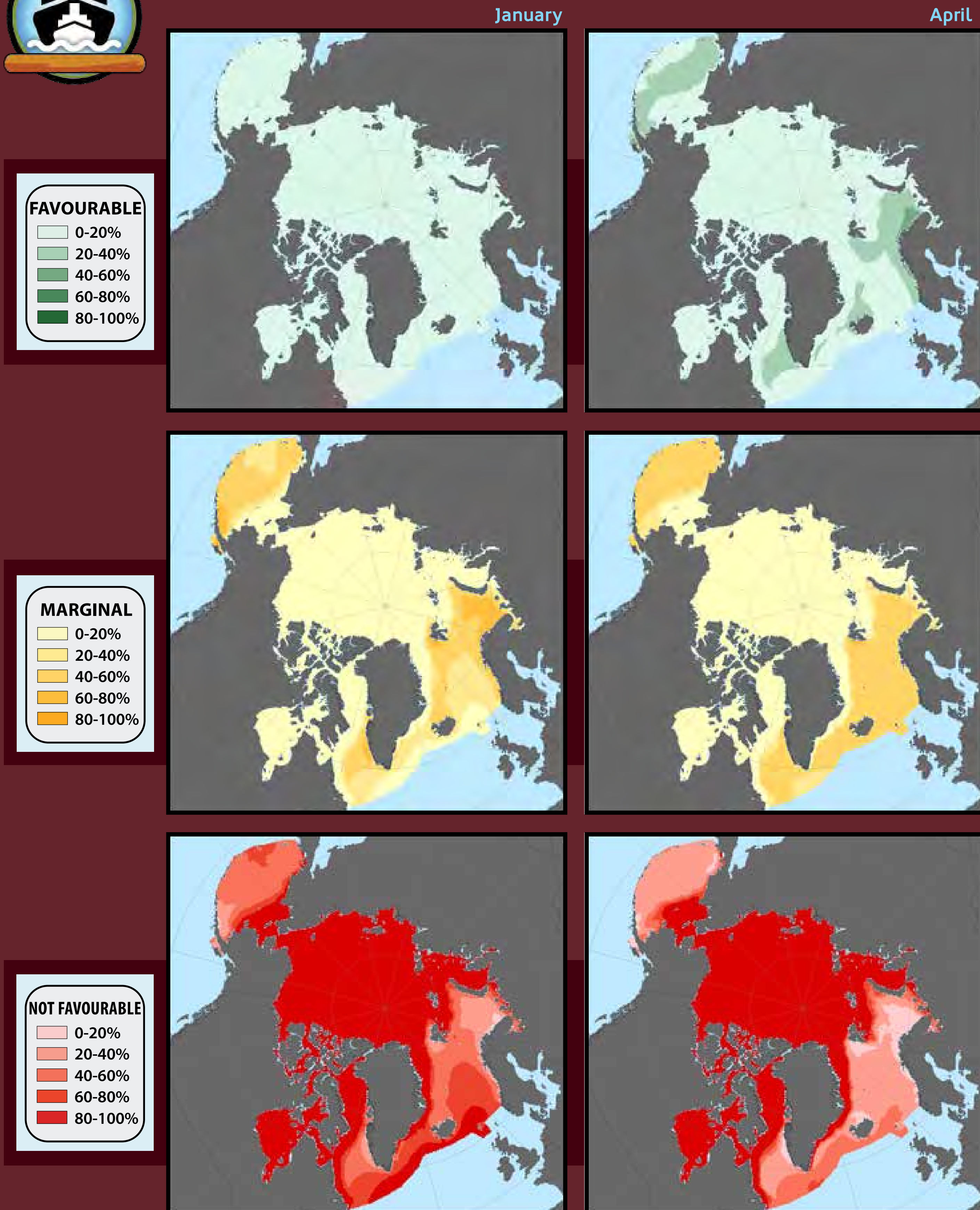
## Results Maps for Each Response System

**(January, April, July, October)**

Maps show the percentage of time that conditions were favourable, marginal, or not favourable around the study area for a particular system and in a particular focus month. For any given month, the aggregated conditions will be 100%, so the maps are presented such that reader can see the results for a particular system across map types (favourable, marginal, or not favourable) as well as months.

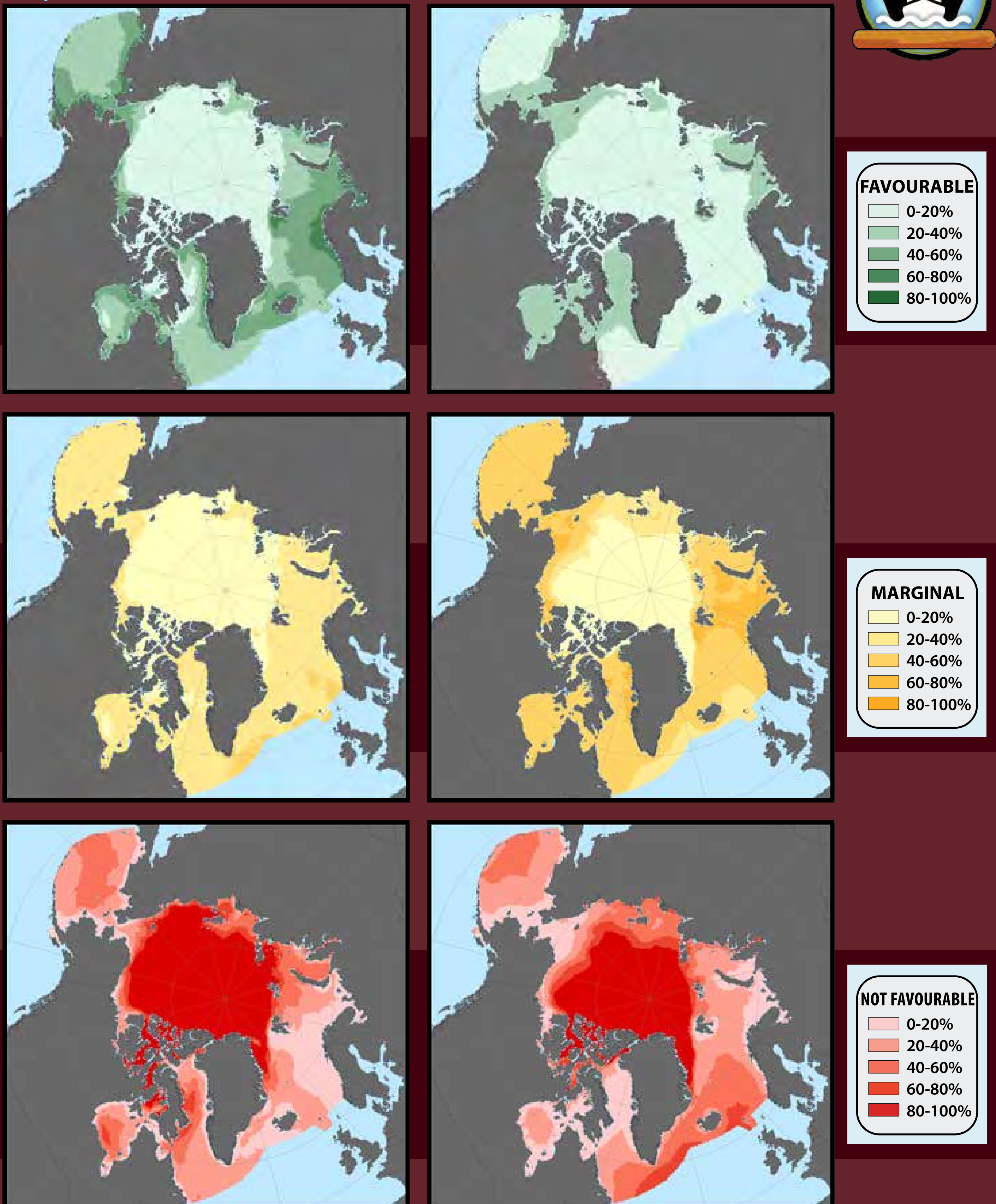
For example, on the following page the results maps are shown for Mechanical Recovery – Two Vessels with Boom. Looking across the months, we see that the percentage of time that conditions are favourable is greatest in July and lowest in January, though the results vary geographically. If conditions are not favourable, then what are they? For this understanding, we can look at the yellow and red maps to see the percentage of time conditions are marginal (darker yellow) or not favourable (darker red).

# MECHANICAL RECOVERY – 2 Vessels with Boom



## MECHANICAL RECOVERY – 2 Vessels with Boom

July | October



# MECHANICAL RECOVERY – Vessel with Outrigger

January

April

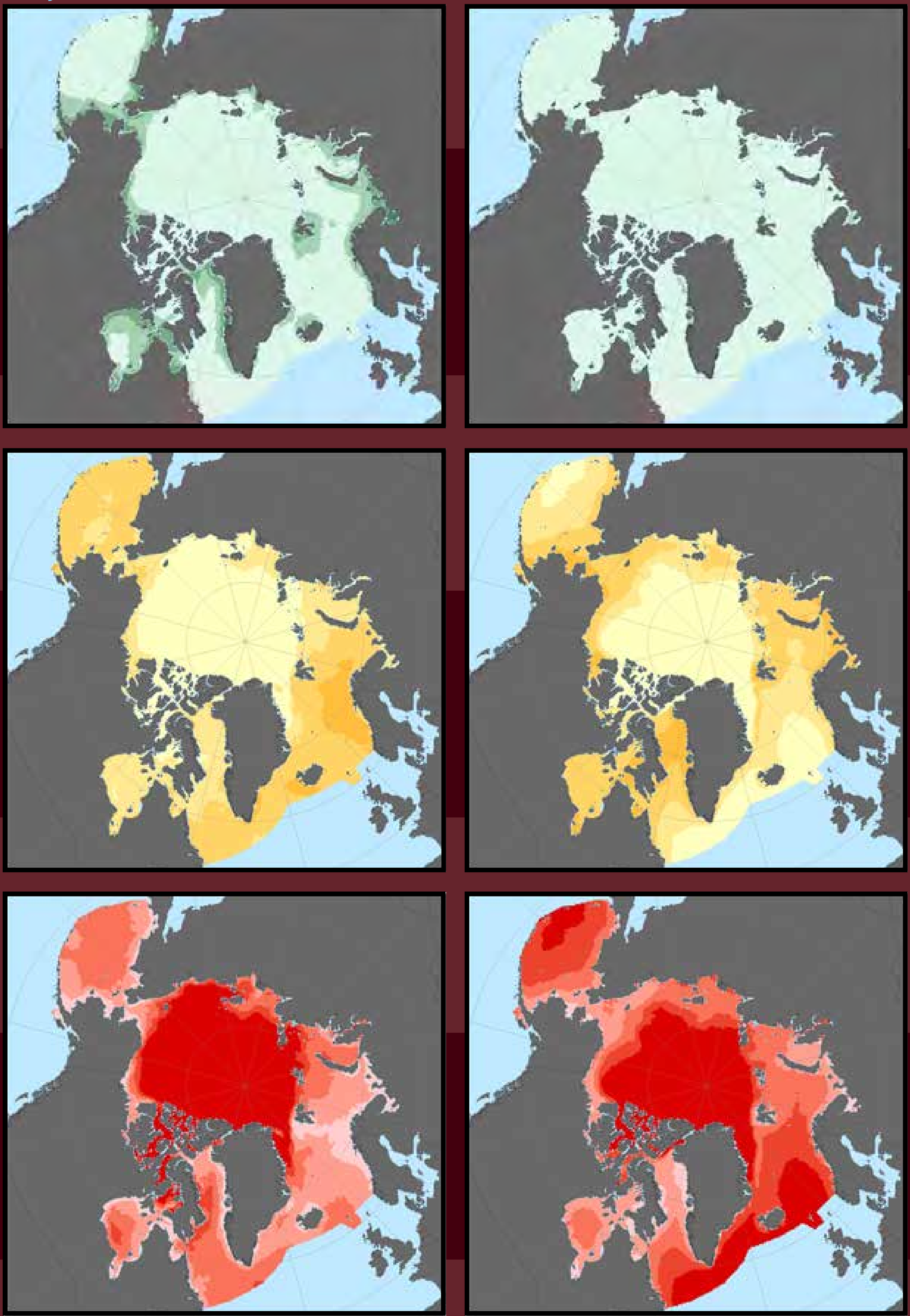
FAVOURABLE
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

MARGINAL
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

NOT FAVOURABLE
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

## MECHANICAL RECOVERY – Vessel with Outrigger

July | October

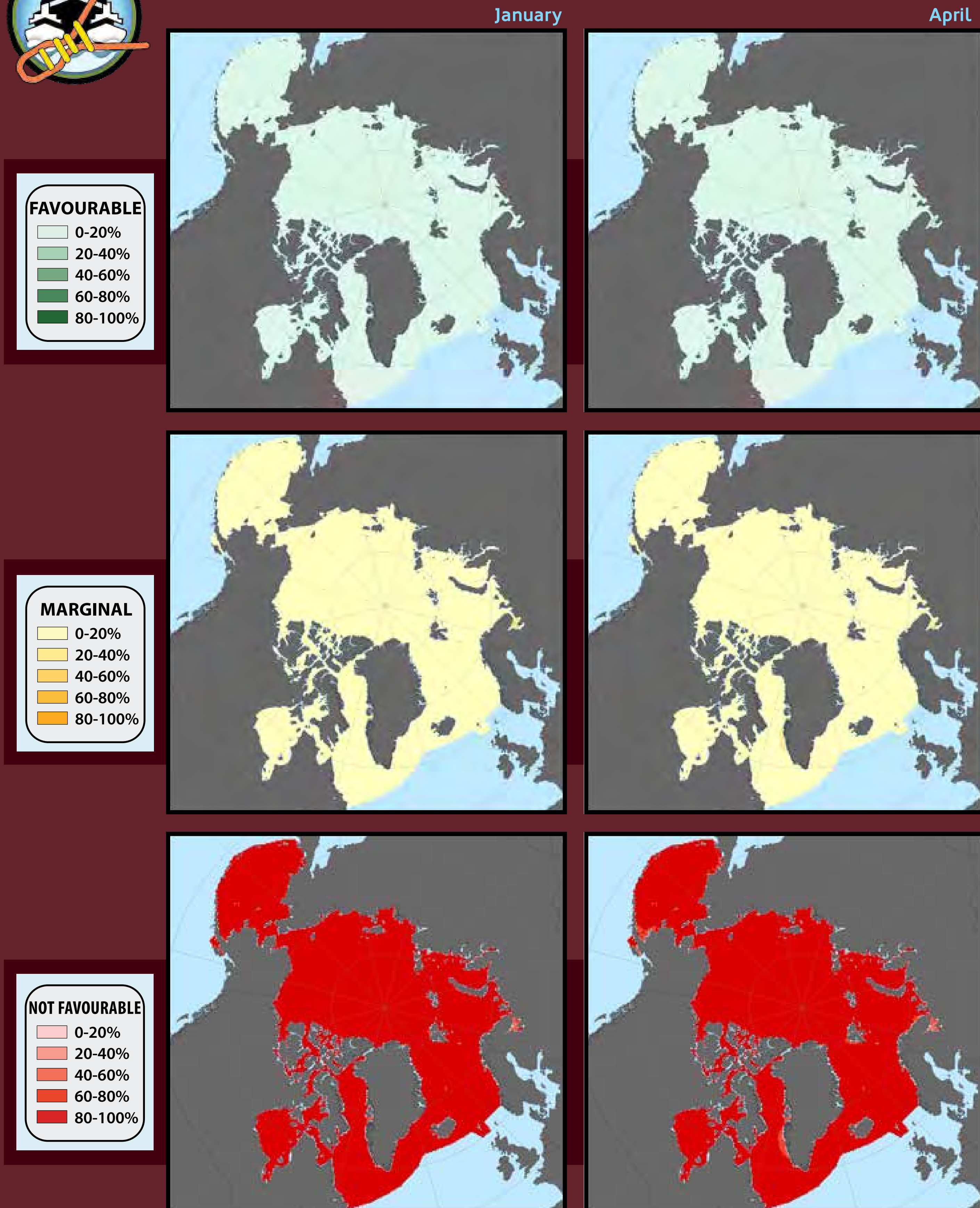


**FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**MARGINAL**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

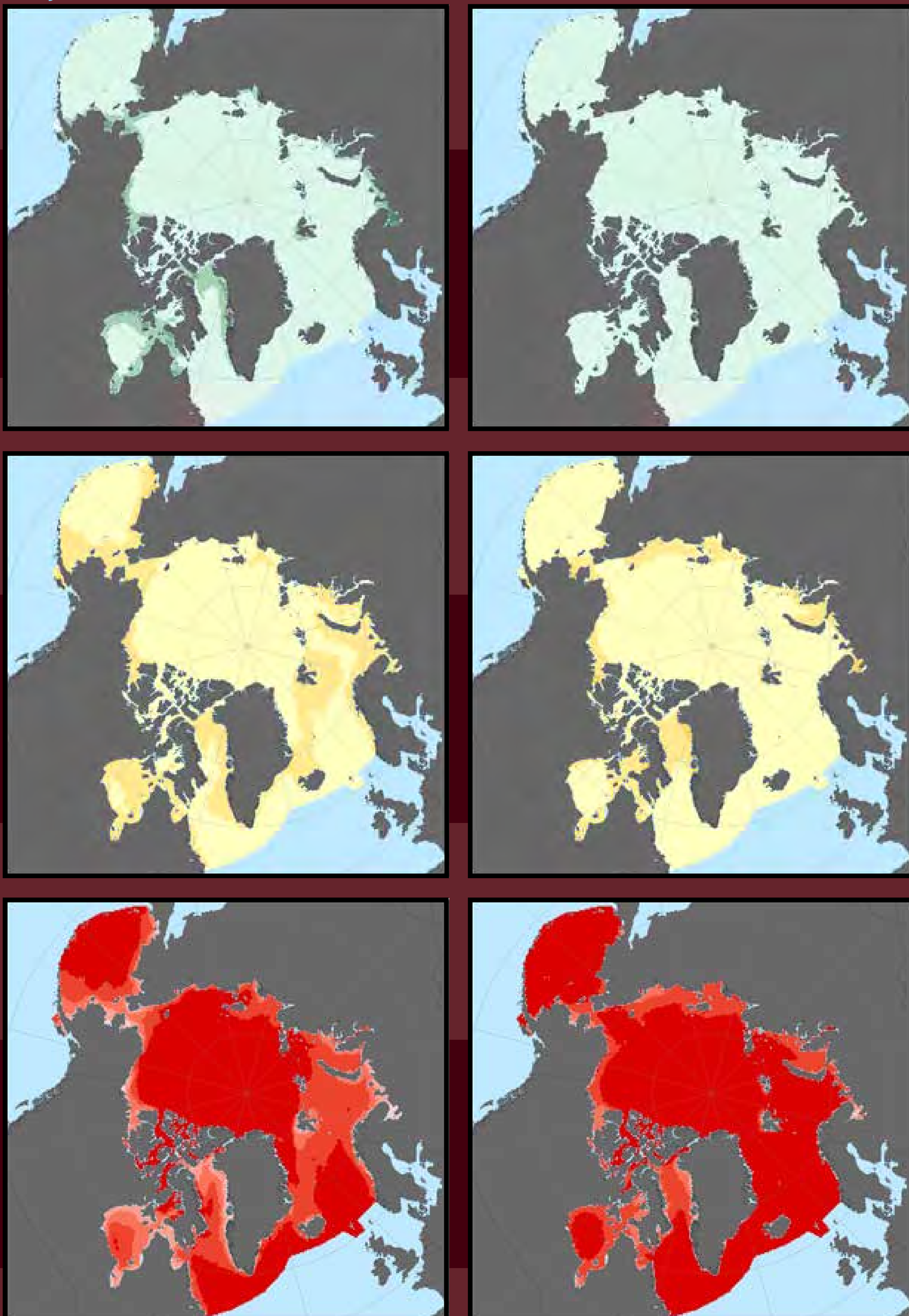
**NOT FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

# MECHANICAL RECOVERY – 3 Vessels with Boom



## MECHANICAL RECOVERY – 3 Vessels with Boom

July | October



**FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**MARGINAL**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**NOT FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

# MECHANICAL RECOVERY – Single Vessel in Ice

January | April

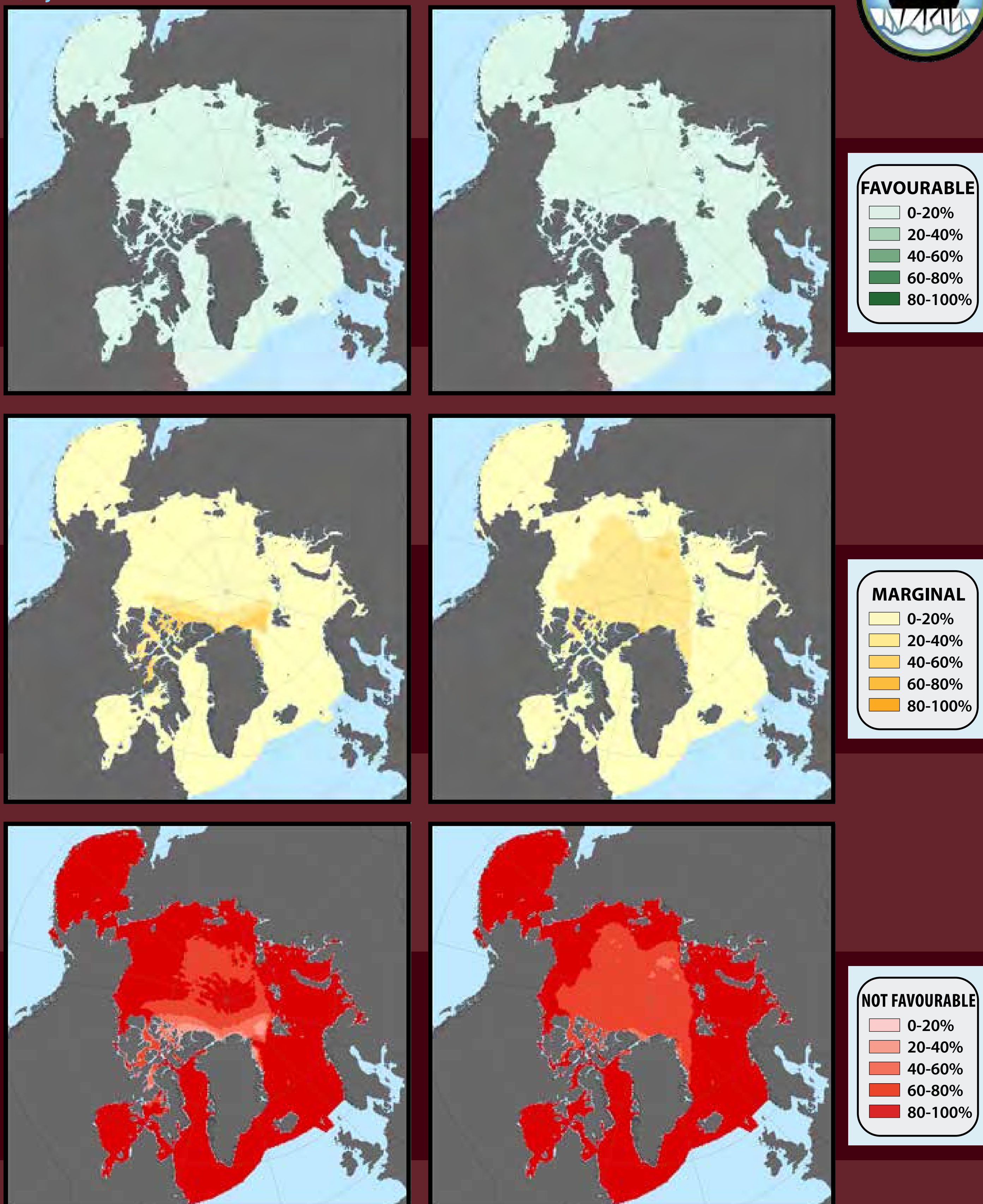
**FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**MARGINAL**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

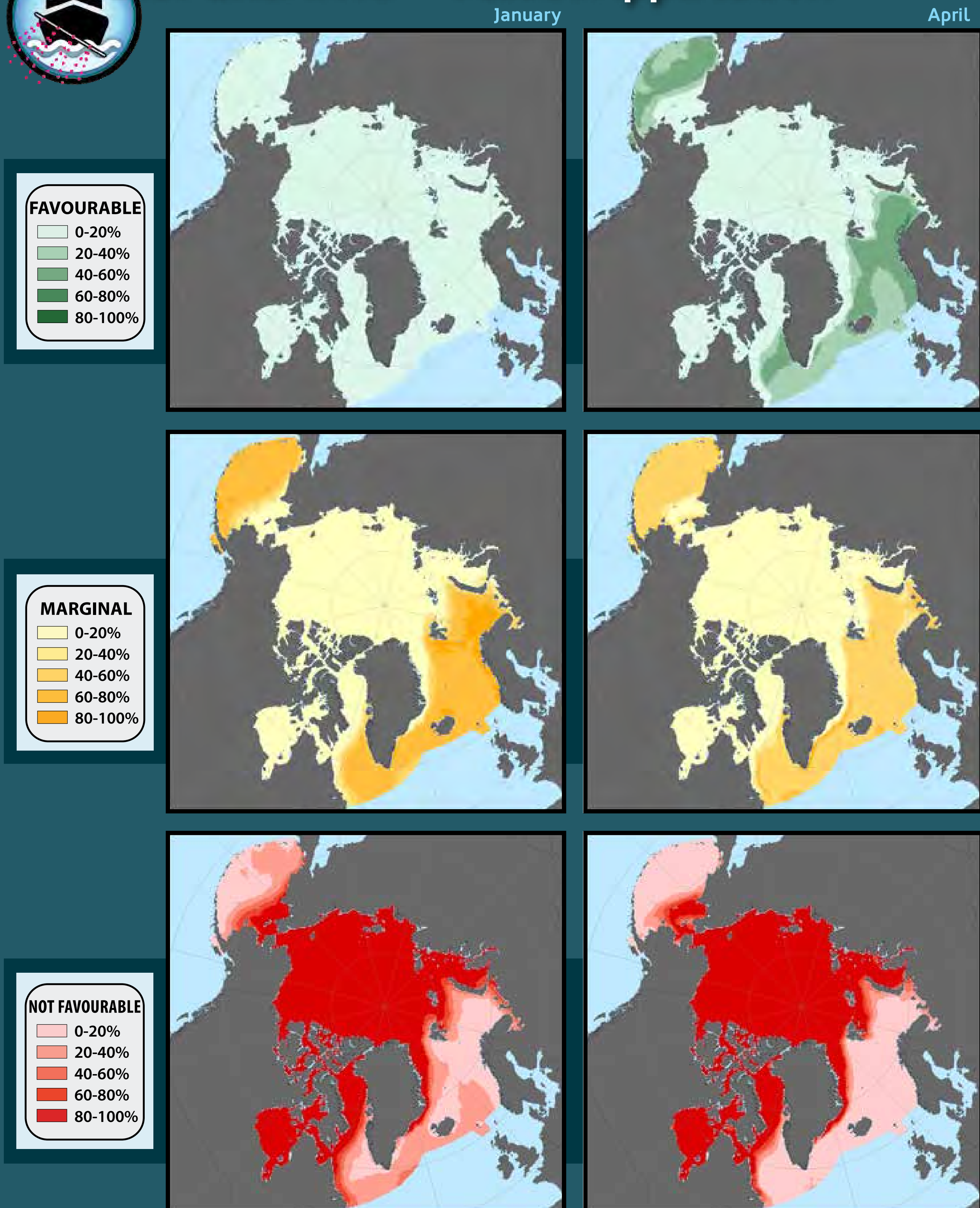
**NOT FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

# MECHANICAL RECOVERY – Single Vessel in Ice

July October



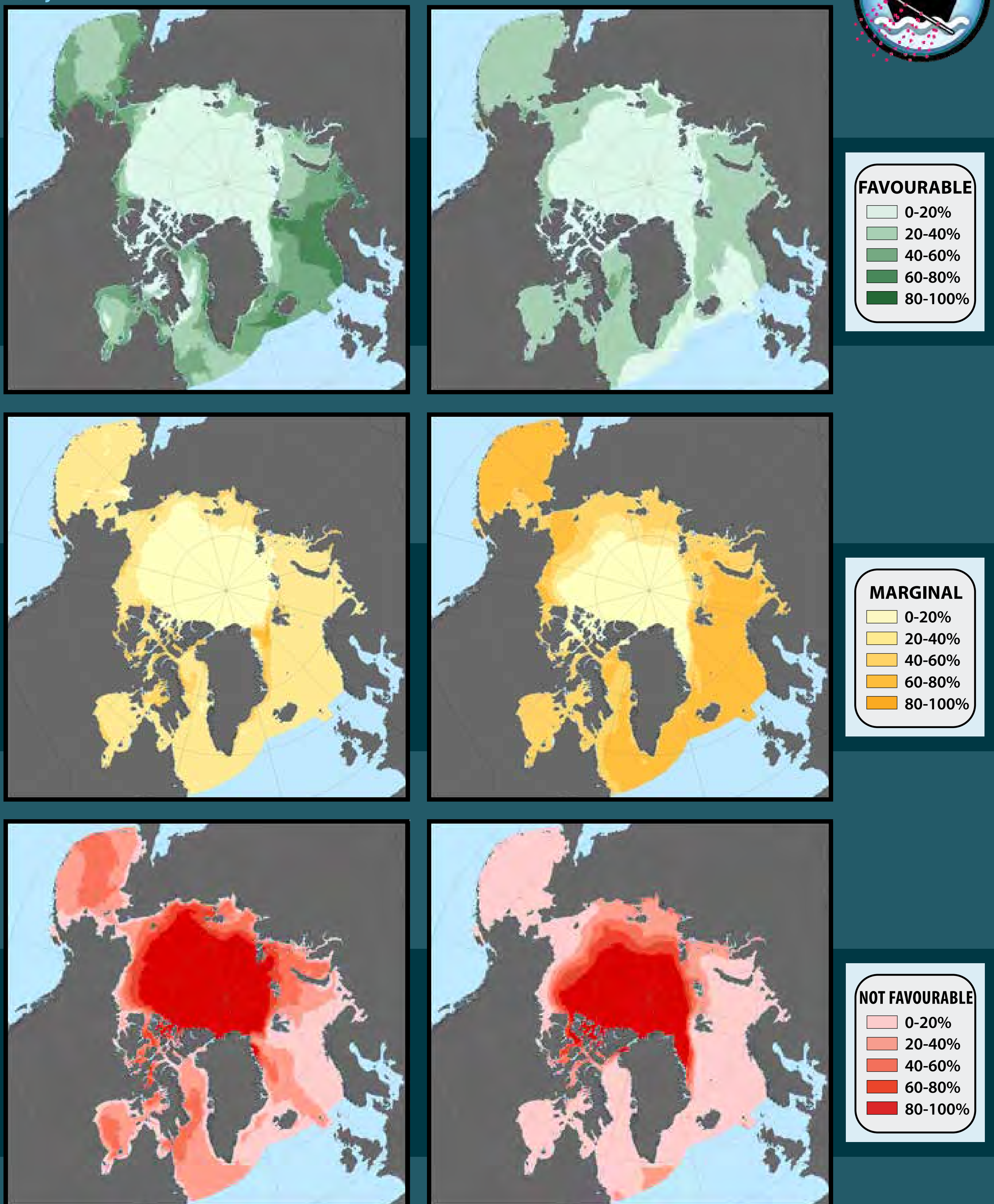
# DISPERSANTS – Vessel Application



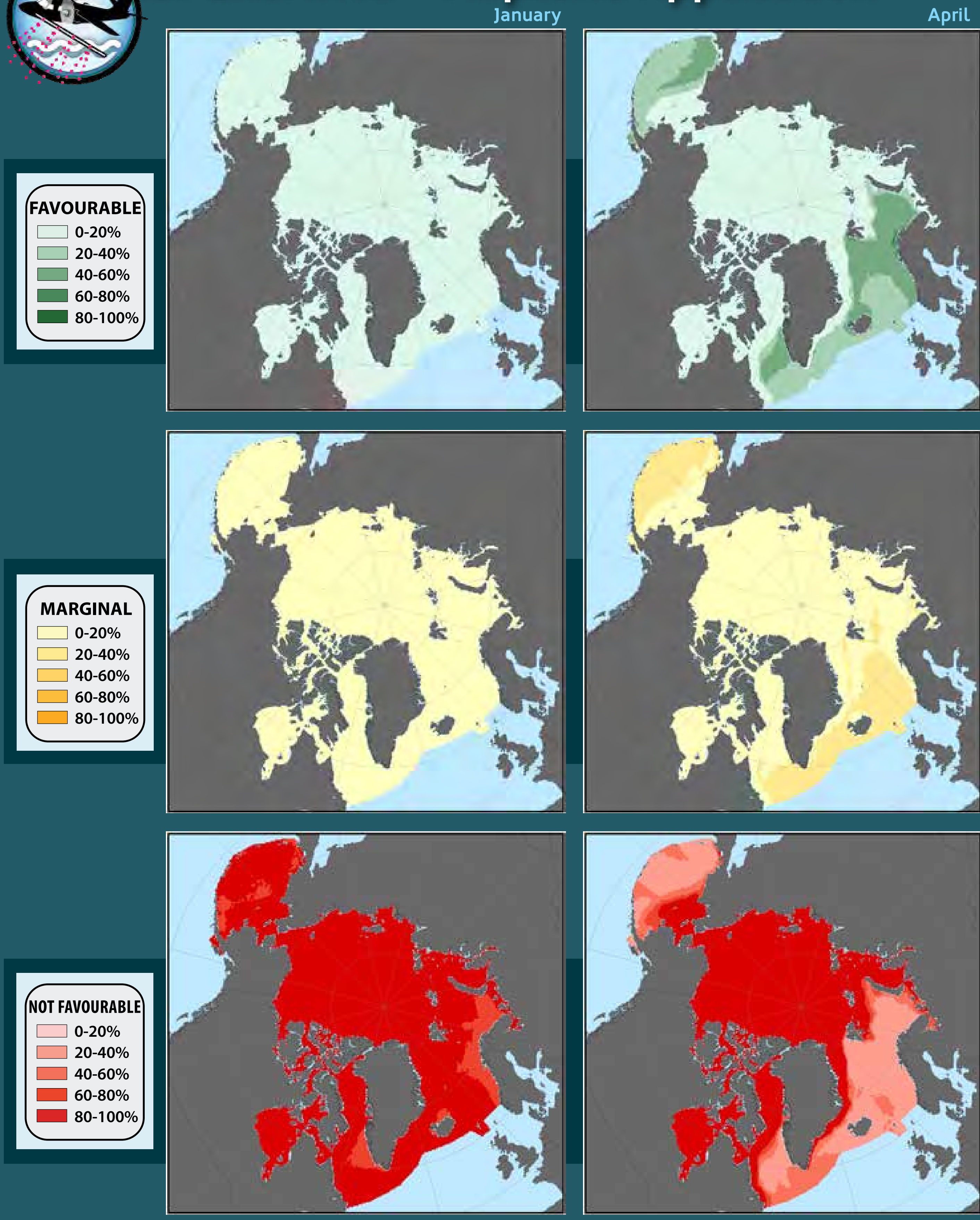
## DISPERSANTS – Vessel Application

July

October



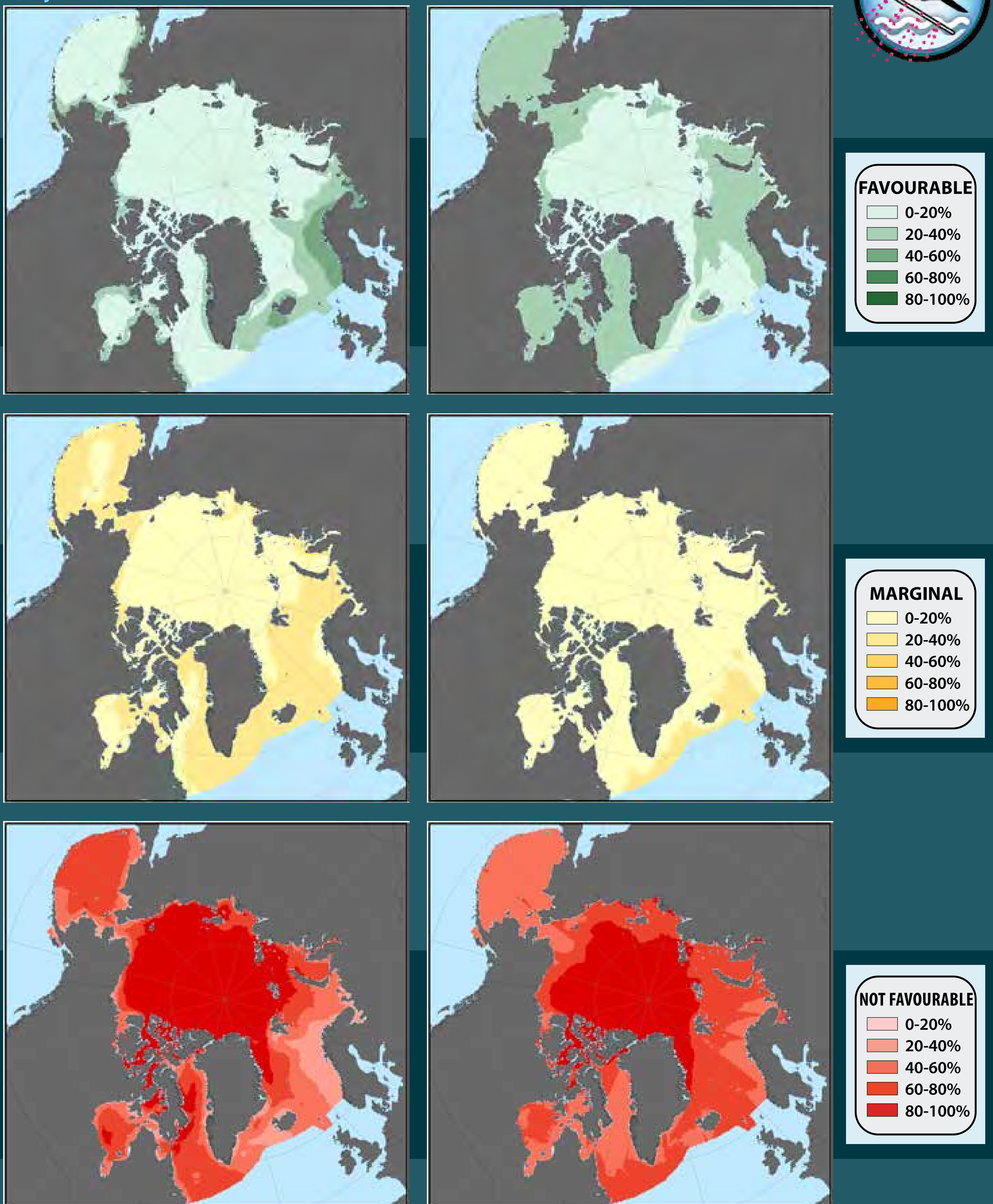
# DISPERSANTS – Airplane Application



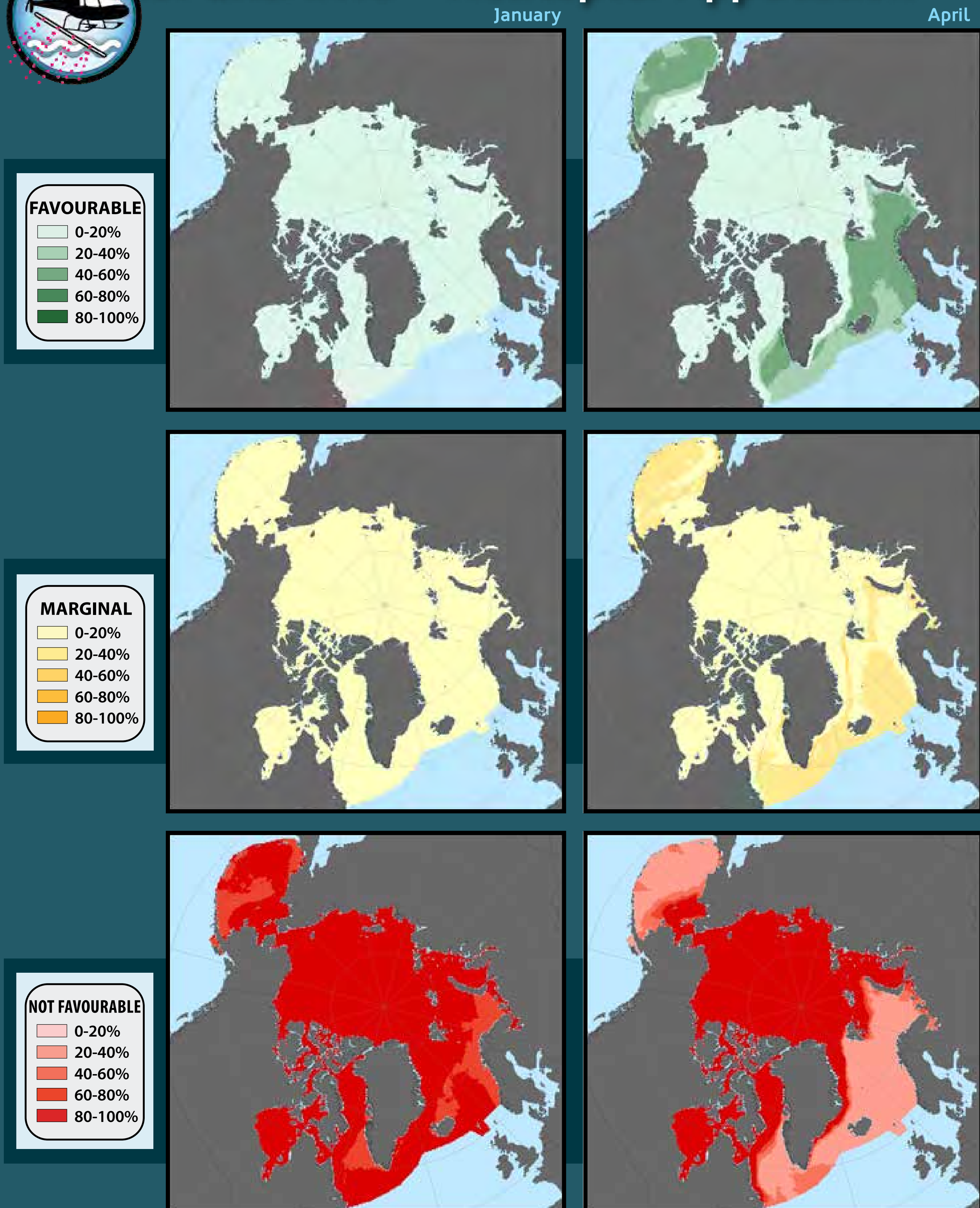
## DISPERSANTS – Airplane Application

July

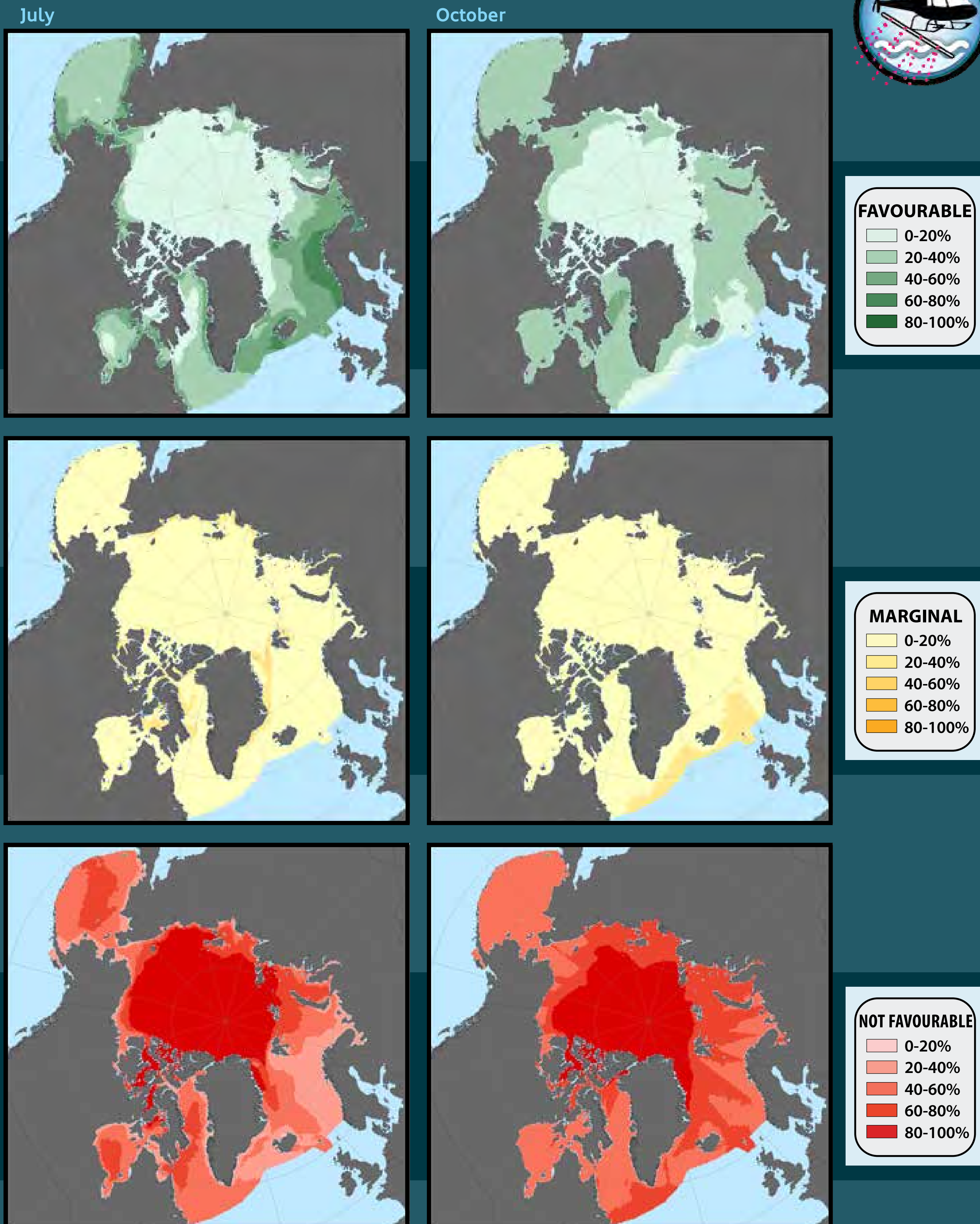
October



# DISPERSANTS – Helicopter Application

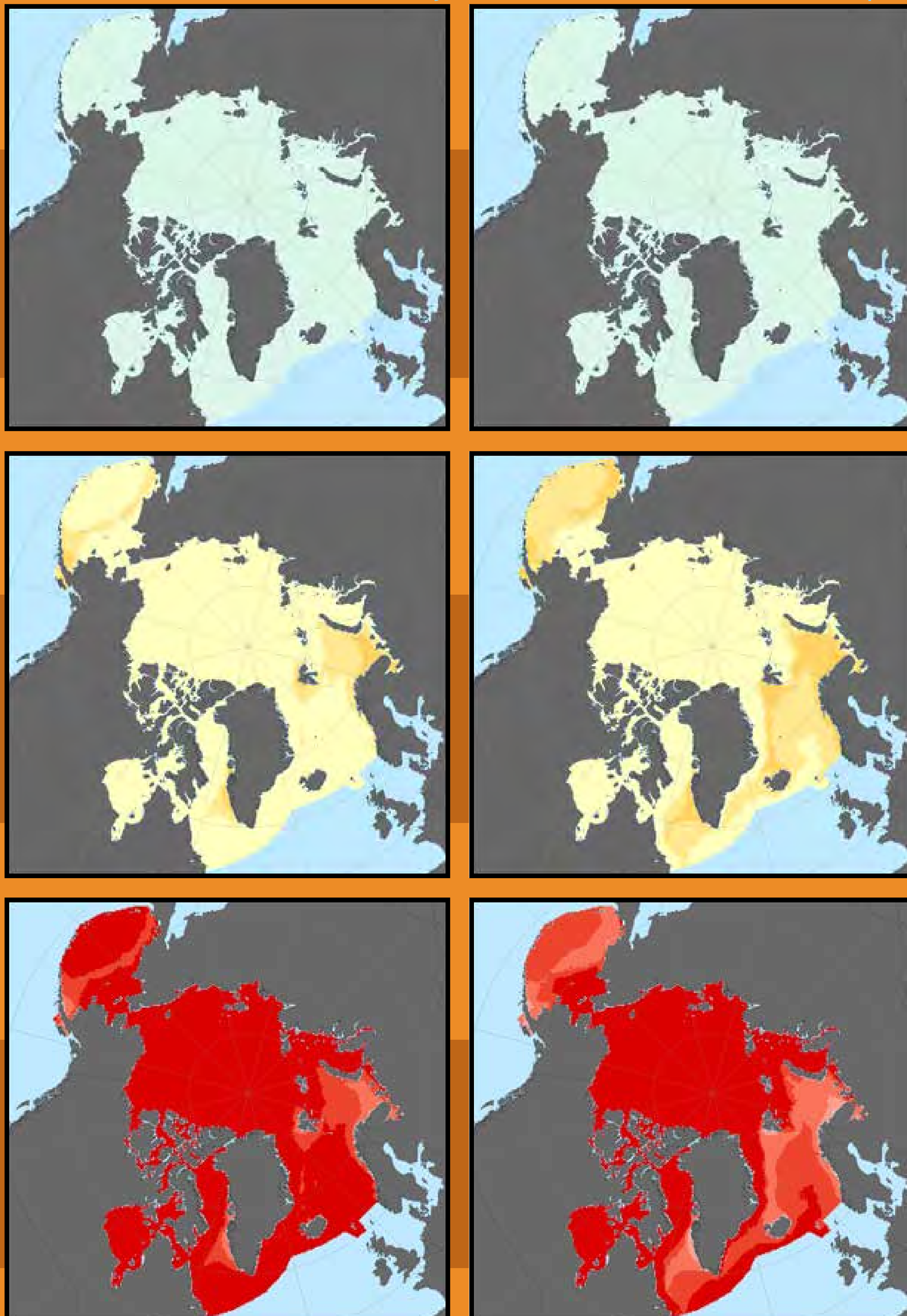


## DISPERSANTS – Helicopter Application



# IN-SITU BURNING – Vessels with Fire Boom

January April

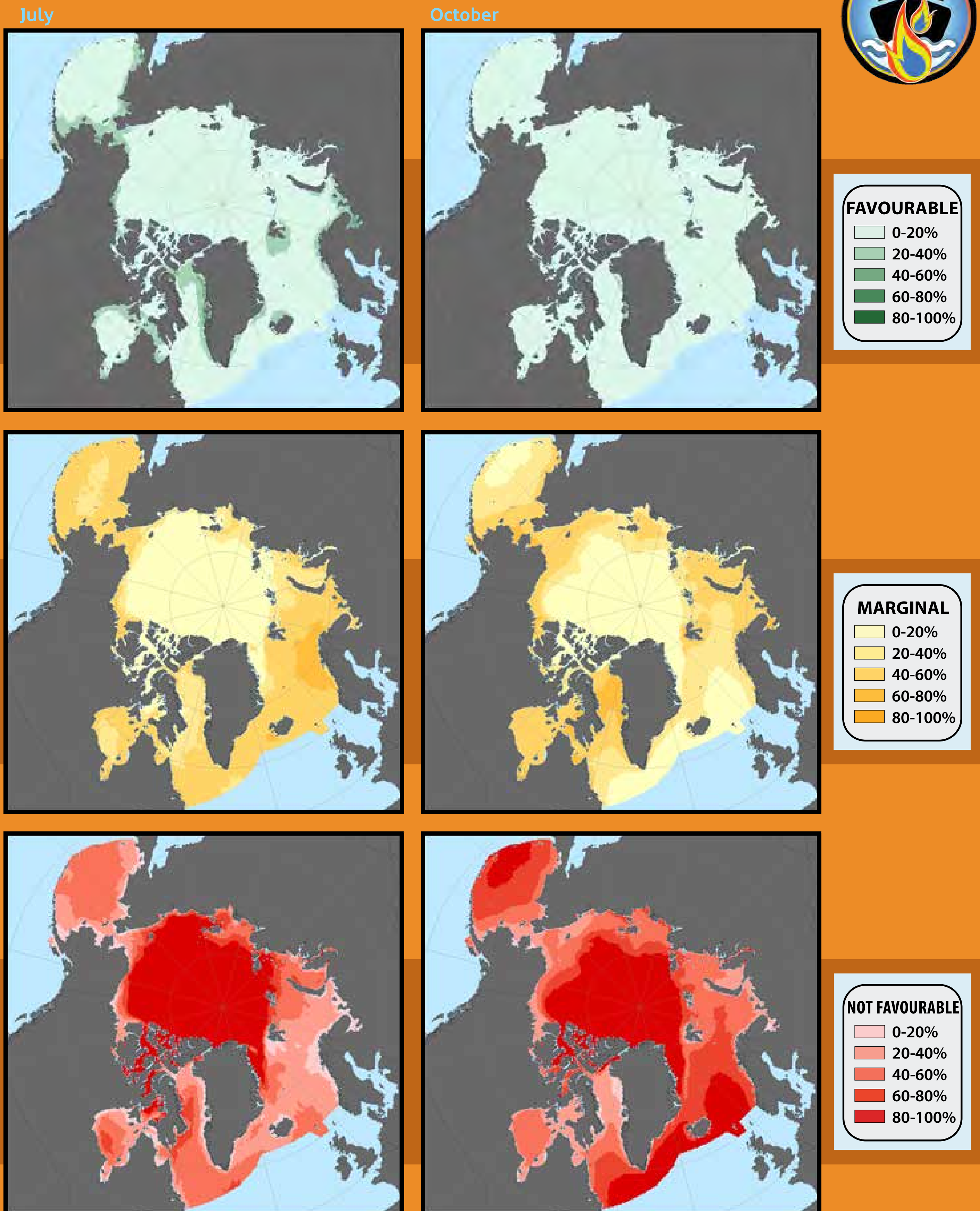


**FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**MARGINAL**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

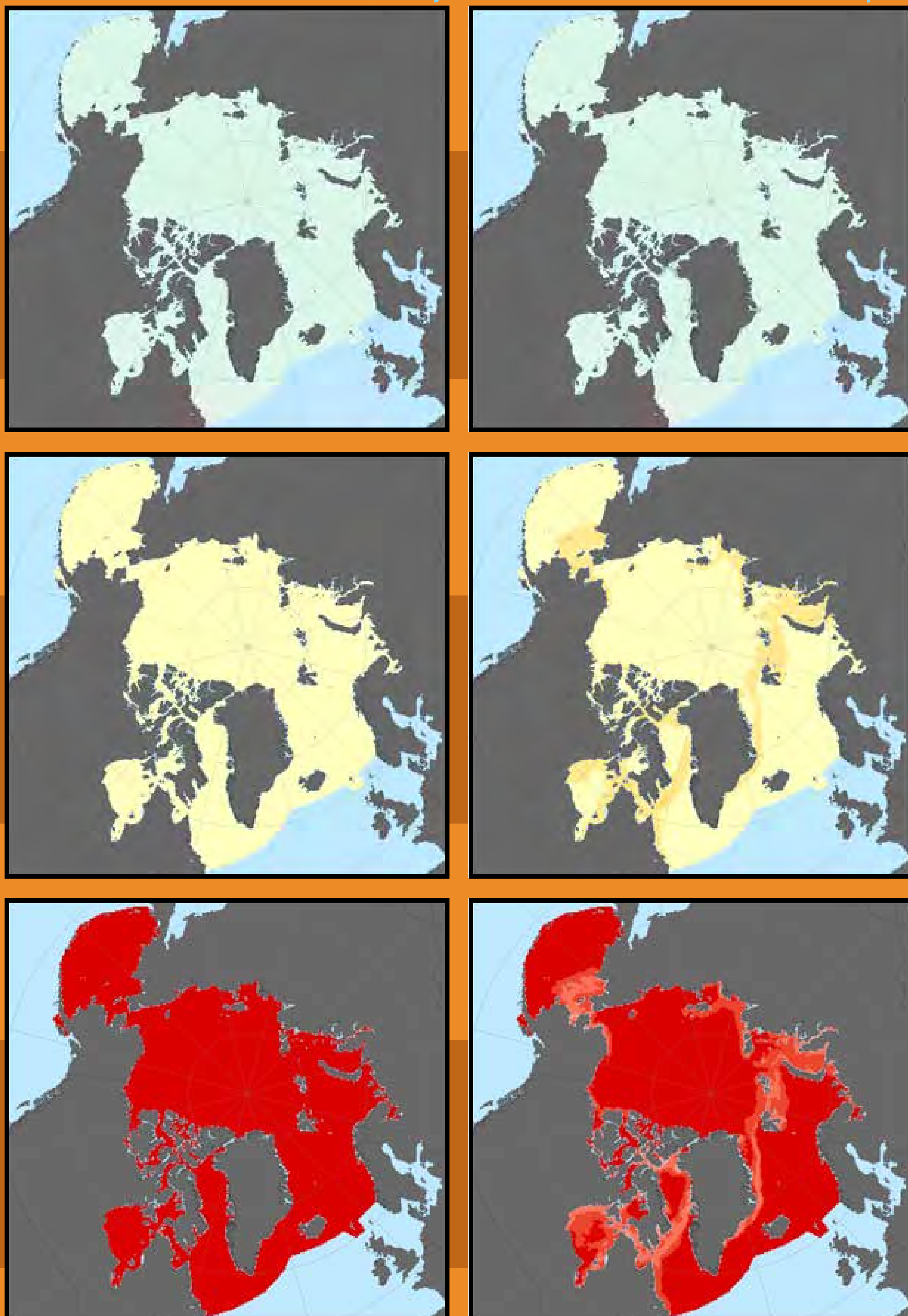
**NOT FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

## IN-SITU BURNING – Vessels with Fire Boom



# IN-SITU BURNING – Helicopter w/Ice Containment

January    April



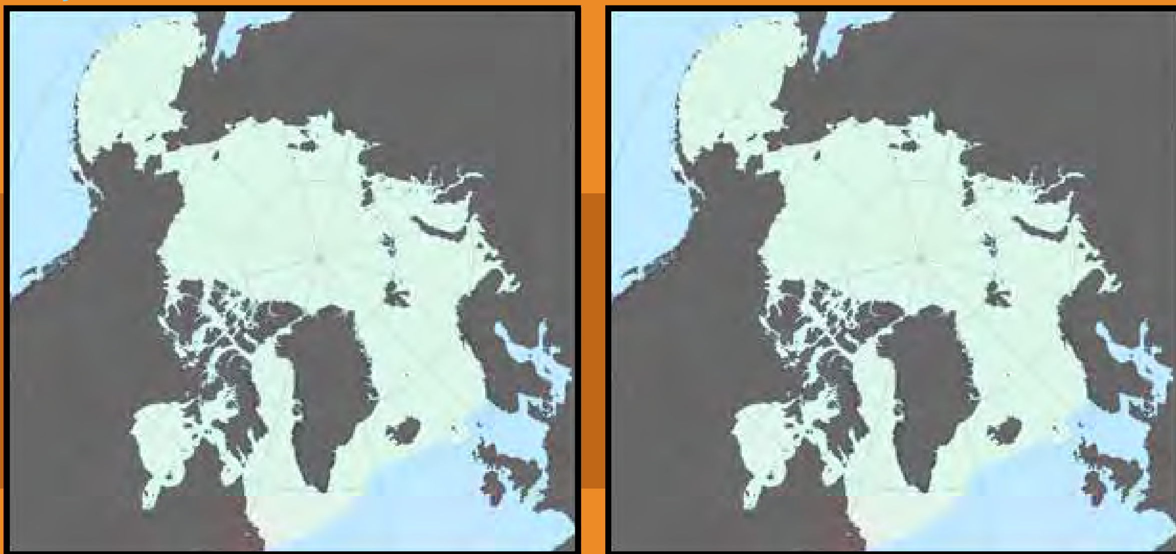
**FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**MARGINAL**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**NOT FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

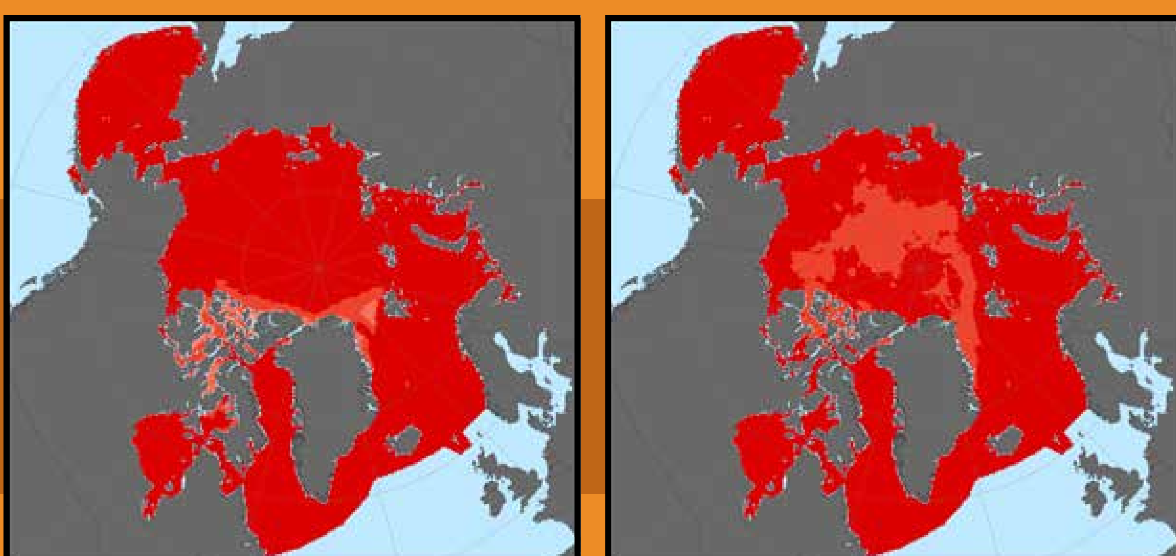
# IN-SITU BURNING – Helicopter w/Ice Containment

July October



**FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

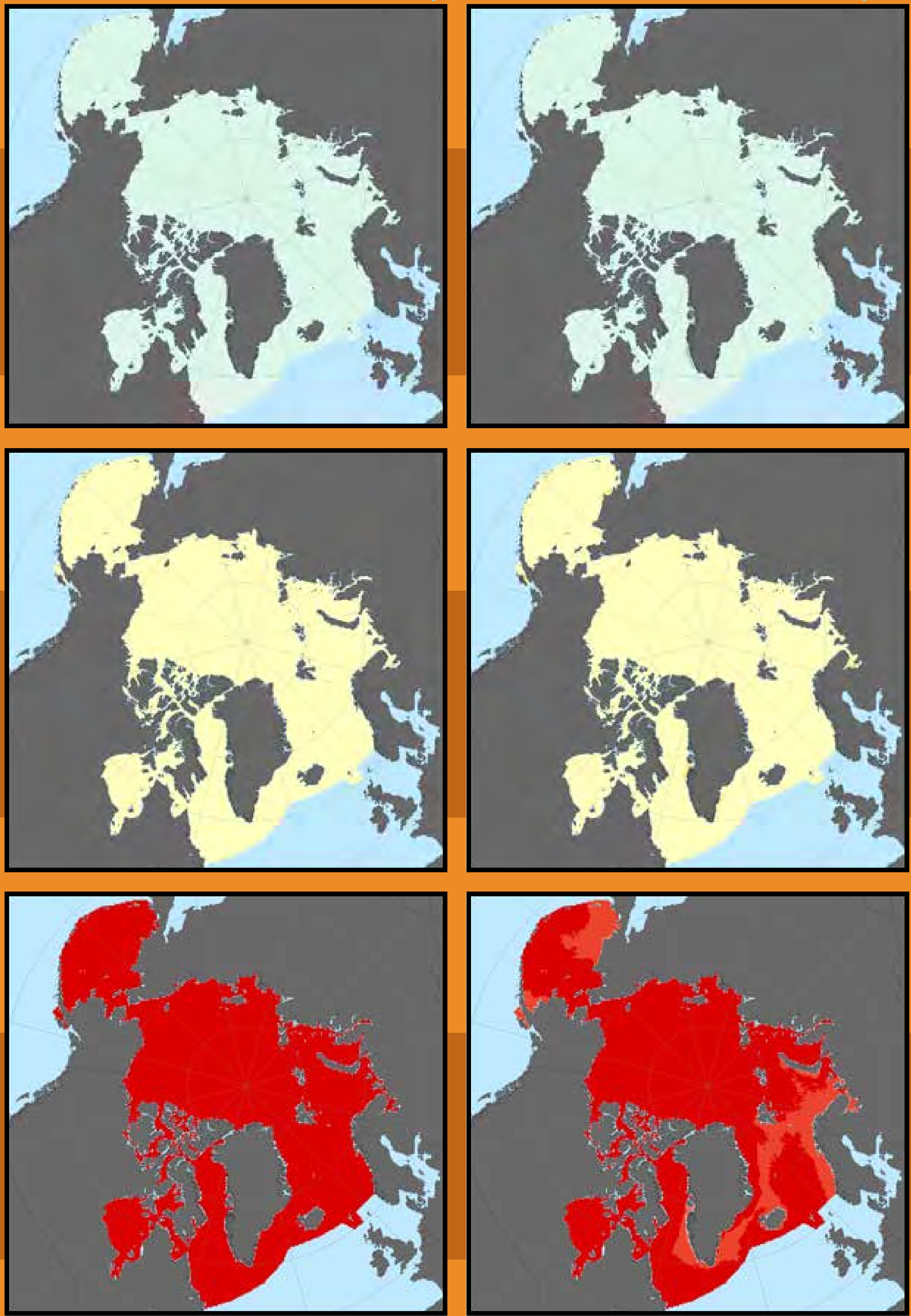
**MARGINAL**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%



**NOT FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

# IN-SITU BURNING – Helicopter with Herders

January | April

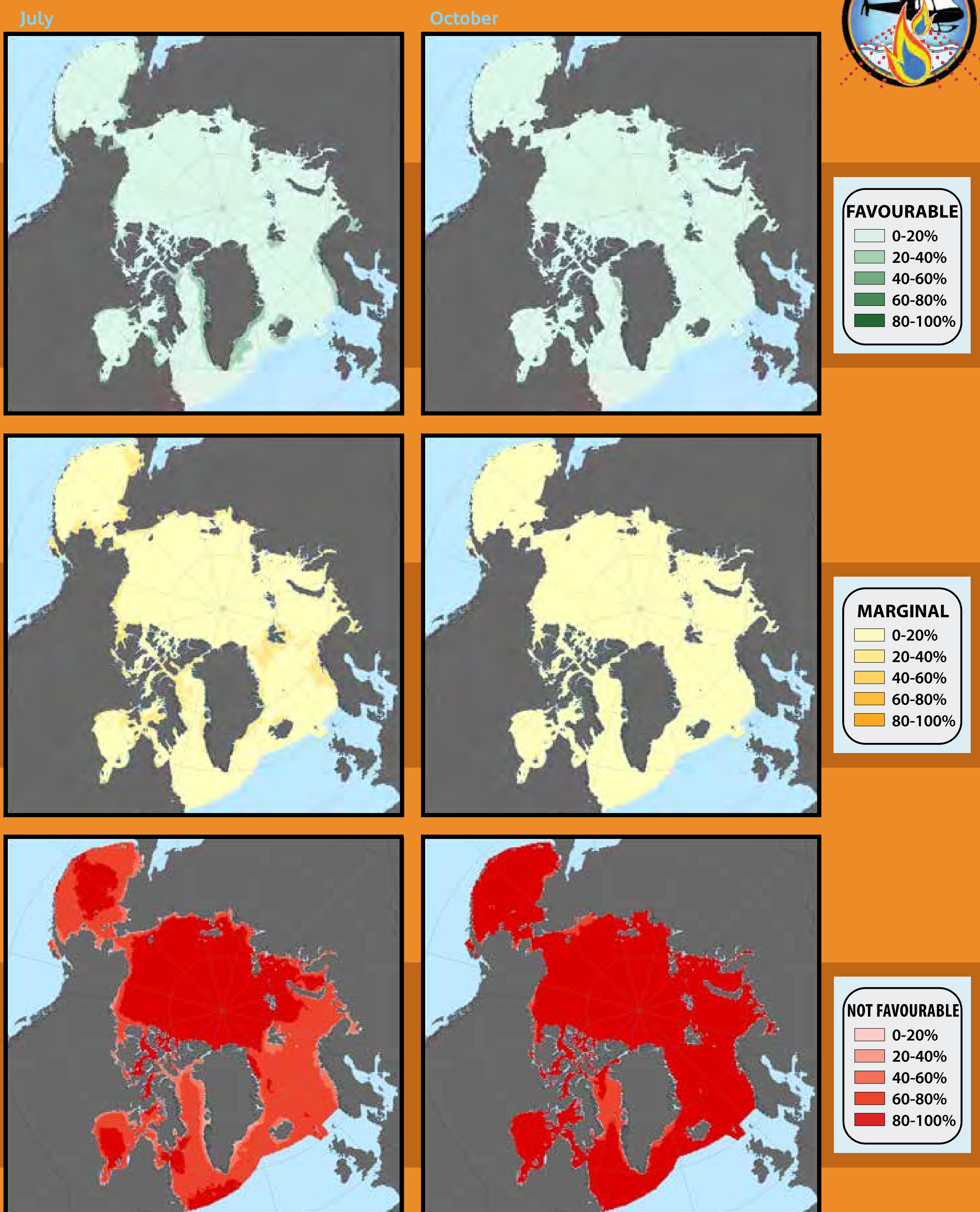


**FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**MARGINAL**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

**NOT FAVOURABLE**
- 0-20%
- 20-40%
- 40-60%
- 60-80%
- 80-100%

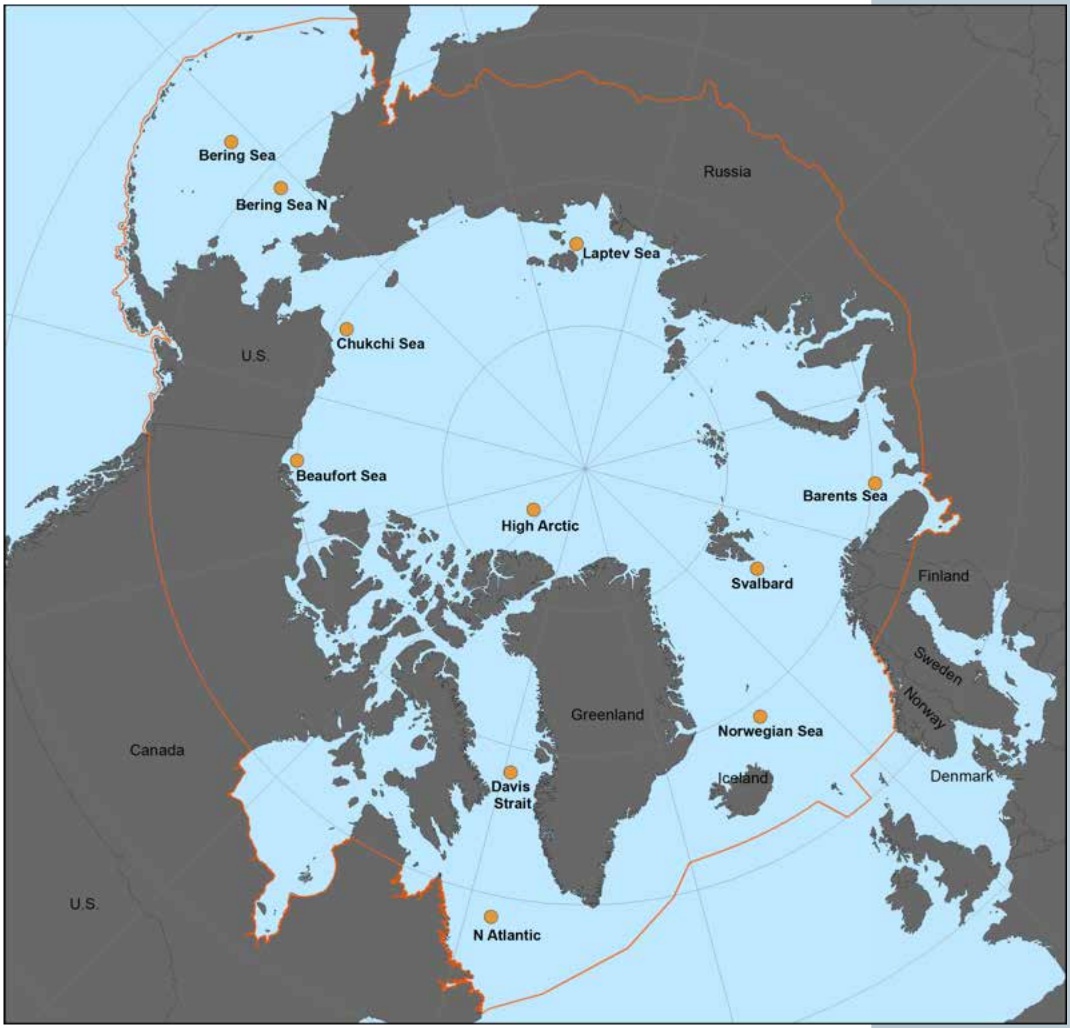
## IN-SITU BURNING – Helicopter with Herders



# Appendix B

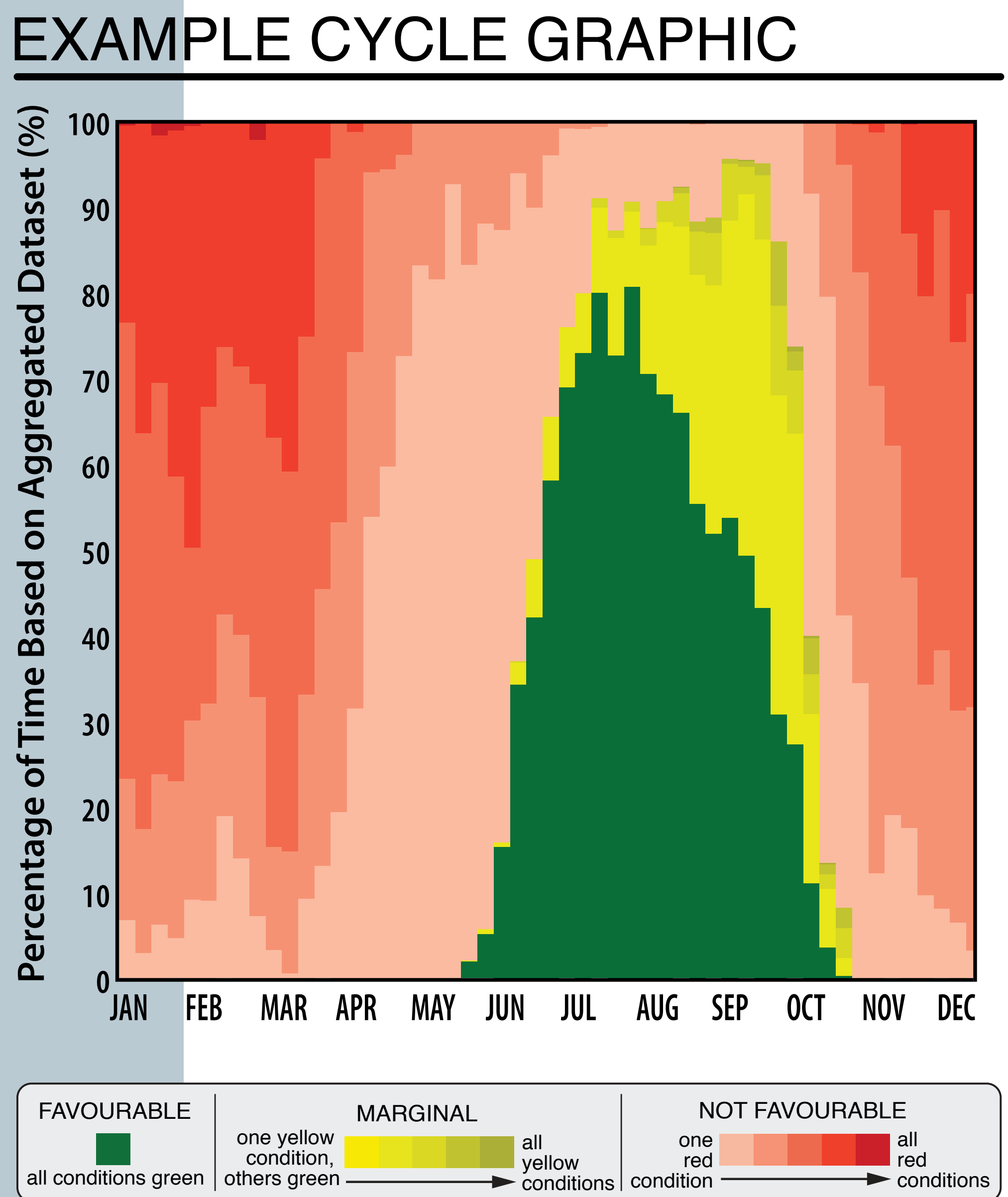
## Results from Location-specific Analysis

This appendix presents the combined results for each system for the 11 locations shown below.



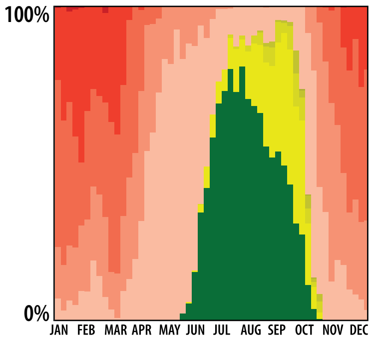
## Example Cycle Graphic

This appendix shows annual cycle graphics for each system studied at each of the 11 locations. Each one represents the percentage of time from 0-100% that conditions were favourable, marginal, or not favourable (as represented by the colors in the legend) based on the combined metocean conditions. Each bar represents the conditions for one week aggregated from the 10 years in the dataset. In the example shown, the week with the highest proportion of combined green and yellow (not red) conditions occured during a week in September, when conditions were green about 55% of othe time, and yellow another 40%, totaling green/yellow conditions more than 95% of the time (and red just under 5% of the time).

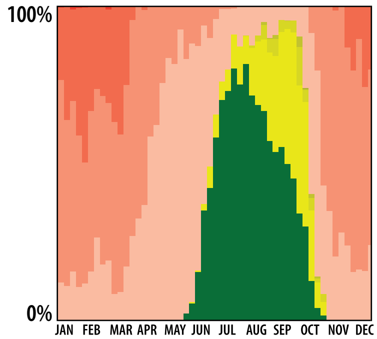


# BEAUFORT SEA

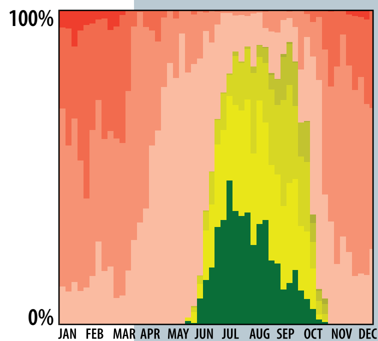
**MECHANICAL RECOVERY** | **DISPERSANTS** | **IN-SITU BURNING**



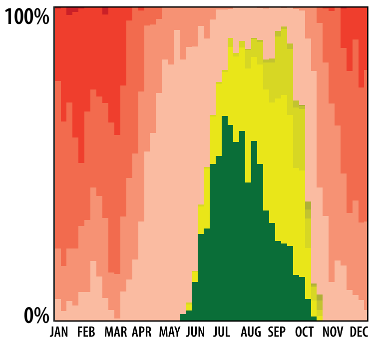

Two Vessels with Boom



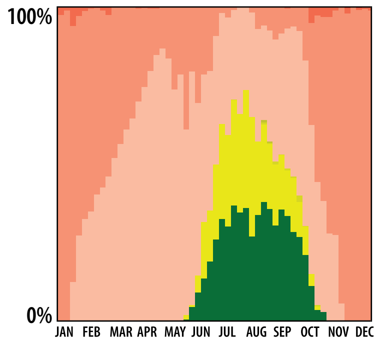

Vessel Application



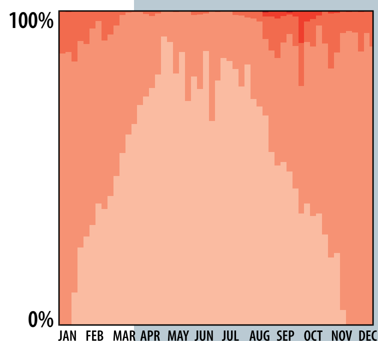

Vessels with Fire Boom



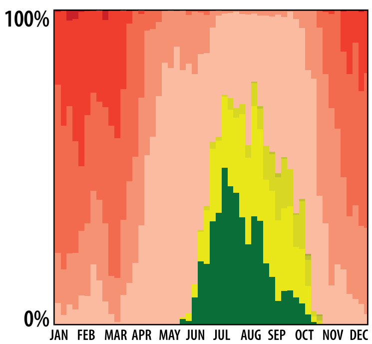

Single Vessel w/ Outrigger



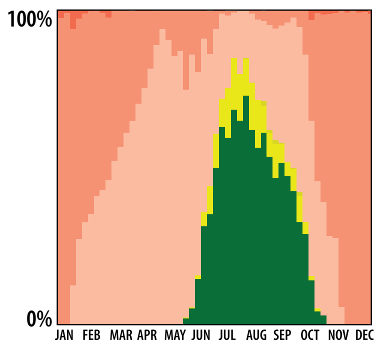

Fixed-Wing Aircraft Application



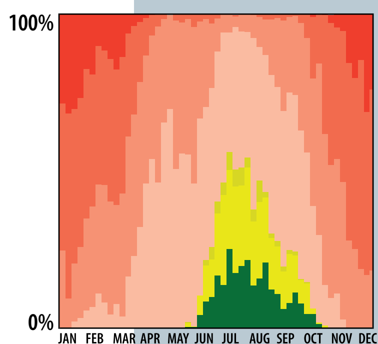

Helicopter with Ice Containment



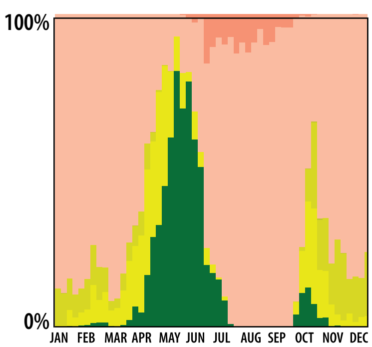

3 Vessels of Opportunity w/ Boom



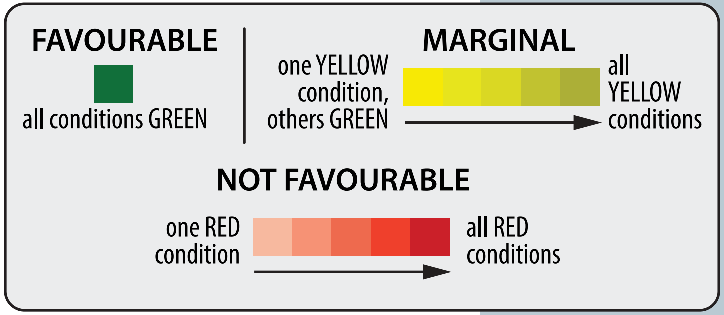

Helicopter Application



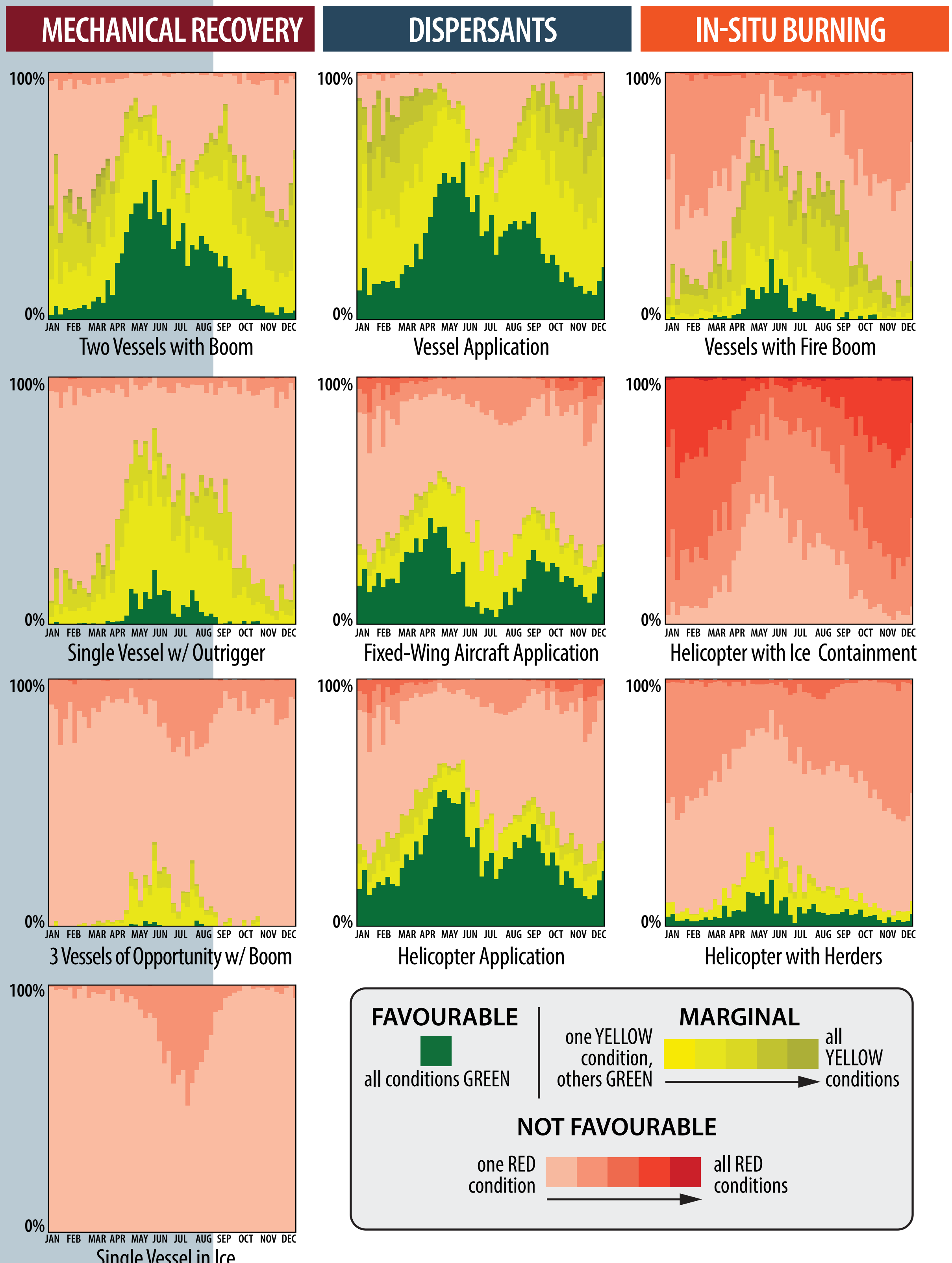

Helicopter with Herders




Single Vessel in Ice

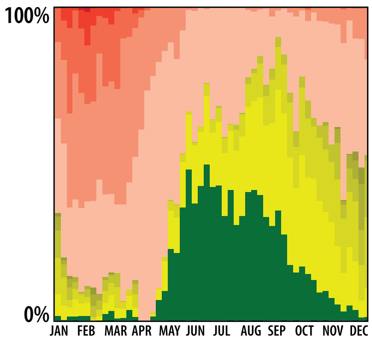


# BERING SEA

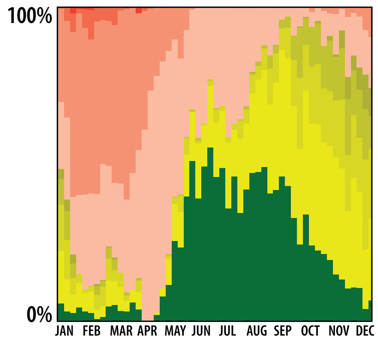

MECHANICAL RECOVERY
DISPERSANTS
IN-SITU BURNING
100%
0%
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
Two Vessels with Boom
Vessel Application
Vessels with Fire Boom
Single Vessel w/ Outrigger
Fixed-Wing Aircraft Application
Helicopter with Ice Containment
3 Vessels of Opportunity w/ Boom
Helicopter Application
Helicopter with Herders
Single Vessel in Ice
FAVOURABLE
all conditions GREEN
MARGINAL
one YELLOW condition, others GREEN
all YELLOW conditions
NOT FAVOURABLE
one RED condition
all RED conditions

# BERING SEA NORTH

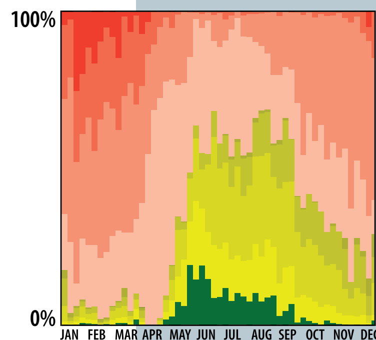
**MECHANICAL RECOVERY** | **DISPERSANTS** | **IN-SITU BURNING**



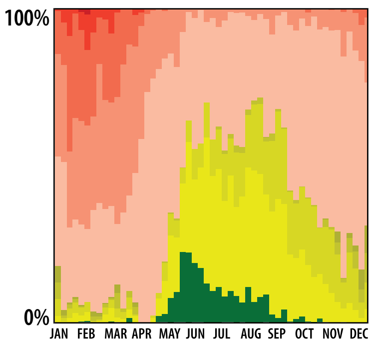
Two Vessels with Boom



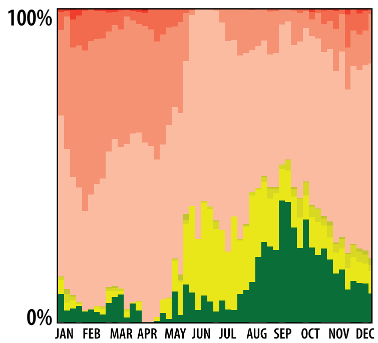
Vessel Application



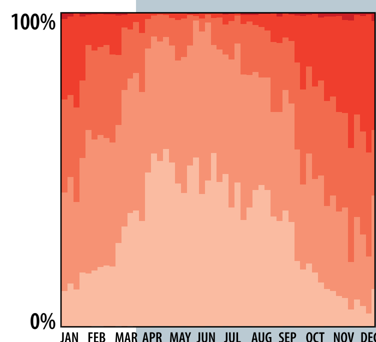
Vessels with Fire Boom



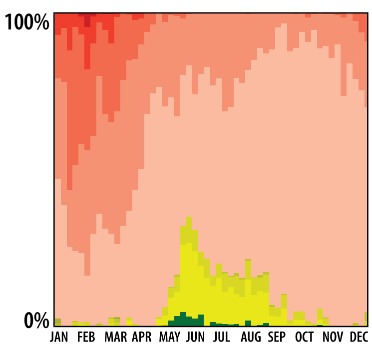
Single Vessel w/ Outrigger



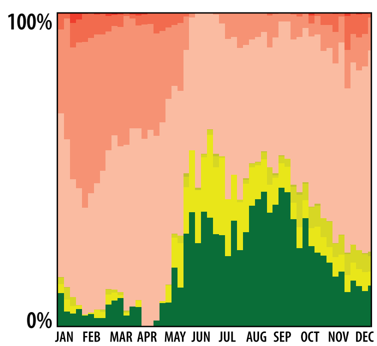
Fixed-Wing Aircraft Application



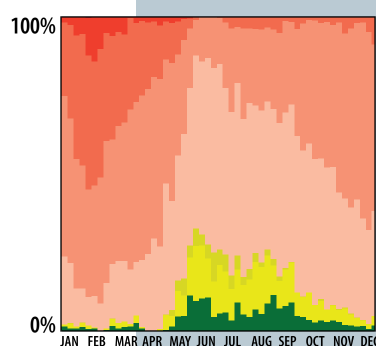
Helicopter with Ice Containment



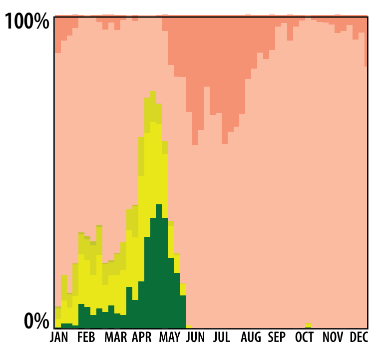
3 Vessels of Opportunity w/ Boom



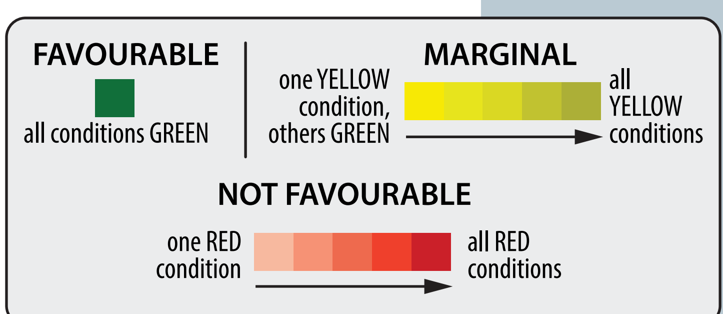
Helicopter Application



Helicopter with Herders

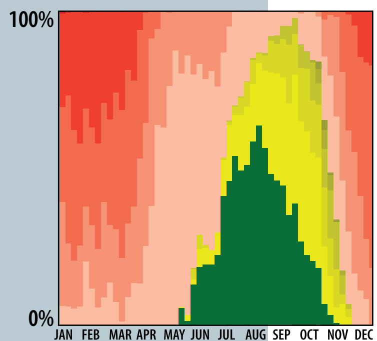


Single Vessel in Ice

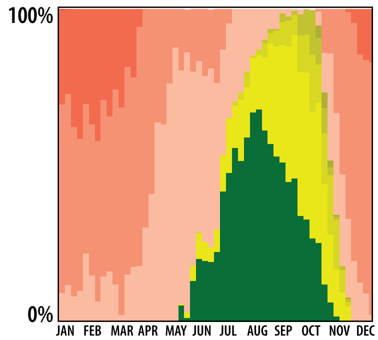


# CHUKCHI SEA

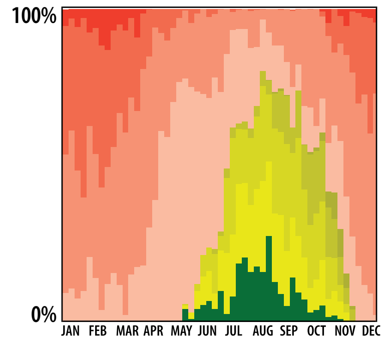
| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
|---|---|---|



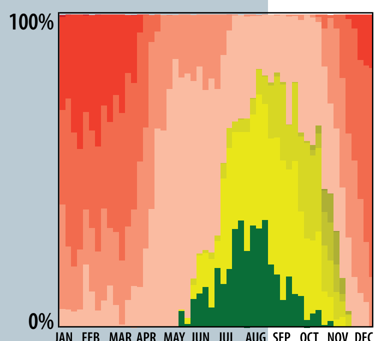

Two Vessels with Boom



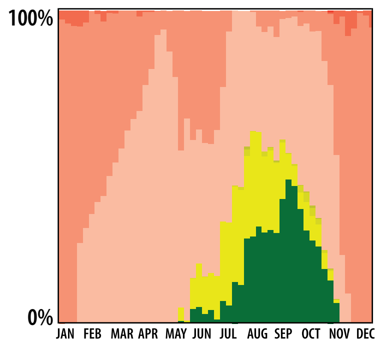

Vessel Application



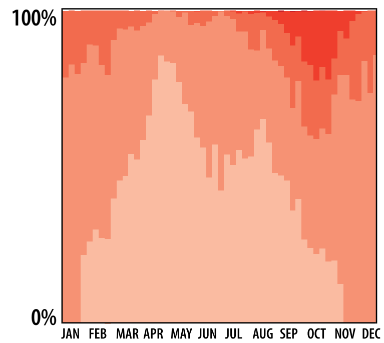

Vessels with Fire Boom



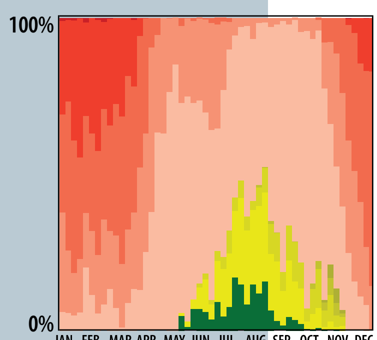

Single Vessel w/ Outrigger



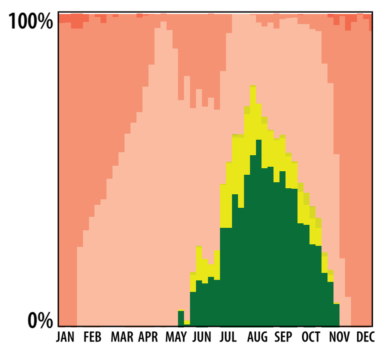

Fixed-Wing Aircraft Application



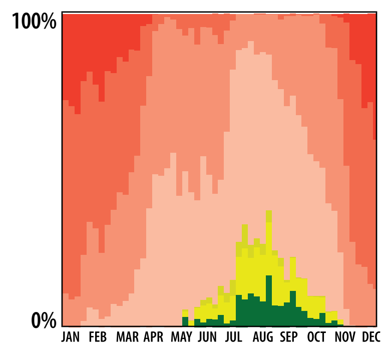

Helicopter with Ice Containment



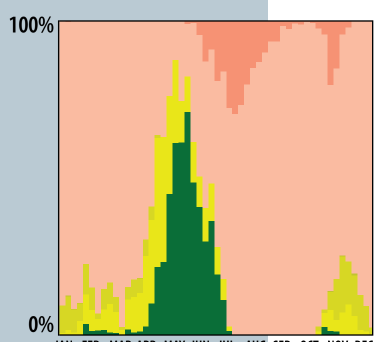

3 Vessels of Opportunity w/ Boom



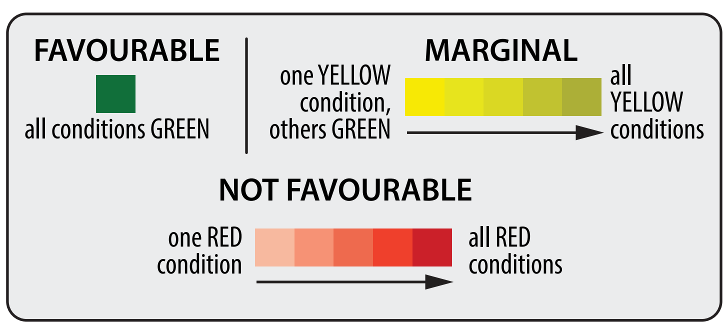

Helicopter Application




Helicopter with Herders

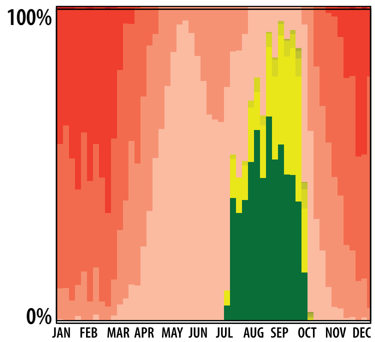



Single Vessel in Ice

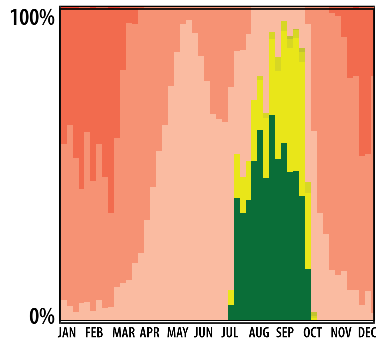


# LAPTEV SEA

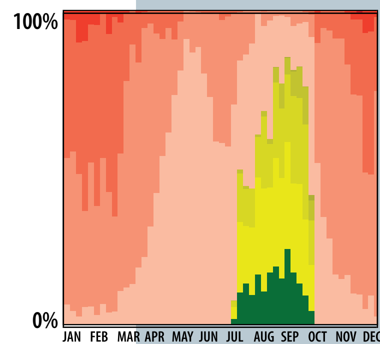
| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
|---|---|---|



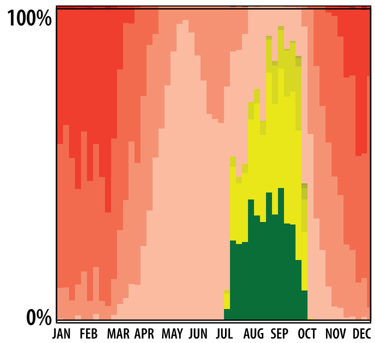
Two Vessels with Boom



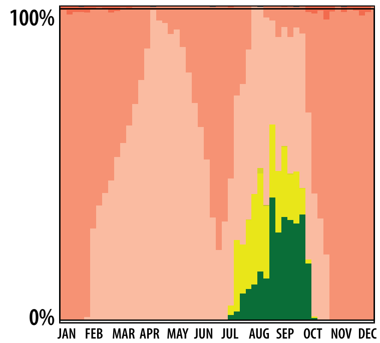
Vessel Application



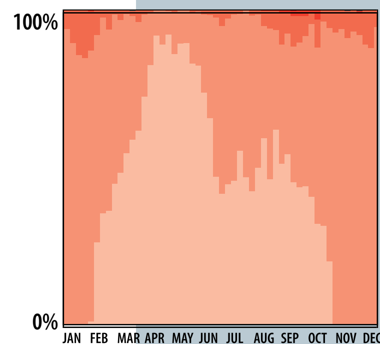
Vessels with Fire Boom



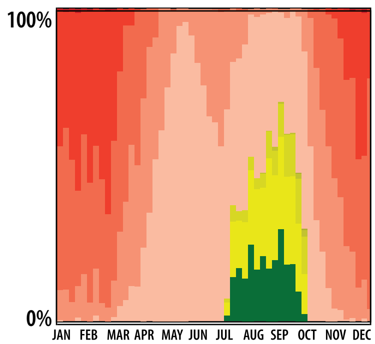
Single Vessel w/ Outrigger



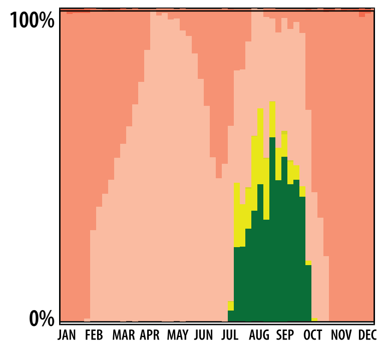
Fixed-Wing Aircraft Application



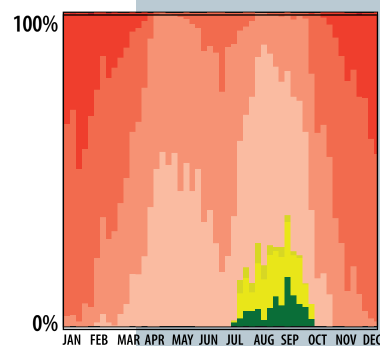
Helicopter with Ice Containment



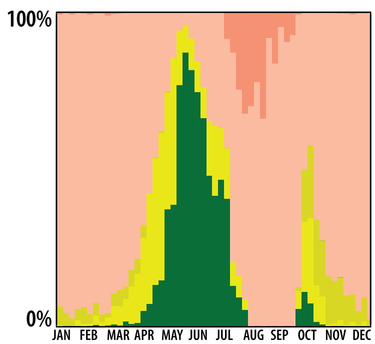
3 Vessels of Opportunity w/ Boom



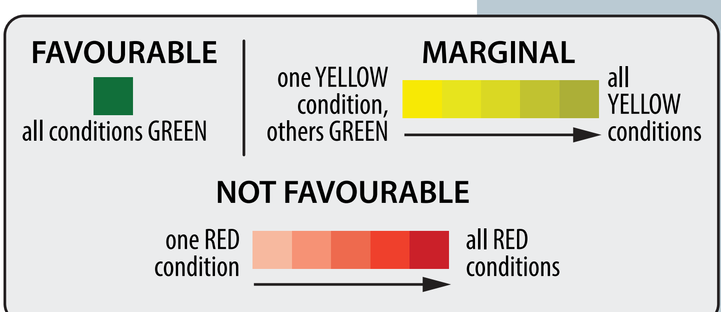
Helicopter Application



Helicopter with Herders

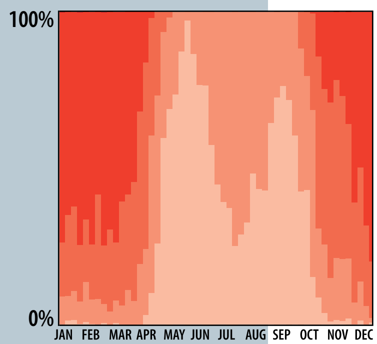


Single Vessel in Ice

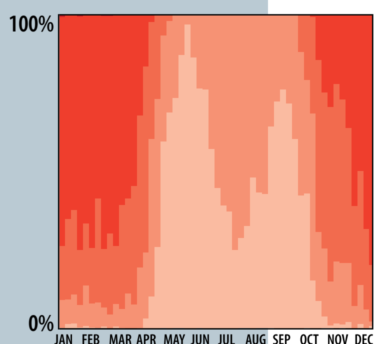


# HIGH ARCTIC

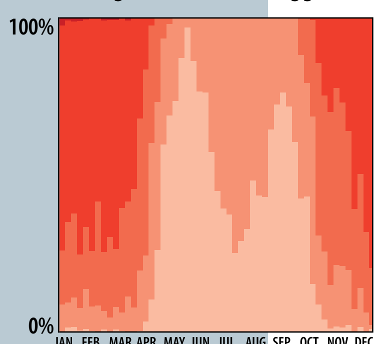
## MECHANICAL RECOVERY



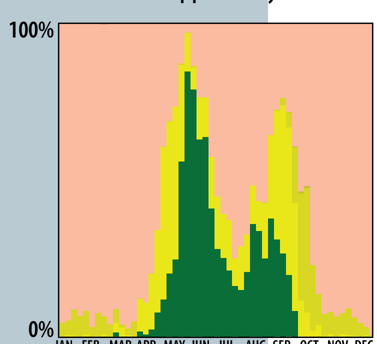
Two Vessels with Boom



Single Vessel w/ Outrigger

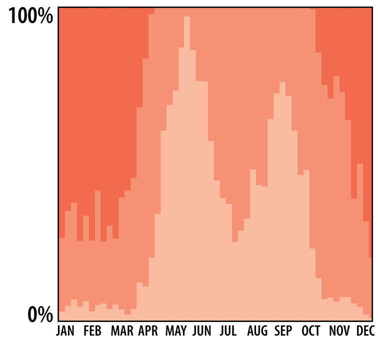


3 Vessels of Opportunity w/ Boom

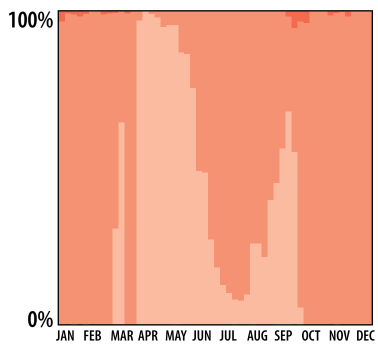


Single Vessel in Ice

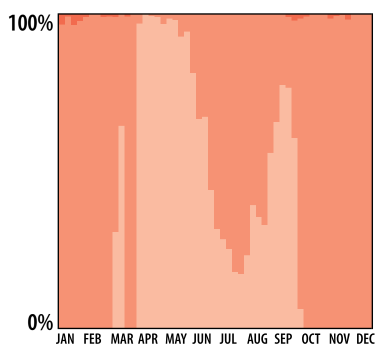
## DISPERSANTS



Vessel Application

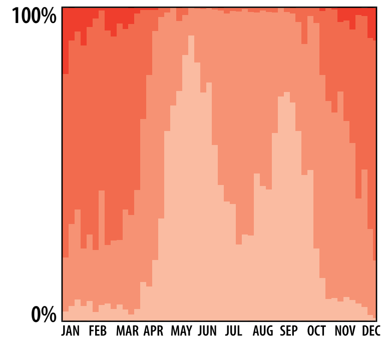


Fixed-Wing Aircraft Application

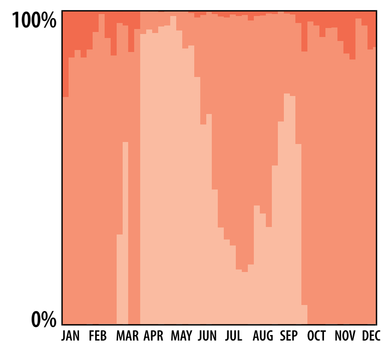


Helicopter Application

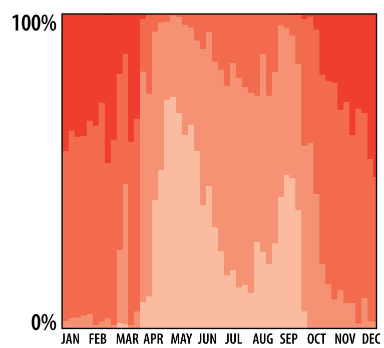
## IN-SITU BURNING



Vessels with Fire Boom



Helicopter with Ice Containment



Helicopter with Herders

**FAVOURABLE**

all conditions GREEN

**MARGINAL**

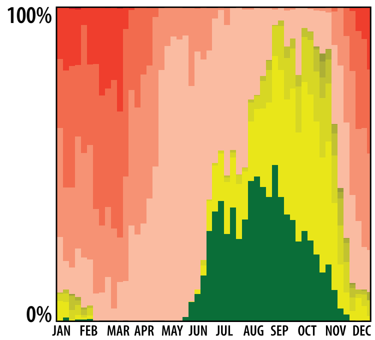
one YELLOW condition, others GREEN → all YELLOW conditions

**NOT FAVOURABLE**

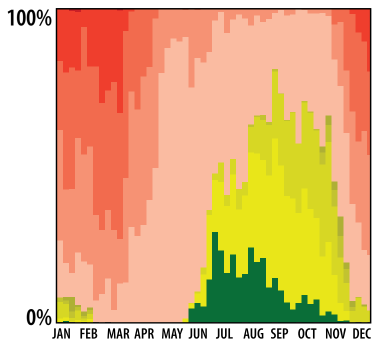
one RED condition → all RED conditions

# DAVIS STRAIT

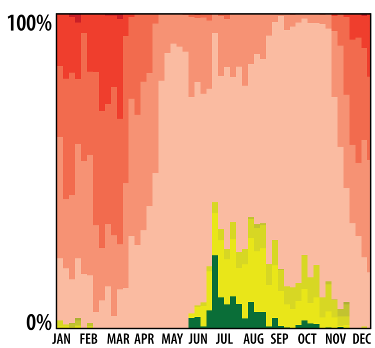
## MECHANICAL RECOVERY



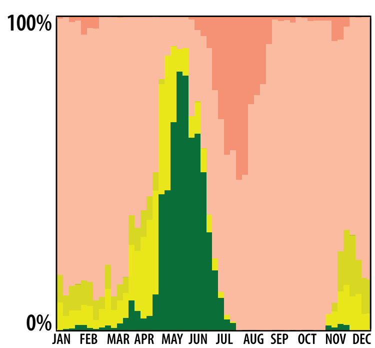
Two Vessels with Boom



Single Vessel w/ Outrigger

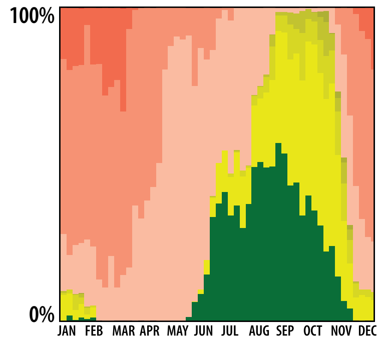


3 Vessels of Opportunity w/ Boom

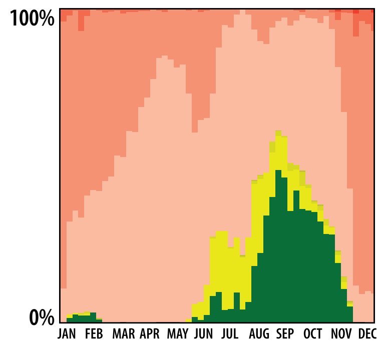


Single Vessel in Ice

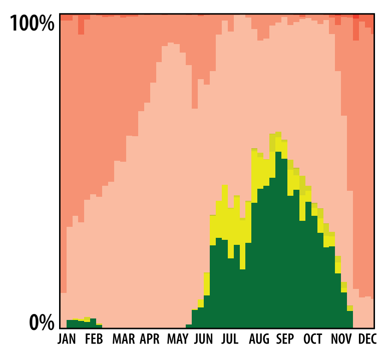
## DISPERSANTS



Vessel Application

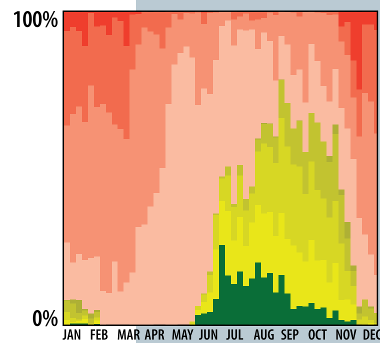


Fixed-Wing Aircraft Application

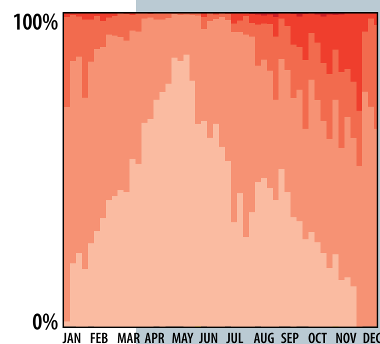


Helicopter Application

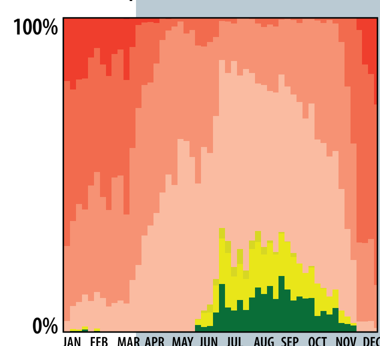
## IN-SITU BURNING



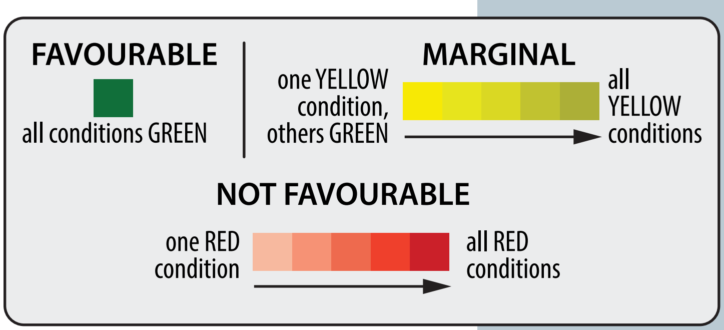
Vessels with Fire Boom



Helicopter with Ice Containment

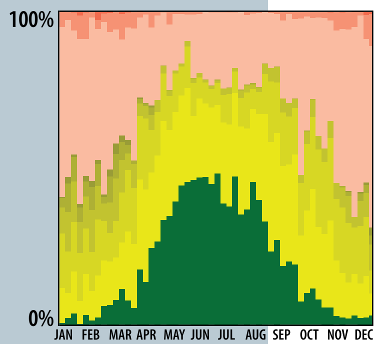


Helicopter with Herders

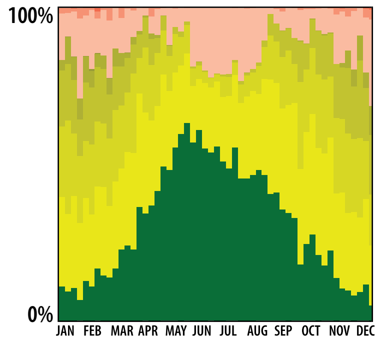


# NORTH ATLANTIC

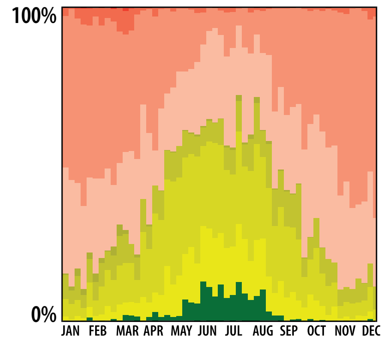
| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
|---|---|---|



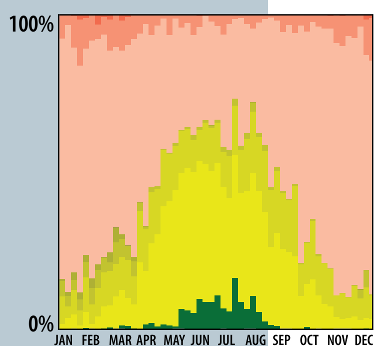

Two Vessels with Boom



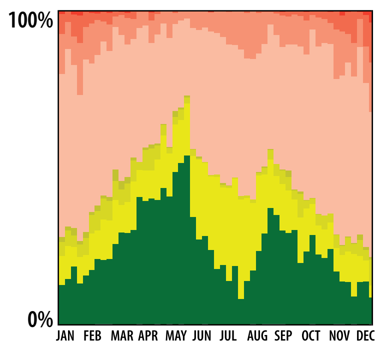

Vessel Application



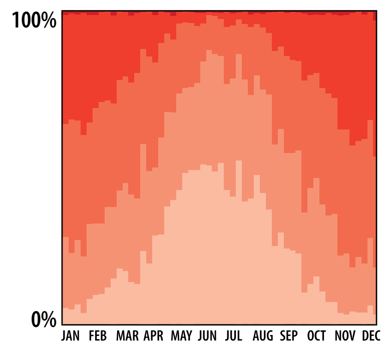

Vessels with Fire Boom



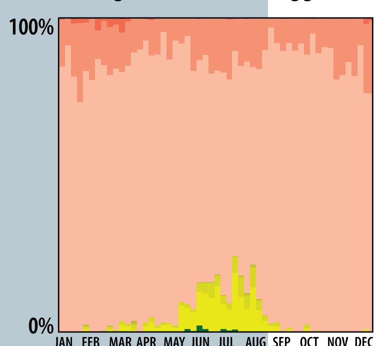

Single Vessel w/ Outrigger



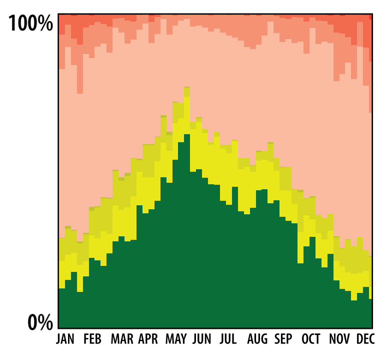

Fixed-Wing Aircraft Application



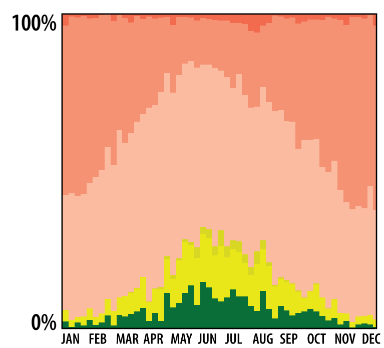

Helicopter with Ice Containment



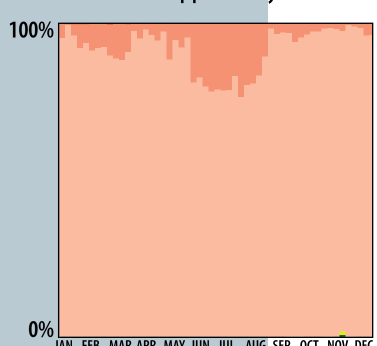

3 Vessels of Opportunity w/ Boom



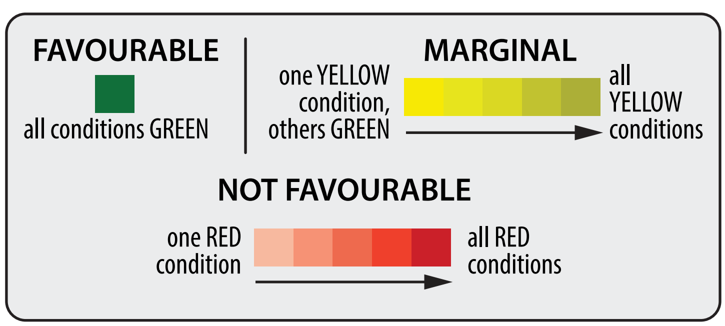

Helicopter Application




Helicopter with Herders

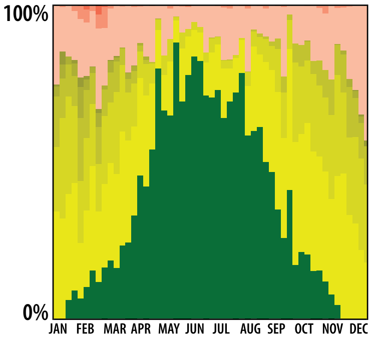



Single Vessel in Ice

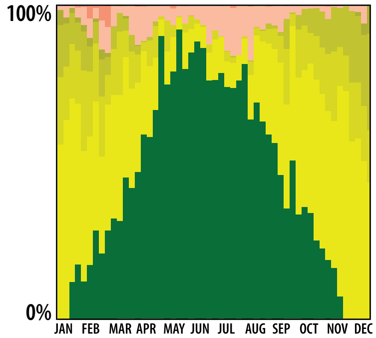


# BARENTS SEA

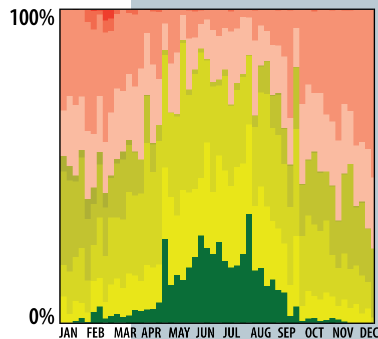
| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
|---|---|---|



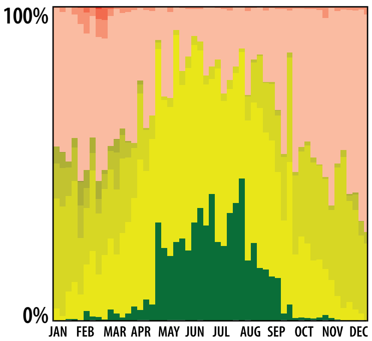
Two Vessels with Boom



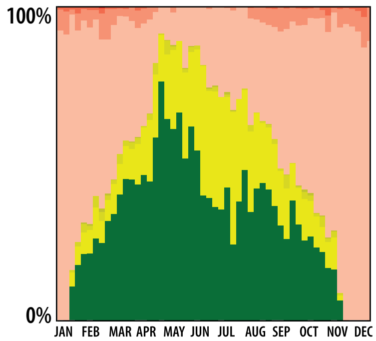
Vessel Application



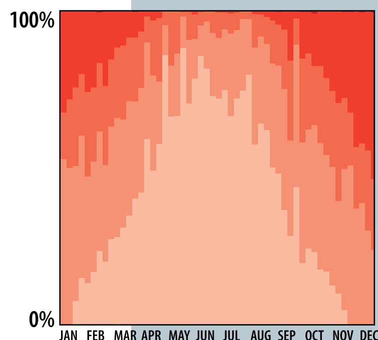
Vessels with Fire Boom



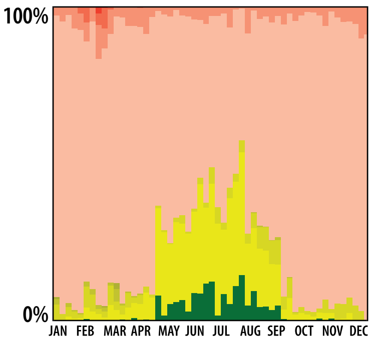
Single Vessel w/ Outrigger



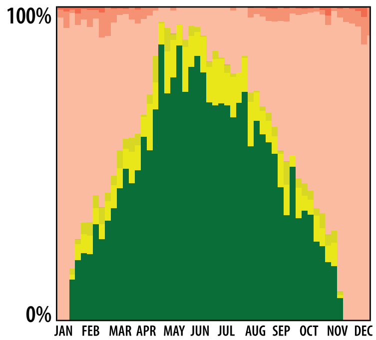
Fixed-Wing Aircraft Application



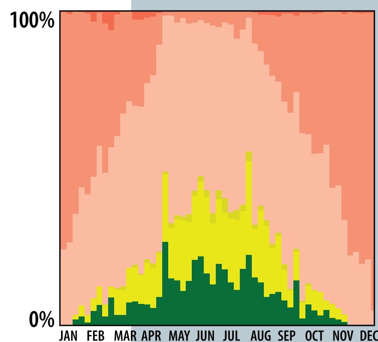
Helicopter with Ice Containment



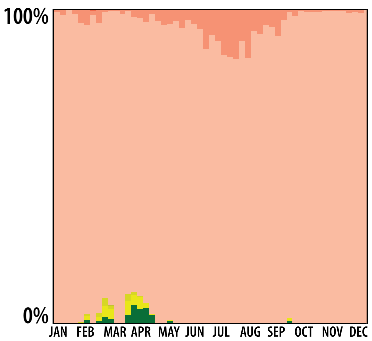
3 Vessels of Opportunity w/ Boom



Helicopter Application



Helicopter with Herders



Single Vessel in Ice

**FAVOURABLE**

all conditions GREEN

**MARGINAL**

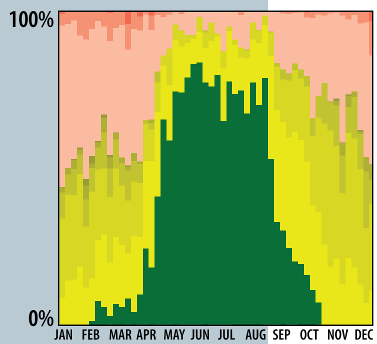
one YELLOW condition, others GREEN → all YELLOW conditions

**NOT FAVOURABLE**

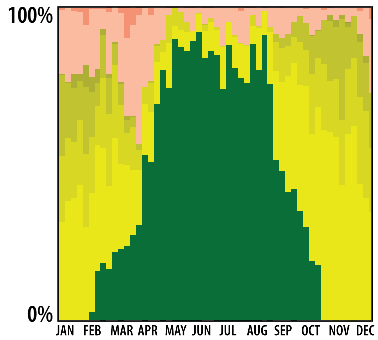
one RED condition → all RED conditions

# SVALBARD

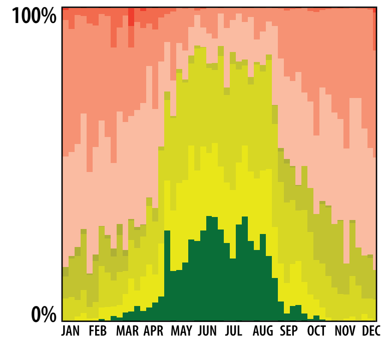
| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
| --- | --- | --- |



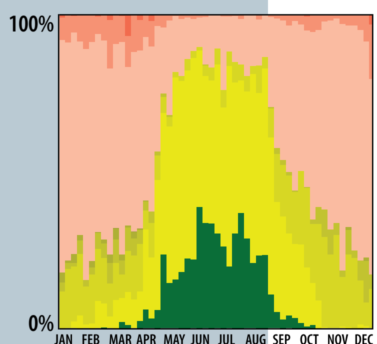
Two Vessels with Boom



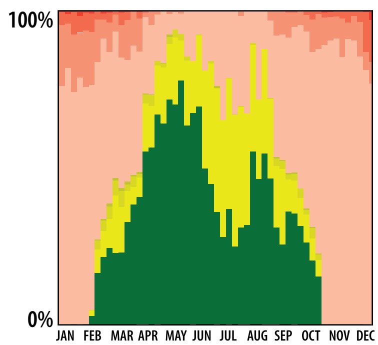
Vessel Application



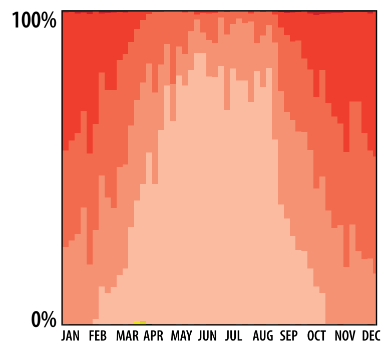
Vessels with Fire Boom



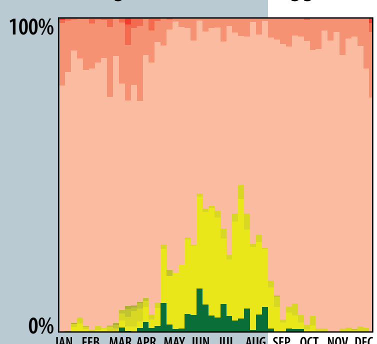
Single Vessel w/ Outrigger



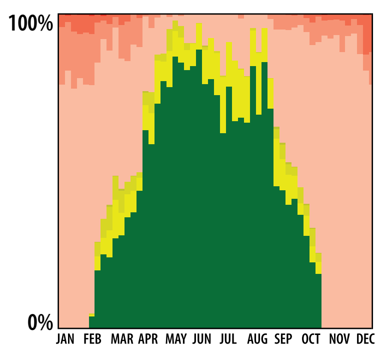
Fixed-Wing Aircraft Application



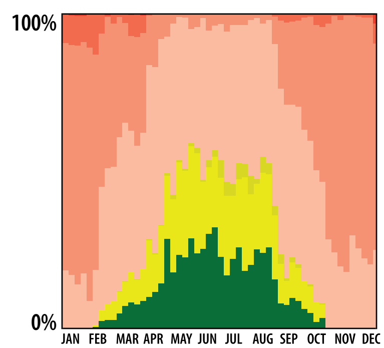
Helicopter with Ice Containment



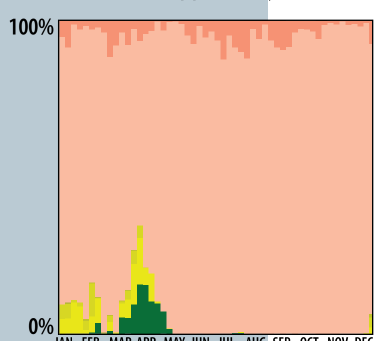
3 Vessels of Opportunity w/ Boom



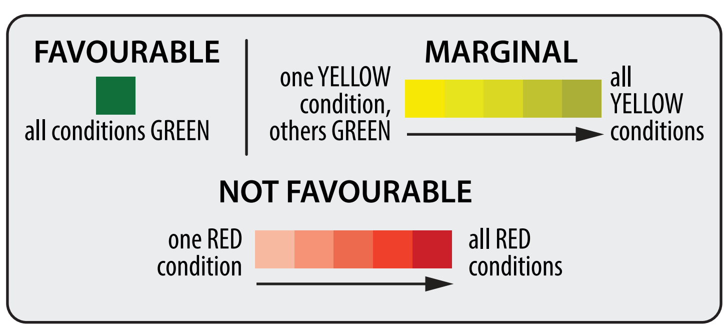
Helicopter Application



Helicopter with Herders

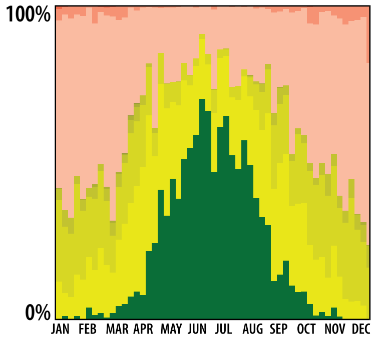


Single Vessel in Ice

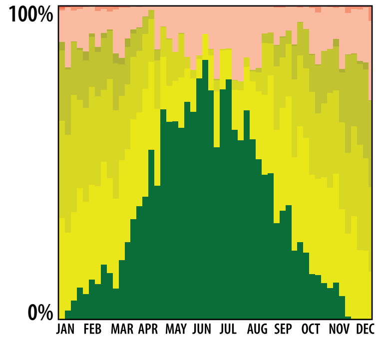


# NORWEGIAN SEA

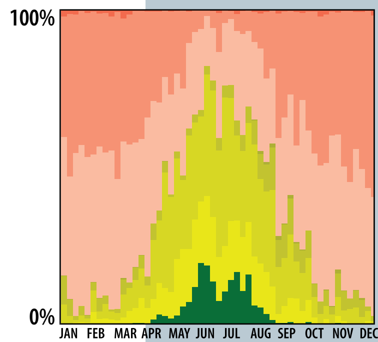
| MECHANICAL RECOVERY | DISPERSANTS | IN-SITU BURNING |
| --- | --- | --- |



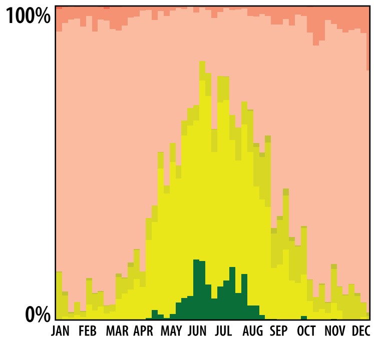

Two Vessels with Boom



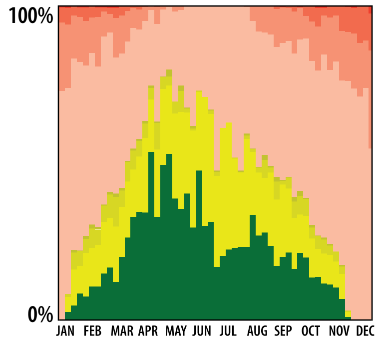

Vessel Application



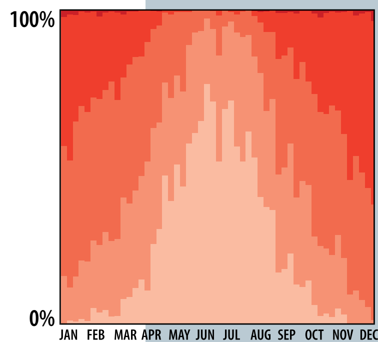

Vessels with Fire Boom



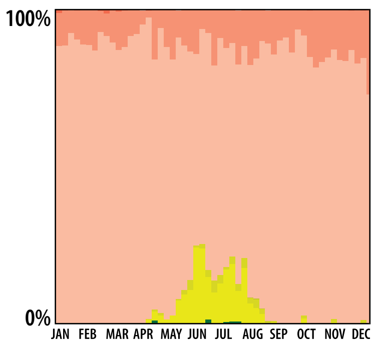

Single Vessel w/ Outrigger



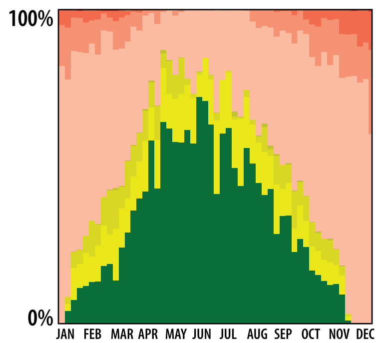

Fixed-Wing Aircraft Application



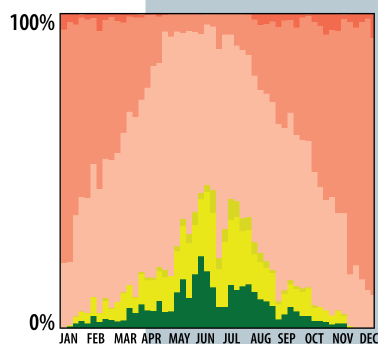

Helicopter with Ice Containment



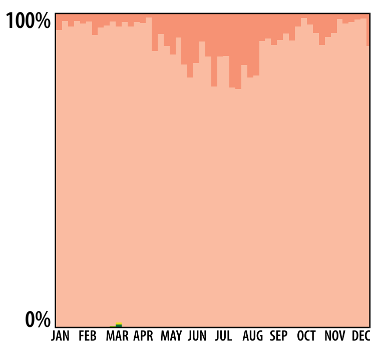

3 Vessels of Opportunity w/ Boom



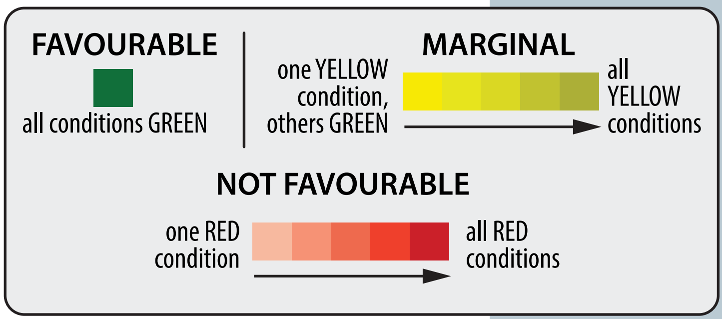

Helicopter Application




Helicopter with Herders



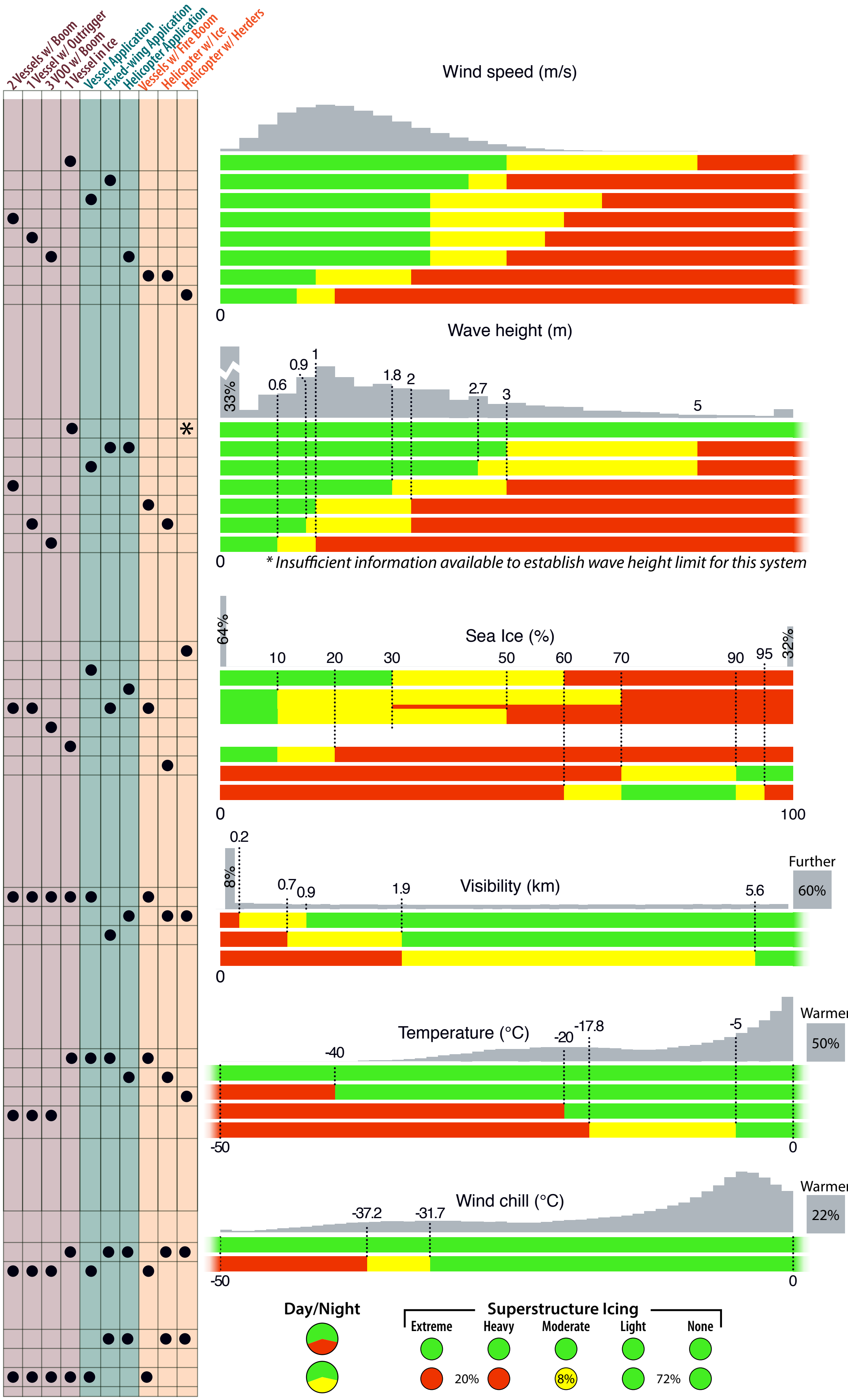

Single Vessel in Ice



# Appendix C

## Comparison of Response Limits and Metocean Conditions

Appendix C shows the response limits for each system in the context of the conditions for each parameter. In figure, the conditions are presented as a histogram of the aggregated year-round conditions from each of the 11 locations analyzed.


2 Vessels w/ Boom
1 Vessel w/ Outrigger
3 VOO w/ Boom
1 Vessel in Ice
Vessel Application
Fixed-wing Application
Helicopter Application
Vessels w/ Fire Boom
Helicopter w/ Ice
Helicopter w/ Herders
Wind speed (m/s)
0
Wave height (m)
33%
0.6
0.9
1
1.8
2
2.7
3
5
0
* Insufficient information available to establish wave height limit for this system
64%
Sea Ice (%)
10
20
30
50
60
70
90
95
32%
0
100
0.2
8%
0.7
0.9
1.9
Visibility (km)
5.6
Further
60%
0
Temperature (°C)
-40
-20
-17.8
-5
Warmer
50%
-50
0
Wind chill (°C)
-37.2
-31.7
Warmer
22%
-50
0
Day/Night
Superstructure Icing
Extreme
Heavy
Moderate
Light
None
20%
8%
72%

# Appendix D

## Supporting References for Operating Limits

**Supporting References for Mechanical Recovery Systems**

| | CONTAINMENT | SKIMMER | GENERAL |
|---|---|---|---|
| **Wind** | • **CurrentBuster 6:** < 8.7 – 10.8 m/s based on Beaufort 5 for offshore (NOFI, 2013)<br>• Unfavourable > 10.3 m/s (ExxonMobil, 2014) | n/a | • < 11.3 m/s (Shell, 2011)<br>• < 15.4-20.6 m/s (RPG, 2013)<br>• < 7.7 – 10.3 m/s (hydraulics & lifts) (ACS, 2015) |
| **Sea state** | • **CurrentBuster 6:** < 3 m in breaking waves, 7 m in swell (NOFI, 2013)<br>• **Ro-boom 3200:** Works in swells < 7 m (DESMI, n.d.)<br>• Unfavourable > 1 m waves (ExxonMobil, 2014) | • TransRec: < 3 m (Nordvik, 1999) | • < 2 m waves (ExxonMobil, 2008)<br>• < 3 m if swell (Shell, 2011)<br>• Impacted < 0.9 m (ACS, 2015)<br>• < 3 m if currents (RPG, 2013) |
| **Sea ice coverage** | • Affected > 10% (ACS, 2015) | • < 30% does not affect most skimmer function, though > 70% a problem (SL Ross & MAR, 2013)<br>• **Lamor Sternmax:** < 100% in up to 1.1 m ice (follows behind icebreaking vessel) (Lamor, n.d.) | • Affected at 10%; marginal < 30% (EPPR, 2015)<br>• < 10%, marginal to < 30% depending on type of ice; may also be unfavourable in trace ice (barge-based system) (Robertson and DeCola, 2000) |
| **Air temp./ wind chill** | • **Ro-boom 3200:** > -20C (DESMI, n.d.) | • At -17.9C, pumping problematic due to viscosity of oil (Campbell et al, 2014) | |
| **Visibility** | n/a | n/a | • > 200-800 m (Shell, 2011)<br>• > 926 m (ACS, 2015) |

| Supporting References for Dispersant Systems | | |
|---|---|---|
| | **DISPERSANT APPLICATION[1]** | **GENERAL** |
| **Wind** | • < 15.4 m/s for application (Lewis & Daling, 2007)<br>• 4-12 m/s is optimum (ITOPF, 2011)<br>• Favourable at 3.6-5.1 m/s due to breaking waves (Lewis et al, 2010)<br>• < 15.4 m/s for application (Lewis & Daling, 2007)<br>• **Aircraft:** < 12.9 m/s (AKRRT, 2016)<br>• **Aircraft:** <13.9 m/s (RPG, 2012)<br>• **Aircraft:** < 15 m/s (Exxon, 2000 in SL Ross, 2014)<br>• **Aircraft:** Favourable < 13 m/s, marginal to 15 m/s (SL Ross, 2014) | • 4-12 m/s is optimum (ITOPF, 2011)<br>• < 15.4-20.6 m/s (RPG, 2013) |
| **Sea state** | • (Favourable with breaking waves – see Lewis et al., 2010 above for associated winds.)<br>• **Aircraft:** < 5-7 m (Exxon Mobil, 2000 in Fingas, 2004)<br>• **Vessel:** 0.1 – 3 m seas (Exxon Mobil, 2000 in Fingas, 2004) | • Need 0.2 m waves for dispersion; natural dispersion becomes equally effective at 3 m waves (Allen, 1988)<br>• Tank tests showed dispersant applied in calm waters could later be effective in presence of Beaufort Scale 3 waves (Lewis et al., 2010) |
| **Sea ice coverage** | • Generally, favourable < 30%; uncertain without mixing energy from 30-80%; not possible from vessel > 90% (SL Ross, 2014)<br>• Demonstrated in 70-80% w/ thrusters (Daling et al, 2010) | • Favourable < 30%; uncertain w/o mixing energy from 30 - 80%, not possible > 90% (SL Ross, 2014)<br>• **Aircraft (fixed wing):** < 10% (Daling, 1990 in Daling et al. 2010)<br>• **Aircraft (fixed wing):** < 20 – 30% (Lewis & Daling, 2007)<br>• **Aircraft:** Favourable < 50%, marginal to 90% (SL Ross, 2014)<br>• **Helo:** May be possible up to 50%, possibly higher (Lewis & Daling, 2007) (Daling, 1990 in Daling et al. 2010 cites up to 20%)<br>• **Vessel:** Demonstrated in 70-80% w/ thrusters (Daling et al, 2010) |
| **Air temp./ windchill** | • Varies with dispersant. Storage favourable 10-20C; too cold at -15C for Dasic Slickgone or 0C for Corexit 9500 (Daling et al, 2010)<br>• Different kinds of Corexit can be applied at -18C (Exxon Mobil, 2008)<br>• < 0 C may cause application device to freeze and affect dosing (Lindgren et al., 2001) | n/a |
| **Visibility** | **Aircraft:** > 304 m cloud ceiling (AKRRT, 2016) | n/a |

[1] Limits for aerial dispersant systems also supported based on personal communication with Arnie Palmer, 2Excel Aviation, Ltd.

**Supporting References for In-situ Burn Systems**

| | CONTAINMENT | IGNITION | GENERAL |
|---|---|---|---|
| | *Except for herder references, these are essentially the same as for mechanical recovery, but citations are focused on ISB.* | | |
| **Wind** | • Favourable to 5.1 m/s, marginal to 10.2 m/s (Buist et al., 2003; SLRoss et al, 2003) | • <9.1 m/s offshore (ExxonMobil, 2014)<br>• 8.3 – 11 m/s upper limit for ignition (assuming no waves) (Buist et al., 2013)<br>• Depending on oil type, ignited up to 10 m/s or 15 m/s in lab tests (Opstad and Guenette, 2000) | • < 10.3 m/s (RPG, 2012) |
| **Sea state** | • Favourable to 0.9 m, marginal to 1.5 m (Buist et al., 2003)<br>• Possible up to 1.8m (ASTM F625 and F2683)<br>• Same as mechanical recovery (RPG, 2012)<br>• *Herders:* Breaking waves broke up slick; swell elongates & breaks up slick in tank test (SLRoss, 2012) | • Marginal 1-1.5m (SLRoss et al, 2003)<br>• Effective burning limited at 1-1.2 m waves or less (Buist et al., 2013) | • Favourable to 0.9 m chop & 1.5 – 1.8m in swell (ADEC et al, 2008) |
| **Sea ice coverage** | • Feasible up to 30% (Potter, 2010)<br>• < 20% ice coverage can affect containment with fire boom (Shell, 2011)<br>• Fire boom works < 10%, marginal 10-30%; use **herders** 30-100%; rely on ice containment >70% (Buist et al., 2013)<br>• **Herders:** One type of herder worked in up to 70% in tank tests; field tests were successful in 30% but not tested at higher concentration (Buist et al, 2008) | n/a | • < 80-90% (Shell, 2011) |

| Supporting References for Platforms | | | |
|---|---|---|---|
| | **VESSEL** | **HELICOPTER** | **FIXED-WING AIRCRAFT** |
| | | | |
| **Wind** | • n/a – assumed to be less significant than the effect of wind on response equipment/operations | • 15.4-20.7 m/s sustained winds, depending on type (NWCG, 2013) | • n/a – assumed to be less significant than the effect of wind on ability to target slick |
| **Sea state** | • n/a – assumed to be less significant than the effect of wind on response equipment/operations | • n/a | • n/a |
| **Sea ice coverage** | • n/a – for study purpose, it is assumed that vessels of appropriate ice class are used | • n/a | • n/a |
| **Air temp./ windchill** | • > - 37.2C wind chill limits crew operations; at -42.7C wind chill, nonemergency work ceases (ACS, 2015) | • > -40C (Canadian Helicopters, Ltd reported in Lewis & Daling, 2007) | • n/a |
| **Structural icing** | • For 20-75 m vessel, light icing = < 0.3 cm/hr; moderate = 0.3-0.8 cm/hr; heavy = 0.8-1.6 cm/hr; extreme > 1.6 cm/ hr (Guest, 2008, based on Overland, 1990) | • n/a | • n/a |
| **Visibility** | • > 200-800 m horizontal for on-water mechanical recovery (Shell, 2011) | • 804 m horizontal visibility (NWCG, 2013) | • *Night:* > 4.8 km horizontal visibility & > 152.4 m vertical visibility; *Day* >1.6 km horizontal & clear of clouds based on low-flying craft under Visual Flight Rules per US regulations (14 CFR 91.155) |

EP
PR

EMERGENCY PREVENTION,
PREPAREDNESS AND RESPONSE

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