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ASSESSING THE INFLUENCE OF METOCEAN CONDITIONS ON OFFSHORE OFFLOADING OPERATIONS IN THE ARCTIC

Jaap van Rijckevorsel [1]
[1] UiT - The Arctic University of Norway, Tromsø, Norway

ABSTRACT

Offshore oil and gas facilities require reliable upstream logistics to provide them with the necessary goods and services for safe and successful operations. Previous research has identified adverse metocean conditions during offshore offloading operations as a main cause of logistics disruptions in the North Sea. In the Arctic, environmental conditions are considered harsher and operational experience is more limited. Understanding the influence of metocean conditions on offloading operability is an essential basis for understanding the vulnerability of the logistics system.

The aim of this paper is to quantify the influence of metocean conditions on the operability of offshore offloading operations for each month of the year in the North- and Barents Seas. For this purpose, the critical subfunctions and metocean hazards in the offshore offloading process were identified and an operability gap analysis was performed using 15 years of hindcast metocean data. The results of this study show that metocean factors have a large influence on offshore offloading operability in the Barents Sea. Although overall operability windows are comparable between the North- and Barents Seas, regional variations exist and the factors causing inoperability in the Arctic are more complex as they involve icing, low temperatures, sea ice and more frequent periods of poor visibility. The presented assessment method can be extended when new information or more accurate data becomes available.

1 Introduction

Offshore oil and gas developments rely on supply- and support operations, or upstream offshore logistics, to provide them with all products and services necessary to operate safely and efficiently. A basic model of an upstream logistics operation consists of a supply vessel shuttling between an onshore supply base and an offshore facility, as described by Milakovíc et al. (2014).

High logistics reliability is required to prevent downtime in the operation that is to be supported (Batalden, 2012). In the North Sea, advantages in cost-efficiency and regularity are obtained by operating in supply pools consisting of fleets of vessels serving multiple offshore installations. Combined with extensive operational experience, close proximity to well-developed infrastructure and the availability of accurate weather forecasts, these pools provide the supply system with a level of flexibility and resilience. It has however been suggested that upstream supply operations could benefit from the application of more formal logistics- and disruption risk management research (Aas, 2008).

With offshore logistics operations following the oil and gas industry into the Arctic, a new operating environment with specific challenges is encountered (Borch et al., 2012). Factors like ice, darkness, low temperatures, long distances and low predictability pose additional threats to the regularity of the logistics chain and the operability of its components. At the same time, the advantages of well-established supply pools are not available in the Arctic so that supply chains will be more vulnerable to disruptions. Therefore, existing operational models will need to be adjusted to deal with the turbulent and complex operating environment, especially when year-round operations are considered (Borch and Batalden, 2013, OpLog, 2014). An essential basis for assessing the vulnerability of a logistics system is developing an understanding of the underlying factors causing disruptions (Asbjørnslett, 2009).

The aim of this paper is to present a preliminary quantitative assessment of the influence of metocean factors on the most vulnerable part of a supply operation, the offshore offloading process, in the North- and Barents Seas. Operability is expressed as the average time per month that metocean conditions are classified as feasible, marginal or unacceptable for offshore offloading operations. This operability-measure is calculated by comparing historical (hindcast) metocean timeseries to given operational limits in an operability gap analysis. Analysis of metocean timeseries is a recommended practice in modeling the performance and safety of marine operations (DNV-GL, 2014c). Gap analysis methods have previously been used to assess the feasibility of oil spill response operations (DNV-GL, 2014b, Nuka, 2006).

Results are presented spatially (as maps) to identify differences in operability between the Norwegian part of the Barents Sea (west of 40 degrees longitude and south of 80 degrees latitude), and the North Sea (east of the UK). Focus within the Barents Sea is directed towards the area currently open for oil and gas exploration, the 22nd licensing area.

2 Existing literature and definitions

Vulnerability assessment and disruption risk management are emerging academic fields where more empirical work is needed to develop and validate theoretical frameworks (Tang and Nurmaya Musa, 2011, Sodhi et al., 2012). A general framework for supply chain vulnerability assessment is described by Asbjørnslett (2009), who defines vulnerability as the "properties of a system that weaken or limit its ability to endure threats and survive accidental events" (Asbjørnslett, 2009). The concepts of 'threat' and 'hazard' refer to stable, latent adverse factors that may cause an accidental event, while the term 'factor' refers to conditions along a scale that can become hazards depending on their level (Asbjørnslett, 2009). For example, the metocean *factor* 'sea state' poses a hazard to marine operations only when it reaches certain *levels* (high or confused waves), not when the water is calm.

An example of a vulnerability assessment framework in maritime transportation systems is provided by Berle (Berle et al., 2011). Severe weather has been identified as one of the most common operational impacts to maritime transportation by Gurning (2011). Adverse conditions during offshore offloading are the main cause of disruptions in upstream supply in the North Sea according to Aas et al. (2009), who describes the main features of offshore supply vessels as offshore offloading capacity, cargo capacity (deck, wet- or dry bulk) and sailing capacity (Aas et al., 2009). Other published work on upstream supply chains involves scheduling problems of PSV's in a pool (Aas et al., 2007, Halvorsen-Weare and Fagerholt, 2011, Maisiuk and Gribkovskaia, 2014).

Issues regarding offshore logistics in the Arctic are described from various perspectives by Borch et al. (2012), Milakovíc et al. (2014), Connelly and Brovkin (2014), the AOH-JIP (2013), and the INTSOK project (2013). Limited operating experience combined with unpredictable and harsh metocean conditions requires more thorough assessments of feasibility, operability and disruption risk, as has been suggested by Keinonen and Martin (2012), Berg (2014) and Batalden (2012).

3 Operational limits and gap analysis method

The average monthly (in-)operability in the Barents- and North Seas will be established through a gap analysis, following the analytical process described below (and in figure 1). An introduction to offshore offloading operations and their critical subfunctions is given in section 3.1

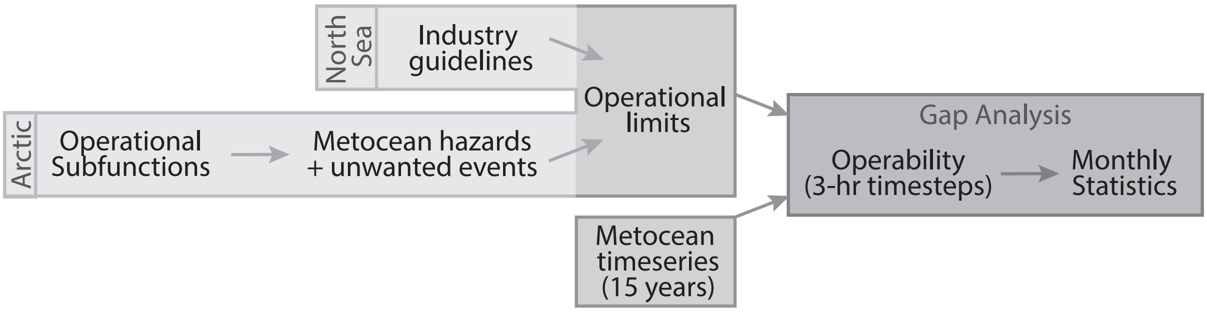

Figure 1:Analytical process. Operational limits and metocean timeseries serve as input to the operability gap analysis.

Input to the operability gap analysis consists of operational limits and metocean timeseries. In the North Sea, operational limits related to metocean conditions are well-established and readily available in industry publications (section 3.2). For offloading operations in the Arctic such guidelines have not yet been formulated due to lower levels of activity and experience in these frontier areas (AOH, 2013). For the purpose of our analysis, the metocean hazards for Arctic operations were therefore identified by an extensive review of information from various sources described in section 3.3, and operating limits for selected paramenters are described in section 3.4. The metocean data and gap analysis process are described in sections 3.5 and 3.6 respectively, while results are presented and discussed from section 4 onwards.

3.1 Offshore offloading operations

The subsequent phases of an offshore offloading operation are described in detail by the Guidelines for Offshore Marine Operations (GOMO, 2013) and its predecessor (NWEA, 2009). Upon arrival of the OSV at the 500-meter facility safety zone, operational procedures are confirmed via VHF-radio and the vessel sets up in close proximity to the facility in station-keeping mode (dynamic positioning). Cargo is transferred by the facilities' crane (deck cargo) or hoses (bulk cargo), facilitated by the deck crews of the vessel and the rig. Based on the guidelines mentioned above, field observations and reviewed operations manuals, the following critical functions of an offloading operation were identified. All these functions need to be performed successfully for the operation to succeed:

- Station-keeping and general vessel safety
- Deck cargo lifting operations (when applicable)
- Bulk cargo hose operations (when applicable)
- Communication, monitoring and documentation

3.2 Metocean hazards and operating limits in the North Sea

Metocean factors influence the safety and successful performance of the critical functions identified above. For example, wind and waves induce vessel motions that affect station-keeping ability, present hazards to deck work (slips, falling loose objects), and may cause cargo damage or decrease crew or vessel safety during the lift (swinging cargo). In non-Arctic environments like the North Sea, these hazards are well-understood and explicit operational limits are defined by the GOMO (2013) and NWEA (2009) guidelines (excerpt in Table 1). The relevant metocean factors are wind speed, wave height or sea state, visibility, and currents with different limits for lee- and weather-side operations. For wind and sea state, multiple risk-levels can be described as follows:

- 'Normal' operating conditions: operations proceed as per normal procedures.
- 'Marginal' conditions: operations require additional risk-reducing measures, and may or may not proceed only after careful evaluation.
- 'Unacceptable conditions': Operations shall be ceased.

Table 1: Excerpt from NWEA adverse weather operating criteria for weather side working. Source: (NWEA, 2009).

Factor	Response
Wind *20-25 kts*	Secure loose items, advise caution
>25kts	Operations cease
Sea State *3m-4m Hs*	Assess operation carefully before arrival
>4m Hs	Cease operation
Currents *>50% power utilization*	Consider delaying until current slackens
Visibility *<250m or crane can't see crew*	Cease or cancel operations. Remain outside safety zone and maintain radar watch.
Vessel motions	Operations may be ceased at lower limits when vessel motions affect station keeping or crew safety.

3.3 Metocean hazards in the Arctic

In the Arctic, the subfunctions of offshore offloading operations are the same as in the North Sea (see section 3.1). However, metocean conditions are considered harsher due to the presence of the following factors: icing, low temperatures, sea ice and icebergs, frequent fogs and polar lows. Many reports describe these Arctic metocean conditions, but few publications address their influence on offshore offloading operations in detail. No industry guideline providing operational limits with regards to these conditions has yet been established, but suggestions for such a document have been put forward by the Arctic operating handbook JIP (AOH, 2013).

In the absence of documented limits related to Arctic metocean factors, an identification of potential metocean hazards to the critical subfunctions of the operation was performed. Identified metocean factors were sea state, wind, currents, visibility, icing, sea ice, icebergs, low temperatures and windchill, some of which can be associated with polar lows. Information from multiple sources was used in this analysis through a grounded theory approach, which is a structured method to identify patterns and categories in qualitative datasets commonly used in qualitative research (Glaser and Strauss, 1967). Data included the

AOH (2013), the OCIMF report on marine operations in ice and extreme sub-zero temperature (OCIMF, 2014), the INTSOK report on Arctic transport and logistics (INTSOK, 2013), the OGP report on health aspects of work in extreme climates (OGP-IPIECA, 2008), the Barents 2020 report (Barents2020, 2009), the ABS guidelines for vessels operating in low temperature environments (ABS, 2010), the IRIS report on technology operational challenges in the High North (Gudmestad and Karunakaran, 2012), NORSOK standards N003 (NORSOK, 2004a) and S002 (NORSOK, 2004b), OLF guidelines 61 and 72 (OLF, 2003, OLF, 2002), the IMO guidelines for ships operating in Polar waters (IMO, 2009), workshops and discussions with industry professionals.

The scope of hazard identification was limited to metocean factors directly influencing offloading operations. General vessel seaworthiness in Arctic waters is assumed to be in place through the relevant class compliance. Non-metocean factors like remoteness, forecast uncerteinty and human factors are not included in this paper but their influence on operations forms an important topic for further research.

Table 2: Metocean influence factors to the critical subfunctions of offshore offloading operations in North Sea and Arctic environments.

	Stationkeeping & Vessel safety	**Deck cargo operations**	**Bulk cargo operations**	**Communication, Documentation, & Monitoring**
North Sea influence factors	Sea state Wind Currents Visibility	Sea state Wind Visibility	Sea State	Visibility
Additional Arctic influence factors	Icing Sea-ice Icebergs (polar low)	Icing Cold Snow (polar low)	Icing Cold (polar low)	Icing (aerials) Frequent poor visibility Weather-forecasts

Table 3: Identified disruptive events in offshore offloading operation subfunctions due to icing (excerpt from full analysis).

	Stationkeeping & Vessel safety	**Deck cargo operations**	**Bulk cargo operations**	**Communication, Documentation, & Monitoring**
…	…	…	…	…
Icing	- Loss of stability due to ice accretion on vessel - Inoperability of critical equipment - Impaired DP-reference sensors - Loss of accessibility	- Falling ice from cargo and cranes - Loss of friction on the deck (shifting cargo) - Frozen slings - Cargo imbalance - Increased cargo weight - Inoperable winches	- Inoperable manifolds, valves and pumps - Hose damage on sharp ice features	- Malfunction of aerials
…	…	…	…	…

In summary of the analysis described above, the metocean influence factors for offshore offloading operations in Arctic and temperate environments are given in Table 2. A comprehensive discussion of all potential disruptive events for all metocean factors is beyond the constraints of this paper. As an example, findings related to icing are presented in table 3. Further analysis of this dataset is suggested, for example by performing a criticality-analysis to prioritize certain scenario's or mitigation measures.

3.4 Operational limits

The operability gap analysis in the following section compares selected historical metocean parameters to the operational limits presented in Figure 2. For wind and waves, limits from the NWEA guidelines for OSV operations are used (NWEA, 2009). Icing and low temperatures are included as additional Arctic metocean factors, based on the findings in section 3.3 and the available metocean data. Following NWEA (2009), limits for these parameters also distinguish between marginal- and unacceptable (ceased) operating conditions.

The rate of sea spray icing can be expressed as 'low', 'medium', 'high' or 'extreme', following the commonly used algorhythm by Overland (1990). Operational limits for marginal and ceased operations are set to 'low' and 'moderate' icing rates respectively, based on information from the OCIMF and IMO (OCIMF, 2014, IMO, 1993). These industry organisations state that that de-icing is considered a complex, time-consuming, and hazardous operation that should be minimized by stopping operations and altering course and speed to avoiding icing conditions whenever possible. Operational limits for cold temperatures relate to human working conditions, and are defined at equivalent windchill temperatures of -21 and -25 for marginal and unacceptable conditions, respecitvely. These limits are based on the risk-levels stated in OCIMF (2014), OGP-IPIECA (2008), and GOMO (2013).

Floating ice (sea ice or icebergs) is not included in the operability gap analysis but sea ice data is presented separately. The presence of ice entails additional offshore support functions like ice management and implies different vessel designs (ice-class) combined with a vastly different organisation of the offshore support system (Juurmaa and Wilkman, 2002), making a direct comparison to regular upstream logistics operations complicated. Representative performance data are not available for operations involved with sea ice or icebergs (AOH, 2013), so an accurate representation of such operations in our model is not feasible.

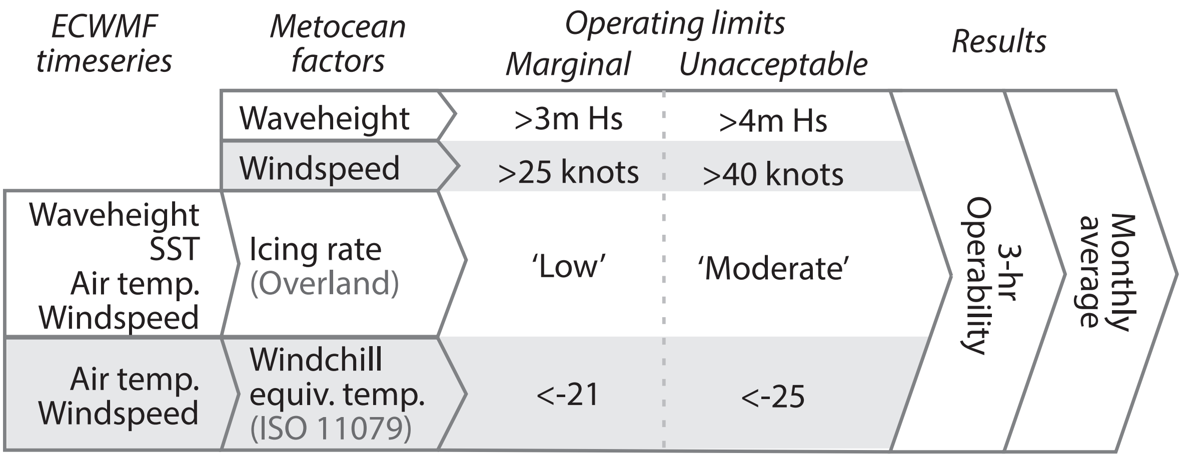

Figure 2: Operability gap analysis method and operating limits. 'Hs' refers to significant waveheight, and 'SST' to Sea Surface Temperature.

3.5 Metocean data

The following metocean variables were retrieved from the ECWMF ERA Interim dataset for the period june 1999 to june 2014: wind (speed and direction), waveheight (combined height of wave and swell), air temperature (2m), sea surface temperature, and sea ice cover (ECWMF, 2011). The parameters were represented in 3-dimensional matrices in their model resolution of 0.75 degrees latitude and longitude and a temporal resolution of 3- (wind, temperatures, sea ice and SST) and 6 hours (waveheight). The 6-hour waveheight data was linearly interpolated to the 3-hour temporal resolution of our analysis.

The best available source of visibility data for our purposes consists of marine observations from different platforms combined in the ICOADS dataset (Worley et al., 2005). This dataset has been used to derive monthly visibility statistics for the Arctic and other areas (DNV-GL, 2014a), but spatial and temporal resolutions were considered too coarse to implement this data into our model.

3.6 Gap analysis process

For every location and at every 3-hour timestep in the metocean model, the modeled metocean factors were evaluated against the given operational limits (see figure 2). Icing rate was calculated by applying Overland's algorhythm (Overland, 1990) using the metocean parameters shown in figure 2 as input. Equivalent windchill temperature was calculated from air temperature and windspeed following ISO standard 11079 (ISO, 2007).

When any one of the factors was evaluated as 'marginal' or 'unacceptable for operations' the cell was classified as 'marginal' or 'ceased operations' respectively for the given 3-hour period. Subsequently, the average time spent under 'marginal' or 'ceased' conditions was calculated for each month of the year over the duration of our timeseries (1999-2014) to minimize the influence of annual variation.

Compared to assessing operational windows based on statistics for separate metocean factors, this approach is more realistic because it takes into account the fact that adverse operating parameters do not occur independently of each other but often occur simultaneously, for example in the case of a polar low causing high windspeeds, large waves, low visibility, heavy snowfall and potential sea spray icing. The presented analysis process will remain valid and can incorporate updated operating limits, more accurate input data or additional metocean factors (like visibility) when this data becomes available.

4 Findings

A clear seasonal pattern in operability values is observed. Throughout our study area, the highest fractions of ceased operations occurring in January (mid-winter) and negligible metocean related inoperability during summer (June). Due to space constraints, results are presented only for January and June in Figure 3.

Overall operability values in the Barents Sea are comparable to other areas on the Norwegian continental shelf for both ceased operations and marginal conditions. Variation exists between sheltered areas (generally more inshore) and more exposed areas (further offshore and in the far North). The effect of metocean hazards on offshore offloading operability is large during winter months, with operations either being ceased or taking place in marginal conditions for more then 50% of the time in January throughout our study area. Maximum values reach up to 80% impaired operability (combining ceased operations or marginal conditions) in the

Western North Sea (Statfjord area) and Northern regions of the 22nd licencing area around Bjornøya.

The metocean factors causing inoperability are different between areas. A comparison of figures 3A (ceased operations due to all metocean factors) and 3C (ceased operations due to wind and wave limits only) reveals that wind and and waves are the main factors causing ceased operations in the North- and Norwegian Sea areas but that their influence on operability diminishes when moving into the Barents Sea. In the Barents Sea, the influence of the Arctic metocean hazards in our model (icing, windchill) is significant, and increases when moving North and East. This result indicates the importance of addressing the effects of specific Arctic meteocean conditions when planning for operational regularity in the Barents Sea.

North of the 22nd licensing area (north of 74 degrees latitude), operability-values show a marked decrease towards 100% inoperability in January. This indicates that with our defined

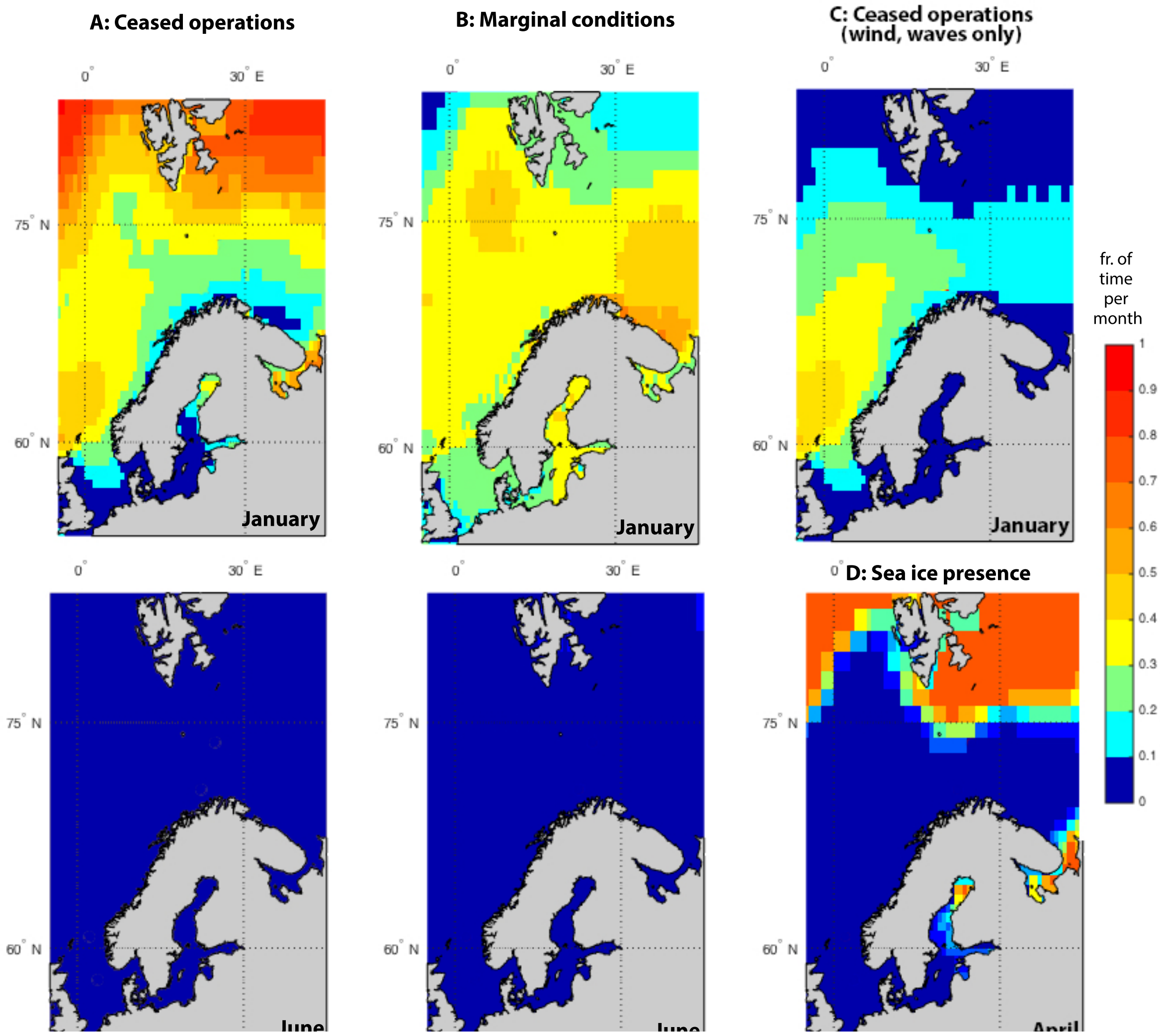

Figure 3: Maps representing operability in our study area for given months (average values over 1999-2014). Values refer to fraction of total time for the given month. Left (A): fraction of ceased operations in January and June. Middle (B): fraction of marginal conditions in January and June. Top-right (C): ceased operations due to wave- and wind-limits only. Bottom-right (D): fraction of time with sea ice concentration >0.1 during the month of maximum ice extent (April).

operating limits offshore cargo operations are not feasible in these waters in January. A further complicating factor that becomes relevant when moving North of 74 degrees latitude is the possible presence of sea ice, with its annual maximum occurring in April, shown in figure 3D. The sea ice extent from the ECWMF model corresponds to the ice occurrence limit with annual probability 10^{-2} given by NORSOK N003 (NORSOK, 2007). These results indicate that year-round operations in this area should at least evaluate the need to design for ice occurrence.

5 Discussion

Due to the lack of documented year-round offshore offloading operations in the Barents Sea, no data for validation of this operability analysis was available. However, the presented findings agree with general statements from industry experts as well as with the recorded level of inoperability from a supply vessel operating in the Southern North Sea measured over 5 years (2009-2014: 25% 'waiting on weather' while at facility between October and February).

The applied operating limits are based on observations and operational best practises in the North Sea and literature on Arctic operations. The absence of Arctic operational guidelines warrants further research into methods for establishing well-found operating limits for areas where operational experience is absent or scarcely documented, as well as methods to assess the effects of design- and winterization measures on operability.

The main limitation of the operability gap analysis is the use of relatively low-resolution metocean data due to data-availability and computational constraints. This results in an under-representation of small- and meso-scale meteorological phenomena including polar lows. Also, the exclusion of visibility as a metocean hazard due to a lack of appropriate data is regarded as a shortcoming as poor visibility is regarded as a major source of logistics disurptions in the Barents Sea area (INTSOK, 2013). Current results should therefore be regarded as non-conservative. Uncertainty in the results is further enhanced by the limitations of the icing prediction algorythm and the uncertain influence of climate change when using these statistics as predictions for future operations. However, the methodology will remain valid and can incorporate more accurate metocean data and operating limits when they become available.

More detailed insights may be obtained by performing a further analysis for a small number of selected locations. It is for instance suggested to assess the seasonal differences between locations and to further investigate the contribution of specific metocean factors to inoperability. Statistical distributions for frequency and duration of disruptions can be derived for specific locations and used in stochastic optimization of routing, fleet composition or logistics design, as shows by (Halvorsen-Weare and Fagerholt, 2011) for a single metocean factor.

Apart from this analysis of metocean factors to offshore offloading operations, a complete vulnerability assessment of the offshore logistics system should also include other parts of the logistics chain (sailing leg, port operations, other in-field functions) and non-metocean factors. Examples of potentially disruptive factors suggested for further research are unreliable satellite signals and communication, remoteness from repair or docking facilities, darkness- and weather induced fatigue, additional manning requirements and competence, offshore personnel transfer, and potential constraints due to multiple vessel functions. Finally, another important factor regarding Arctic marine operations is the higher uncertainty of Arctic weather forecasts, causing significantly less operability for operations that require stable weather windows based on forecasts, or so-called 'weather restricted operations' (DNV-GL, 2011).

6 Conclusion

This paper has identified metocean factors that affect offshore offloading operations and has quantified their effect on monthly operability windows in the North- and Barents Seas. It was found that metocean-factors have a significant effect on operability in the 22nd licensing area in the Barents Sea: operations are impaired by metocean influences up to 80% of the time in January in the harshest parts of our study area. Similar values were found in the North Sea, but underlying causes differ. The influence of wind and waves decreases when moving further North and East in the Barents Sea, while icing and low temperatures form additional underlying causes of inoperability in the Arctic. Data was found insufficiently available to assess the influence of sea ice, poor visibility and non-metocean factors on offshore offloading operability. Together with operating limits for Arctic operating conditions, these topics require more data collection and further research.

Resilience to disruptions in upstream logistics operations is generally regarded as lower in the Arctic compared to more established areas. Strategic assessment of disruption risks provides insights to better understand and reduce operational vulnerability, especially in frontier areas. The operability gap analysis presented in this paper provides a preliminary quantitiave assessment of one of the major sources of disruptions in offshore upstream logistics: adverse weather during offloading. More empirical work in close cooperation with Arctic logistics operators is needed to further develop and implement disruption risk assessment methods.

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