University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore Technology Marine and Subsea Technology	Spring semester, 2012 Open access
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Titel of thesis:

Alpha factors for the calculation of forecasted operational limits for marine operations in the Barents Sea

Credits (ECTS): 30

Key words: Alpha factor Weather forecast uncertainty Polar low Marine operation Barents Sea	Pages: 59 + enclosure: 7 Stavanger, 19.06.2012

ABSTRACT

The execution of marine operations often depends on the wave heights being low enough for safe operations. This needs to be the case for the time the operation takes. Weather forecasts are used to predict the wave heights. Uncertainties are connected to weather forecasts and higher wave heights than expected during a marine operation can potentially lead to accidents. Thus Det Norske Veritas introduced the so called “alpha factors” for the North and Norwegian Sea in its standard for Marine Operations ([1], [18]). Alpha factors downgrade the operational wave height limit to a forecasted operational wave height limit to take care of the weather forecast uncertainty in these areas.

This thesis explains the calculation as well as the use of the alpha factor. Comparisons to how other standards and guidelines treat the weather forecast uncertainty are drawn. Due to potentially more marine operations in the Barents Sea in the near future it is discussed how to take care of the weather forecast uncertainty in this region. Alpha factors for the Barents Sea are calculated. They indicate that the weather forecast uncertainty is bigger in the Barents Sea than further south.

The small scale storms that are characteristic to Polar Regions called “polar lows” are described: These are threats to marine operations in the Barents Sea. Alpha factors are not sufficient to take care of the forecast uncertainty connected to polar lows. Thus the suggestion is made that the polar low probability forecast should be a requirement for the execution of marine operations in the Barents Sea.

ZUSAMMENFASSUNG

Die sichere Durchführung von „Marine Operations“ hängt meist davon ab, dass die Wellenhöhe niedrig genug ist. Dies muss für den Zeitraum, den die „Marine Operation“ dauert, gegeben sein. Zur Vorhersage der Wellenhöhen werden Wettervorhersagen genutzt. Diese sind jedoch zu einem gewissen Grad ungenau und höhere Wellen als erwartet können während einer „Marine Operation“ zu Unfällen führen. Aus diesem Grund hat „Det Norske Veritas“ so genannte „Alpha Faktoren“ für die Nordsee und die Norwegische See in den Standards für „Marine Operations“ ([1], [18]) eingeführt. „Alpha Faktoren“ reduzieren die maximale Wellenhöhe, bei der eine „Marine Operation“ durchgeführt werden kann, zu einer maximal vorhergesagten Wellenhöhe.

Diese Masterarbeit erklärt die Berechnung sowie die Anwendung von „Alpha Faktoren“. Vergleiche zu anderen Standards und Richtlinien werden im Bezug darauf gezogen, wie diese mit der Unsicherheit in der Wettervorhersage umgehen. Aufgrund von potenziell mehr „Marine Operations“ in der Barentssee in naher Zukunft wird diskutiert, wie in dieser Region mit der Unsicherheit der Wettervorhersage umgegangen werden kann. „Alpha Faktoren“ für die Barentssee werden berechnet. Diese deuten darauf hin, dass die Unsicherheit in der Wettervorhersage in der Barentssee größer ist als in der Nordsee und der Norwegischen See.

Die so genannten „Polaren Tiefdruckgebiete“ werden beschrieben. Sie sind kleine Stürme und charakteristisch für arktische Gebiete. Für „Marine Operations“ in der Barentssee sind sie eine Gefahr. „Alpha Faktoren“ sind nicht ausreichend, um das Risiko, dass mit der Vorhersageunsicherheit durch „Polare Tiefdruckgebiete“ verbunden ist, zu mindern. Aus diesem Grund wird die Empfehlung gegeben, Wahrscheinlichkeitsvorhersagen für „Polare Tiefdruckgebiete“ für „Marine Operations“ in der Barentssee verpflichtend zu machen.

ACKNOWLEDGEMENT

Special thanks go to my supervisor at the University of Stavanger, Dr Ove Tobias Gudmestad, for his guidance and encouragement in spite of tight schedules.

I like to thank my external supervisor from Det Norske Veritas, Florus Korbijn, for giving me the opportunity to write this thesis with the support from DNV. I also thank him for answering so patiently all the questions that came up.

Thanks go to Dr Gunnar Noer from the Norwegian Meteorological Institute for giving me advice regarding polar lows and for providing me with measured wave heights.

I also like to thank Einar Nygaard from Statoil and Siri Kalvig and Knut Lisæter from StormGeo for providing me with measured and forecasted wave height data.

Finally special thanks go to my wife, Anja Wilcken, for sharing my dream of moving to Norway and all the love and moral support she gave me throughout the two years of the course. She made it possible for me to complete this Master's programme.

Sara Wilcken

Stavanger, June 2012

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$\bar{d}$	mean duration of sea states with the wave height below OP_{WF}
DNMI	Det Norske Meteorologiske Institutt
DNV	Det Norske Veritas
ECMWF	European Centre for Medium-Range Weather Forecasts
F(H)	cumulative probability distribution of wave height
H	wave height
H_{error}	deviation between forecasted and observed significant wave height (error value)
$\overline{H}_{error}$	mean error value
$H_{forecast}$	forecasted significant wave height
$H_{highest}$	highest wave height
H_{max}	maximum wave height for fixed forecasted significant wave height
H_{max_WF}	maximum wave height taking into account uncertainty in weather forecast
$H_{observed}$	measured significant wave height
H_{rms}	root-mean-square of all measured wave heights
H_S	significant wave height
$H_{S,C}$	characteristic significant wave height, significant wave height with defined probability of exceedance
H_{S_F}	forecasted significant wave height
JIP	Joint Industry Project
LOC	London Offshore Consultants
m	number of events with a wave height that is lower than the operational criterion

m_0	zero order moment of wave spectrum
MWS	Marine Warranty Surveyor
n	number of waves
OP_{LIM}	operational environmental limit criterion
OP_{WF}	forecasted operational criterion
P( )	cumulative probability distribution
$p(H,H_S)$	joint probability density function of the wave height H and the significant wave height H_S
$P(H_{highest} \leq H)$	cumulative probability distribution of highest wave height
$p(H_S)$	probability density function of the significant wave height H_S
$p(H \mid H_S)$	conditional probability density function of the wave height H
P_{not}	probability of not completing the operation in the first m events
T_C	estimated contingency time
t_F	forecasting period
T_P	peak wave period
T_{POP}	planned operation period
T_R	reference period – duration of marine operation
T_Z	zero up-crossing wave period
α	α-factor
γ	peakness parameter for Jonswap wave spectrum (peak enhancement factor)
σ	standard deviation

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1. INTRODUCTION

This thesis is dedicated to the development of “alpha factors” for waves for the Barents Sea. Alpha factors are used to take care of the uncertainties in the weather forecast when planning a marine operation. Marine operations can be of various types, e.g.:

- Subsea pipeline installation
- Transportation of heavy/big objects (e.g. transportation of jacket structure on barge, towing of concrete platform
- Lifting operations (e.g. lifting of subsea equipment to the sea bottom, lifting of topside structure onto jacket structure, lifting of wind turbine parts onto each other)
- Mooring operation (e.g. to moor a production platform in its position)
- Well intervention activities with specialized vessels

The time needed for a marine operation can be from hours to months. They are often performed due to the demands of infrastructure for the offshore oil and gas industry. In the near future more activities related to the oil and gas industry will be going on in arctic regions. Among other countries also Norway is searching for oil and gas in arctic regions on its continental shelf. Recently some discoveries have been made in the Barents Sea (see Figure 1). There will possibly be even more discoveries now that Russia and Norway have agreed on a boarder line in this region (see Figure 2). That also means that there will be a need for a lot of marine operations.

Marine operations are mostly sensitive to waves and wind. The weather conditions in the Barents Sea can be harsh and quite unstable. Depending on the length of a marine operation it can be planned as a weather restricted or unrestricted operation. If the operation has to be planned as an unrestricted operation it will usually be much more costly to perform it because big vessels that can cope with all except extreme weather conditions have to be used. An operation can only be planned as a weather restricted operation if the time needed is not more than a couple of days because that is the range for a reliable weather forecast.

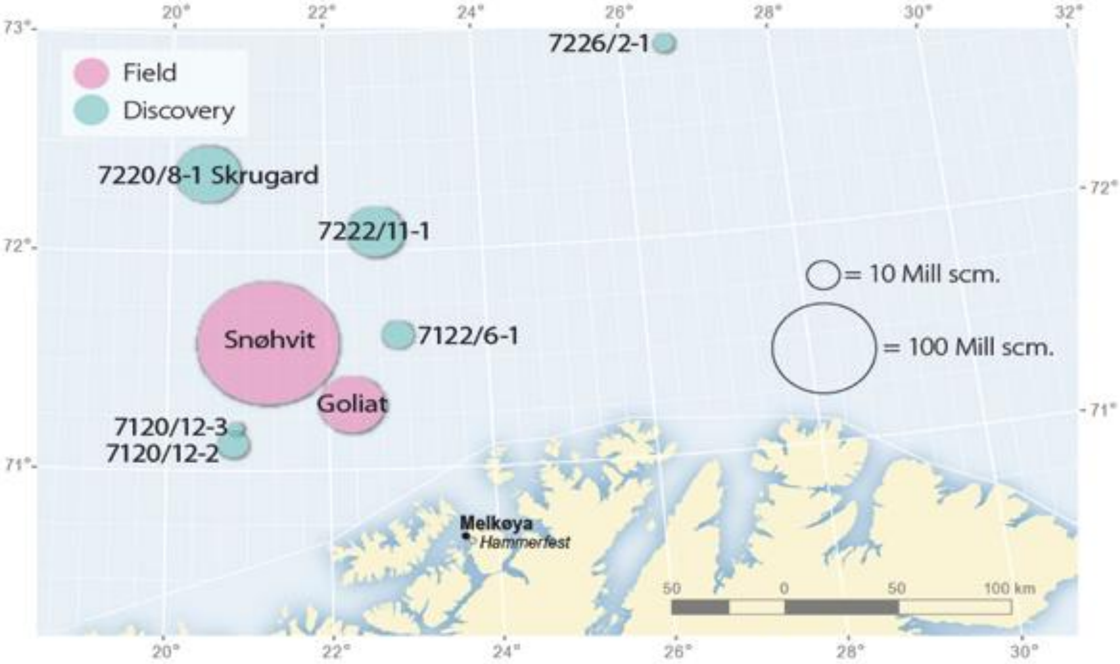


Figure 1: Fields and discoveries in the Norwegian sector of the Barents Sea. The size of the circle indicates the total remaining resource volume. [2]

Figure 2: New boarder line in the Barents Sea [3]

Weather forecasts are usually produced by numerical models and then the forecaster fine-tunes it. There are uncertainties connected to the weather forecast. Models try to present reality with formulas and this does not work perfectly. Furthermore models rely on the input data which are measurements of the conditions in the atmosphere. These measurements are also flawed. Even if the errors are small they become bigger the further into the future the forecast reaches. That is because each forecast time step uses the output data of the previous time step as input data and thus the error becomes bigger and bigger. For wave forecasts which are the most important forecasts for marine operations, the uncertainties are possibly even bigger than the uncertainties connected to the forecast of atmospheric conditions. That is the case because the output of the numerical model for the atmosphere, namely the wind, is used as input to another numerical model for predicting wave conditions.

For a marine operation the consequences of weather conditions that are worse than predicted can reach from monetary loss to catastrophes with loss of lives and environmental pollution. Thus alpha factors were developed to account for the uncertainties in the weather forecast. The operational wave height limit is reduced by the alpha factor to a forecasted wave height limit. For the operation to be executed the weather forecast for the time needed has to be below the calculated forecast wave height limit. Alpha factors are basically calculated by comparing the actual wave height with the forecasted wave height. They were first developed in a joint study by DNMI (Det Norske Meteorologiske Institutt) and DNV (Det Norske Veritas) in 1996. In 2005 a Joint Industry Project was started to review the alpha factors. The results were implemented in DNV’s standard for Marine Operations [1].

Generally it is important to have alpha factors that are neither too low nor too high. If the alpha factors are too high the uncertainties are not considered properly and the risk of problems and a catastrophe during an operation becomes too high. If the alpha factors are too low, it will be difficult to find a weather window with sufficiently low wave heights. The costs for a marine operation will rise drastically. That is because a lot of waiting on weather might be necessary in order to find a weather window that is long enough, alternatively costly, big vessels that can cope with bigger waves are needed.

The alpha factors in the Marine Operations standard [1] apply to the North Sea and the Norwegian Sea. It is possible that the error in the weather forecast is worse further north because "the mobility of weather systems is generally greater in the north, leading to somewhat larger errors due to the difficulties which the models sometimes experience in specifying the intensity and rapidity of developments" [30]. Beside this, another problem is that observation stations which provide measurements as input to the numerical forecast models are relatively scarce on the ocean anyway but even more in the Barents Sea. Furthermore polar lows develop in these waters relatively often during the winter season. These weather systems are small in scale and can be severe. They are difficult to predict and thus have to be considered carefully when planning a marine operation.

Taking into account these difficulties connected to weather forecasting that are specific to arctic regions like the Barents Sea, it becomes clear that the uncertainties in the weather forecast need to be evaluated for this region. As mentioned there will be more marine operations in the Barents Sea in the near future and therefore it is necessary to check whether the existing alpha factors for the North Sea and the Norwegian Sea are sufficient also for the Barents Sea. Even if they are sufficient still suggestions are needed on how to deal with the scare of polar lows in the winter season.

This thesis explains in detail how the alpha factor is used for the planning of marine operations according to DNV's Marine Operations standard [1]. Comparisons are drawn to how other standards and guidelines for marine operations deal with the uncertainties connected to the weather forecast. The weather phenomenon of polar lows is explained as it poses a huge threat to marine operations in the Barents Sea. Furthermore the Joint Industry Project that developed the new alpha factors for the North Sea and the Norwegian Sea in 2005 is presented with a detailed explanation on how the calculations of the alpha factors were done. Finally alpha factors for the Barents Sea are calculated and recommendations are given on how to treat the weather forecast uncertainty for marine operations in the Barents Sea.

2. STATE OF THE ART

2.1. Marine operations – The Alpha Factor and operational issues according to DNV-OS-H101 [1]

In this chapter considerations for marine operations with respect to the weather in general are presented as they are given in Section 4 of the DNV-OS-H101 [1].

2.1.1. Weather restricted or unrestricted operations?

A difference between “weather restricted” and “unrestricted” operations is how the design and operation criteria are selected. The design criteria are “The criteria applied for verification of systems, equipment, structures etc. for the planned marine operation.” [1]. The ***environmental design criteria*** can be described as the environmental conditions (wave height, wave period, wind speed etc.) that the systems, equipment, structures etc. have to be able to cope with under adverse emergency conditions. The ***operational environmental limit criterion*** is the criterion that defines the maximum environmental conditions under which an operation can be carried out.

For ***weather unrestricted operations*** the environmental criteria are based on extreme value statistics. That is because the operation is supposed to be done in all weather conditions except in extreme conditions, thus the design and the operation have to be done in a way that all non extreme conditions are acceptable. In the case of ***weather restricted operations*** the environmental criteria are selected by people (i.e. the owner) based on different considerations, for example the limits set by the insurance, waiting time for suitable weather and thus costs.

The ***operational environmental limit criterion*** (OP_{LIM}) for both types of operations does not only depend on the environmental design criteria: According to the DNV Offshore Standard [1] “The OP_{LIM} shall not be taken greater than the minimum of:

- The environmental design criteria. See Sec.3 B300 and Sec.3 C300.
- Maximum wind and waves for safe working- (e.g. at vessel deck) or transfer conditions for personnel.
- Equipment (e.g. ROV and cranes) specified weather restrictions.
- Limiting weather conditions of diving system (if any).
- Limiting conditions for position keeping systems.
- Any limitations identified, e.g. in HAZID/HAZOP, based on operational experience with involved vessel(s), equipment, etc.
- Limiting weather conditions for carrying out identified contingency plans.” [1]

Whether a marine operation is regarded as weather restricted or unrestricted depends on the time needed for the operation. The duration of a marine operation is called the reference period T_R.

$$T_R = T_{POP} + T_C \quad (1)$$

T_{POP}, the planned operation period is the sum of the time that is expected to be needed for the operation and the time between the issuance of the last weather forecast and the start of the operation. The contingency time T_C is supposed to cover uncertainties in the assessment of T_{POP} and other possible problems that might occur according to a risk analysis. If this is not assessed in detail T_R should be as least two times T_{POP}. That means that T_C increases if T_{POP} increases. The weather window that is required for an operation is the time from the start of the operation till the end of the contingency time (see Figure 3).

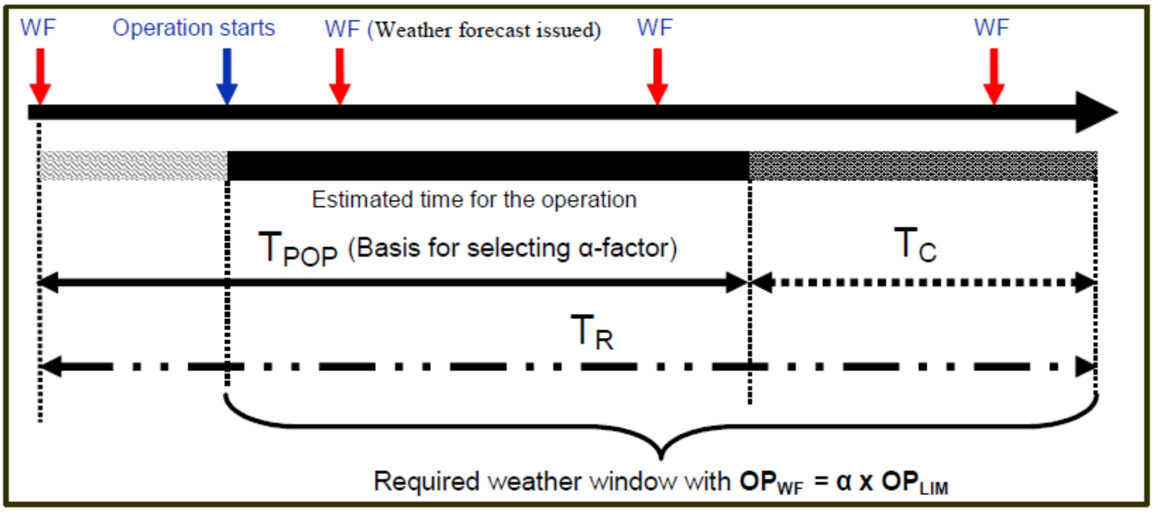


Figure 3: Operation Periods [1]

An operation can only be regarded as weather restricted if the reference period, T_R, is less than 96 hours and the planned operation period, T_{POP}, is less than 72 hours. DNV regards this as the maximum period for a sufficiently reliable weather forecast, but it is also stated that these periods should be reduced in case of areas or seasons in which the weather forecast is too unreliable for predictions far ahead.

In case it is possible to halt an operation by bringing the handled object into a safe condition within the same reference period and planned operation period as mentioned above, the operation can also be defined as weather restricted. In order to be able to do that, it is necessary to monitor the weather forecast and the actual weather throughout the operation. Figure 4 illustrates how to categorize the operation.

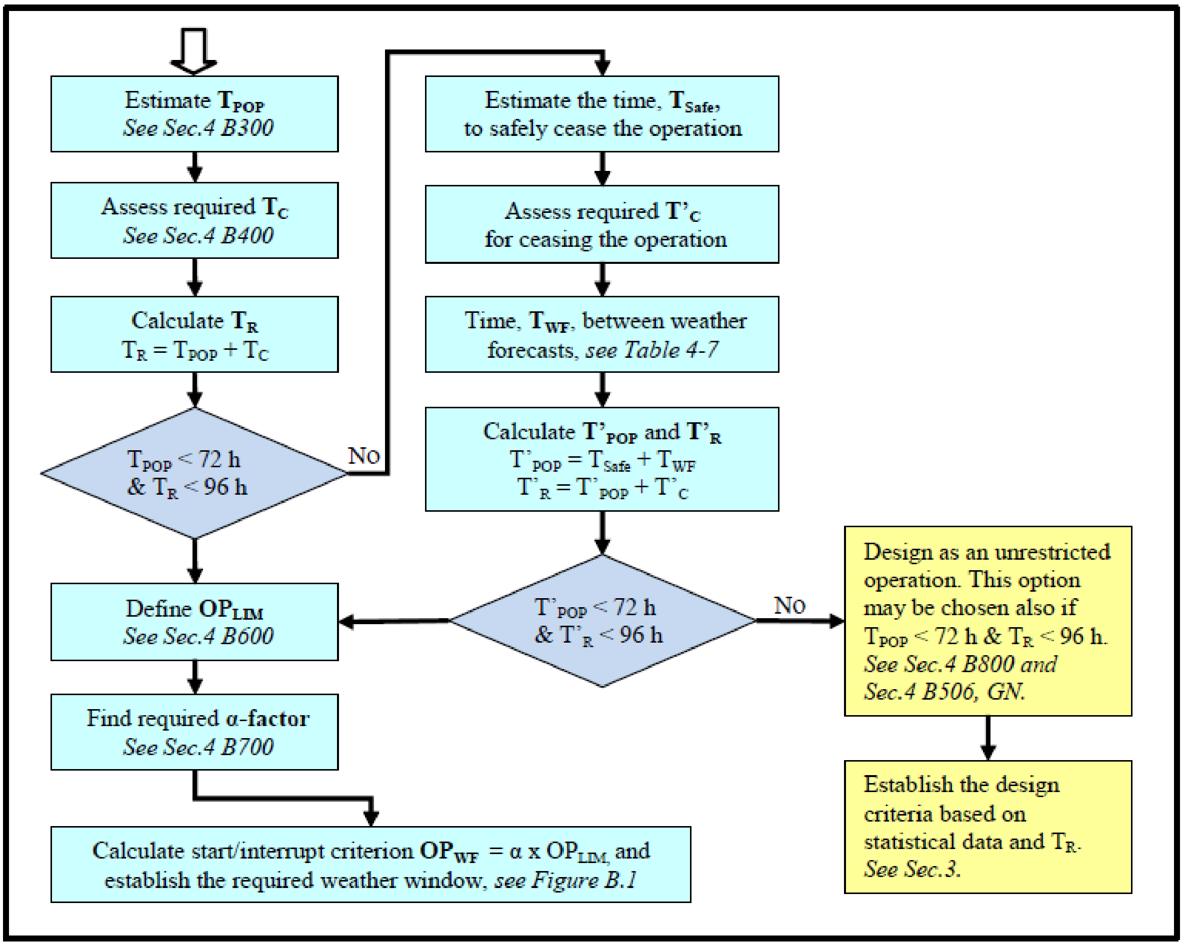


Figure 4: Restricted or unrestricted operation [1]

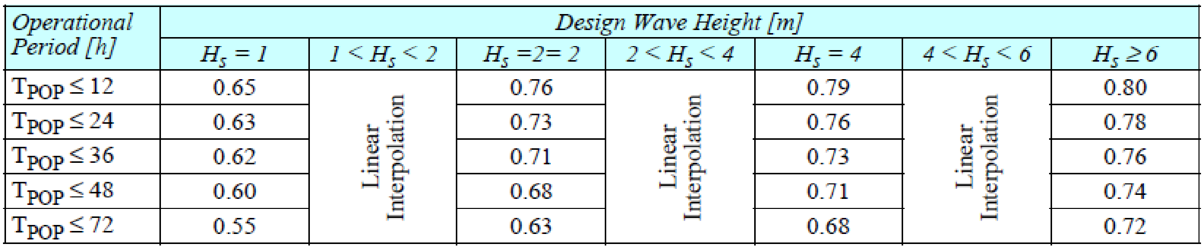
2.1.2. Operational limits for weather restricted operations

It is possible to monitor and to forecast the weather but both monitoring and forecasting are connected with uncertainties. The weather forecast is uncertain because the weather is so complex that meteorologists are not able to predict with 100% certainty how the weather will develop, not even in the near future. Therefore a forecasted operational criterion OP_{WF} is used.

$$OP_{WF} = \alpha \times OP_{LIM} \qquad (2)$$

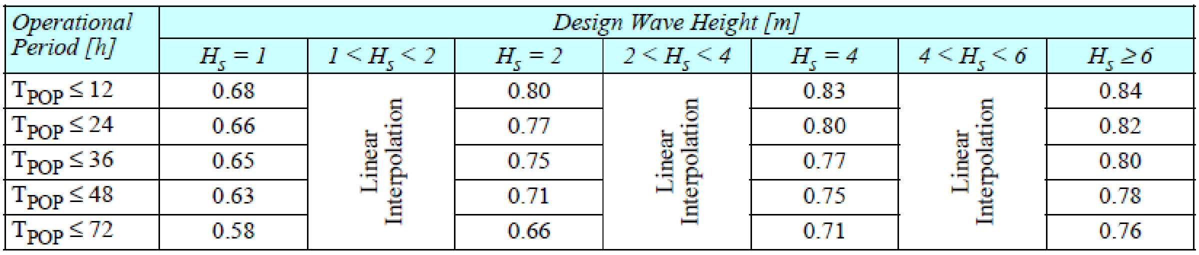
The operational environmental limit criterion (OP_{LIM}) is reduced by the "alpha factor". The alpha factor accounts for the uncertainties connected to the weather. In the DNV Offshore Standard [1] alpha factors for the North Sea and the Norwegian Sea are tabulated for wind and waves. For both, the alpha factor depends on the planned operation period and the design wind speed or the design wave height, respectively, as they are called in the DNV Offshore Standard. The design values are the operational limit criteria OP_{LIM} that were decided on. The alpha factor depends on the design wind speed and wave height because for lower wind regimes and wave heights the wind speed and wave height forecast is connected to even bigger uncertainties. For waves the alpha factor is tabulated for different weather forecast scenarios because it can be increased in case a meteorologist is on site, two independent weather forecasts are used or/and the weather is monitored (there is less weather forecast uncertainty in these cases) (see Tables 1 to 5).

Table 1: North Sea and Norwegian Sea alpha factor for waves; no meteorologist on site, one forecast source [1]



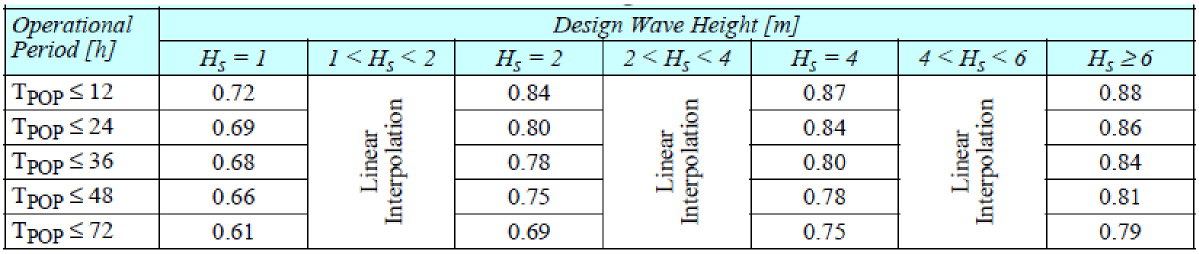
Operational Period [h]	*Design Wave Height [m]*						
	$H_S = 1$	$1 < H_S < 2$	H_S =2= 2	$2 < H_S < 4$	$H_S = 4$	$4 < H_S < 6$	$H_S \geq 6$
$T_{POP} \leq 12$	0.65	Linear Interpolation	0.76	Linear Interpolation	0.79	Linear Interpolation	0.80
$T_{POP} \leq 24$	0.63		0.73		0.76		0.78
$T_{POP} \leq 36$	0.62		0.71		0.73		0.76
$T_{POP} \leq 48$	0.60		0.68		0.71		0.74
$T_{POP} \leq 72$	0.55		0.63		0.68		0.72

Table 2: North Sea and Norwegian Sea alpha factors for waves; no meteorologist on site, highest forecasted wave height from at least two independent sources is considered [1]



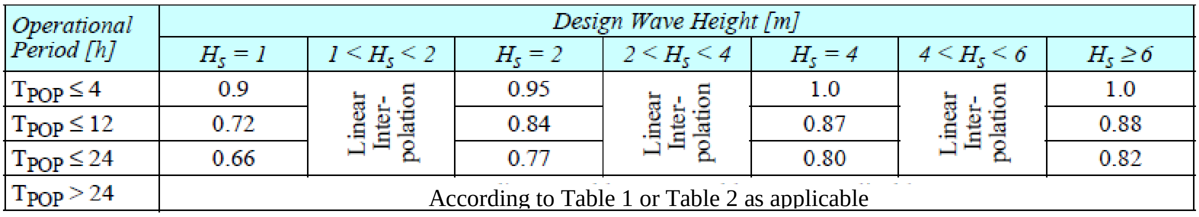
Operational Period [h]	*Design Wave Height [m]*						
	$H_S = 1$	$1 < H_S < 2$	$H_S = 2$	$2 < H_S < 4$	$H_S = 4$	$4 < H_S < 6$	$H_S \geq 6$
$T_{POP} \leq 12$	0.68	Linear Interpolation	0.80	Linear Interpolation	0.83	Linear Interpolation	0.84
$T_{POP} \leq 24$	0.66		0.77		0.80		0.82
$T_{POP} \leq 36$	0.65		0.75		0.77		0.80
$T_{POP} \leq 48$	0.63		0.71		0.75		0.78
$T_{POP} \leq 72$	0.58		0.66		0.71		0.76

Table 3: North Sea and Norwegian Sea alpha factors for waves; meteorologist on site, several forecast sources are considered by meteorologist [1]



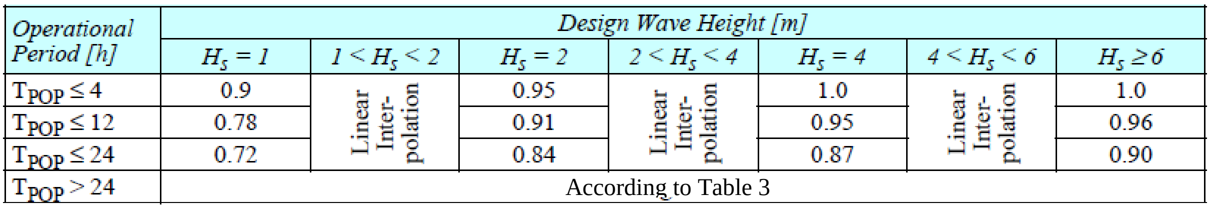
Operational Period [h]	*Design Wave Height [m]*						
	$H_S = 1$	$1 < H_S < 2$	$H_S = 2$	$2 < H_S < 4$	$H_S = 4$	$4 < H_S < 6$	$H_S \geq 6$
$T_{POP} \leq 12$	0.72	Linear Interpolation	0.84	Linear Interpolation	0.87	Linear Interpolation	0.88
$T_{POP} \leq 24$	0.69		0.80		0.84		0.86
$T_{POP} \leq 36$	0.68		0.78		0.80		0.84
$T_{POP} \leq 48$	0.66		0.75		0.78		0.81
$T_{POP} \leq 72$	0.61		0.69		0.75		0.79

Table 4: North Sea and Norwegian Sea alpha factors for waves; weather forecast calibrated based on monitoring of the weather [1]



Operational Period [h]	*Design Wave Height [m]*						
	$H_S = 1$	$1 < H_S < 2$	$H_S = 2$	$2 < H_S < 4$	$H_S = 4$	$4 < H_S < 6$	$H_S \geq 6$
$T_{POP} \leq 4$	0.9	Linear Inter-polation	0.95	Linear Inter-polation	1.0	Linear Inter-polation	1.0
$T_{POP} \leq 12$	0.72		0.84		0.87		0.88
$T_{POP} \leq 24$	0.66		0.77		0.80		0.82
$T_{POP} > 24$	According to Table 1 or Table 2 as applicable						

Table 5: North Sea and Norwegian Sea alpha factors for waves; meteorologist on site, monitoring of weather [1]



Operational Period [h]	*Design Wave Height [m]*						
	$H_S = 1$	$1 < H_S < 2$	$H_S = 2$	$2 < H_S < 4$	$H_S = 4$	$4 < H_S < 6$	$H_S \geq 6$
$T_{POP} \leq 4$	0.9	Linear Inter-polation	0.95	Linear Inter-polation	1.0	Linear Inter-polation	1.0
$T_{POP} \leq 12$	0.78		0.91		0.95		0.96
$T_{POP} \leq 24$	0.72		0.84		0.87		0.90
$T_{POP} > 24$	According to Table 3						

2.2. Consideration of weather forecast uncertainty for weather restricted marine operations in various standards and guidelines compared to DNV's approach

A literature review of various standards and guidelines shows that the uncertainty in the weather forecast is considered in most marine operations guidelines and standards but not as thoroughly as in the marine operations standard from DNV [1]. Guidelines and standards reviewed are:

- ISO 19901-6, Marine operations [4]
- LOC, Guidelines for Marine Operations [5]
- Various GL Noble Denton guidelines, reference [6] to [12]
- BWEA, Guidelines for the Selection and Operation of Jack-ups in the Marine Renewable Energy Industry [13]

As described in section 2.1 the forecast uncertainty in DNV's marine operations standard is considered in two ways: On the one hand a contingency time is added to the time the operation takes and on the other hand the alpha factor is used to account for the uncertainty in the forecasted values of the weather condition.

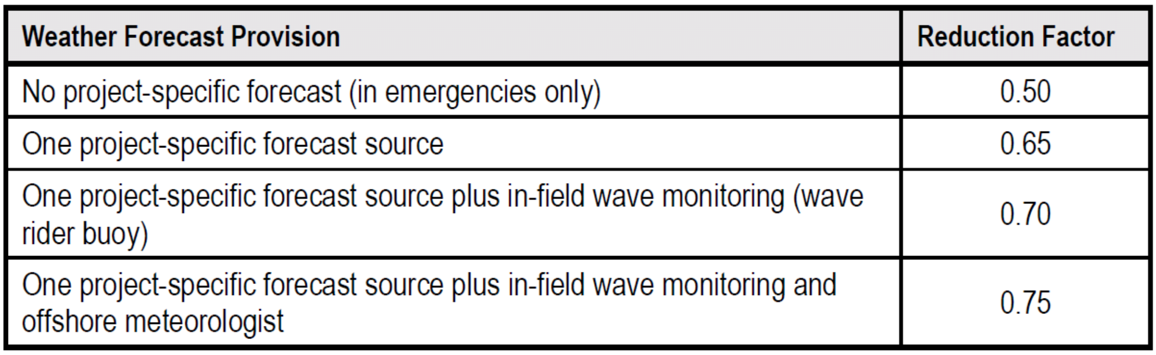
The contingency time can make up for inaccuracies in timing of the weather forecast. It is the extra time that is added to the time the operation is planned to take in order to account for uncertainties. The time the operation is planned to take plus the contingency time represents the minimum forecasted weather window. All of the above mentioned guidelines and standards make use of contingency time. GL Noble Denton writes for example: "When defining the weather window required for a time-critical marine operation the schedule should be as realistic as possible. The window duration should include contingencies for: .... Inaccuracy in the timing and length of window predicted by the metocean forecast." [7]. In the ISO standard it says: "The forecast window duration shall be in excess of the total critical operational schedule. This should be evaluated against a background of the planned operation and the consequences of exceedance. As a guideline, the following points should be considered: ... – extra allowance for operations in geographical areas and/or seasons where conditions are difficult to predict.” [4].

The uncertainties in the forecasted values of the physical environment are considered to a variable degree in the various rules and standards. All of them do at least mention that there is an uncertainty in the weather forecast and that it needs to be taken into account. LOC (London Offshore Consultants) wrote in the paragraph about towing steel jackets: “For tows to offshore locations, the MWS normally recommend that the tow be designed to withstand the seasonal 10 year return period extreme environmental condition. The rational for this is that, although the planned tow duration may be within the duration of a reliable forecast (i.e. in the range of 24 to 48 hours), delays may occur offshore due to any of the following: ... – Weather deterioration, despite previous good forecasts.” [5] (MWS: Marine Warranty Surveyor). This is a relatively strict approach because although the operation could be regarded as weather restricted, still the design is done for a weather unrestricted operation with extreme values for environmental conditions. Generally the approach of the LOC is a different one. Depending on the kind of operation they usually simply indicate the maximum forecasted wind speed for the necessary weather window, see for example [5] page 7 and 92.

The ISO standard gives a quite general statement with respect to uncertainties connected to weather forecasts but has basically the same approach as DNV, namely reducing the limiting criteria: “Consideration shall be given to applying a reduction factor to the limiting criteria in order to account for remaining uncertainties. The reduction factor should be determined as a function of the duration of the operation, the number of data sources and the quality of the available data.” [4]. The BWEA guidelines for jack-ups [13] also follow this approach for jack-ups that are afloat: “The operating criteria shall be set lower than the design criteria to allow for potential inaccuracy in wave height forecasts. Typically weather restricted towages should not commence in seastates greater than 50% of the design maximum as the observer will often report the significant wave heights rather than the maximum wave height.” [13].

GL Noble Denton sets the operational criteria lower than the design criteria just like DNV, BWEA and ISO: ”To undertake any operation, the “operational criteria” shall be less than the “design criteria”. The margin is a matter of judgement, dependent on factors specific to each case, ...” [12]. GL Noble Denton and DNV both reduce the design seastate to a forecasted seastate by using tabulated factors. Table 6 shows GL Noble Denton’s reduction factors. Comparing that to DNV’s factors (Table 1 to Table 5) shows that DNV’s standard is in this respect much more detailed and complete. GL Noble Denton’s factors are not subdivided into wave heights, are only tabulated for a maximum operational duration of 24 hours and are not specific to an area. It seems that they are rather based on judgement than on data analysis, as it is the case for DNV’s factors.

Table 6: Seastate Reduction Factors for 24 hour Operational Duration, ref. GL Noble Denton [12]



Weather Forecast Provision	Reduction Factor
No project-specific forecast (in emergencies only)	0.50
One project-specific forecast source	0.65
One project-specific forecast source plus in-field wave monitoring (wave rider buoy)	0.70
One project-specific forecast source plus in-field wave monitoring and offshore meteorologist	0.75

The reduction factor 0.70 “One project-specific forecast source plus in-field wave monitoring (wave rider buoy)” from Table 6 can be compared to DNV’s factors for an operational period of 24 hours from Table 4. The factor 0.65 “One project-specific forecast source” from Table 6 can be compared to DNV’s factors for an operational period of 24 hours from Table 1. GL Noble Denton’s factors are lower than DNV’s factors except the one for one meter design wave height. This will result in different waiting on weather times, costs and probabilities to get the operation done. Thus care should be taken when deciding which standard to follow.

The following case study will demonstrate what impact the difference between DNV’s and GL Noble Denton’s factors can have on the probability of conducting an operation. The wave data used for this case study are from the oil and gas field Åsgard (see Appendix 1). Åsgard is located in the Norwegian Sea.

It is assumed that the planned operation period T_{POP} is 24 hours and the reference period T_R is 48 hours. The design wave height is a significant wave height of 4m. No meteorologist is on site and only one weather forecast source is used. From Table 1 it can be recognized that for this case an alpha factor of 0.76 is recommended by DNV. This results in a forecasted operational criterion OP_{WF} of around 3m. GL Noble Denton recommends a factor of 0.65 (see Table 6). This results in a forecasted operational criterion OP_{WF} of 2.6 m.

The duration of a given event may be described by a Weibull distribution.

$$P\left(d < T_R \middle| H < OP_{WF}\right) = 1 - \exp\left[-\left(\frac{T_R}{\delta}\right)^{\beta}\right];\ T_R \geq 0 \qquad (3)$$

If it is assumed that $\beta=1$ and δ is estimated with $\bar{d}$, then the probability that the period is less than the period T_R, given that the wave height is less than the wave height of the operational criteria, becomes [14]:

$$P\left(d < T_R \middle| H < OP_{WF}\right) = 1 - \exp\left[-\left(\frac{T_R}{\bar{d}}\right)\right];\ T_R \geq 0 \qquad (4)$$

d	duration of a sea state with the wave height below OP_{WF}
T_R	reference period - duration of marine operation
H	wave height
OP_{WF}	forecasted operational criteria
$\bar{d}$	mean duration of sea states with the wave height below OP_{WF}
m	number of events with a wave height that is lower than the operational criterion
P_{not}	probability of not completing the operation in the first m events

If m is chosen to be the number of events in one month, then P_{not} is the probability of not completing the operation within that month [14].

$$\left(P\left(d < T_R \middle| H < OP_{WF}\right)\right)^m = P_{not} \qquad (5)$$

For this case study it is assumed that $\bar{d}$ and m can be evaluated by linear interpolation in the interval 2 to 3m from Appendix 1.

Tables 7 and 8 show the probabilities of **not completing** the operation within each month of the year for this case study. Table 7 shows the probabilities in the case of an alpha factor of 0.65 and a consequential operational criterion of 2.6m wave height and Table 8 shows the probabilities in the case of an alpha factor of 0.76 and a consequential operational criterion of 3m wave height.

Table 7: Probability of not conducting the operation for a factor of 0.65 and a forecasted operational criterion of 2.6m wave height

Month	$\bar{d}$ [hours] (Appendix 1)	m (Appendix 1)	Probability that a period of suitable weather is less than 48 hours	P_{not}
Jan	60.6	4.4	0.55	0.07
Feb	66	4.4	0.52	0.06
Mar	81	4.7	0.45	0.02
Apr	121.2	4.8	0.33	0.00
May	214.4	4.2	0.20	0.00
Jun	270.4	3.7	0.16	0.00
Jul	325	3.3	0.14	0.00
Aug	248.6	3.3	0.18	0.00
Sep	104	4.9	0.37	0.01
Oct	65.8	5.2	0.52	0.03
Nov	53	5.2	0.60	0.07
Dez	50	4.6	0.62	0.11

Table 8: Probabilities of not conducting the operation for a factor of 0.76 and a forecasted operational criterion of 3m wave height

Month	$\bar{d}$ [hours] (Appendix 1)	m (Appendix 1)	Probability that a period of suitable weather is less than 48 hours	P_{not}
Jan	73	5.1	0.48	0.02
Feb	80	4.7	0.45	0.02
Mar	99	5.1	0.38	0.01
Apr	156	4.7	0.26	0.00
May	288	3.5	0.15	0.00
Jun	376	2.9	0.12	0.00
Jul	451	2.4	0.10	0.00
Aug	327	2.5	0.14	0.01
Sep	126	4.9	0.32	0.00
Oct	75	5.9	0.47	0.01
Nov	63	6.0	0.53	0.02
Dez	58	5.6	0.56	0.04

By comparing the probabilities of not completing the operation within a specific month, it becomes obvious that the differences between the two factors are not significant during summer but can be significant during the winter season. The difference in the forecasted operational criterion is just 0.4m but that small difference leads to a difference of around 5% in completing a marine operation during one month in the time period from November to February. Still the probabilities of not completing the operation are relatively small but they have to be seen in light of the fact that in this case study it was assumed that the weather forecast actually does predict the period of suitable weather correctly. That is not necessarily the case and therefore the probabilities of completing the operation will be even lower. Furthermore other parameters like the actual wave period might also be of importance in order not to get into resonance between the construction vessel and the waves. That will decrease the probability of completing an operation even further.

GL Noble Denton’s sea state reduction factors might be a little too conservative for the North Sea and the Norwegian Sea and this case study shows that this can have a significant influence on conducting an operation especially during winter. DNV’s factors are based on data and for conducting an operation in the North Sea or Norwegian Sea they are probably more appropriate. GL Noble Denton’s factors could lead to unnecessary high costs due to waiting on weather.

3. POLAR LOWS – CHALLENGES IN THE BARENTS SEA

The weather in arctic regions like in the Barents Sea can change rapidly. Strong storms develop quickly. These events are mesoscale weather events. That means their horizontal length scale is less than 1000 km. Their intensity can be from insignificant vortices (leading to no surface winds) to severe storms with winds up to hurricane force [19]. The more severe storms are called ***polar lows***. Meteorologists did not yet agree on a common definition of polar lows but the general definition given by Rasmussen and Turner describes the main features:

> “A polar low is a small, but fairly intense maritime cyclone that forms poleward of the main baroclinic zone (the polar front or other major baroclinic zone). The horizontal scale of the polar low is approximately between 200 and 1000 kilometres and surface winds near or above gale force.” [19]

One reason that meteorologists were not able to find a common definition yet is that there are different forcing mechanisms that can lead to a polar low. The relative importance of these forcing mechanisms leads to a “spectrum” of mesoscale cyclones including purely baroclinic and purely “convective” systems [19]. The term “polar low” is in this section just like in the meteorological community [19] used for the whole range of mesoscale systems. In general polar lows develop in areas where big temperature differences between water and air are present. That is the case for the Barents Sea. Figure 5 shows the extent of the sea ice in the Barents Sea. Dark blue represents ocean without ice cover and the two brighter blue areas the ice cover in March and September respectively. In Figure 6 the currents in the Barents Sea region are shown. Red represents warm water and blue cold water. Warm water from the Carribbean is transported along the Norwegian coast into the Barents Sea. The sea ice isolates the relatively warm ocean from the atmosphere very well, thus the air masses above can cool down. In case of a cold air outbreak (see Figure 7) the cold air flows southward over the warm sea which can then lead to polar lows due to strong convection, for example. However, as noted earlier other forcing mechanisms can also lead to polar low developments [19].

Figure 5: Sea ice coverage in Nordic Seas in March and September [20]

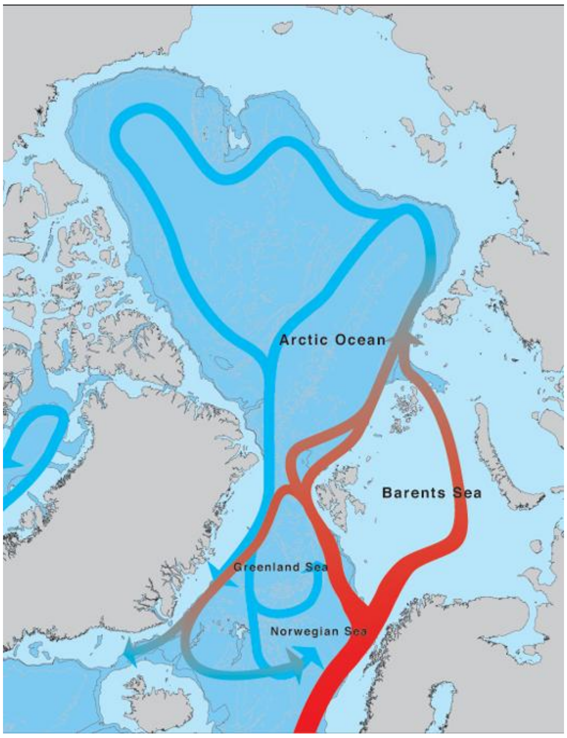


Figure 6: North Atlantic and Arctic currents [21]

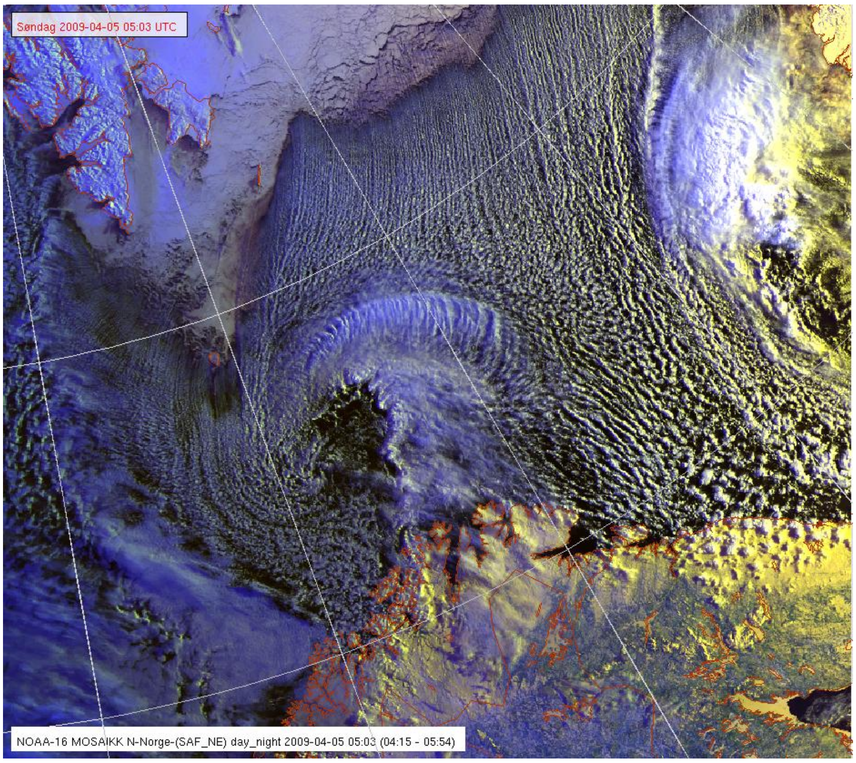


Figure 7: Cold air outbreak from the ice edge between Svalbard and Novaja Semlja with a polar low in the middle of the picture, in the Barents Sea [22]. Picture: NOAA/met.no

Polar Lows are often unexpected as they are difficult to forecast. They last on average only a day or two and they can lead to severe weather with strong winds, showers and occasionally heavy snow and relatively big waves [19]. If a polar low would be stationary the wave height that could develop would be quite limited due to a limited fetch length and also a quite short duration of the low. Due to the fact that they do move, also big waves can develop. These develop on that site of the low where the wind speed has the same direction as the direction of the low itself. The waves that have a group velocity equal to the velocity of the polar low can stay in the low for quite some time and can thus develop into larger waves (see Figure 8) [19].

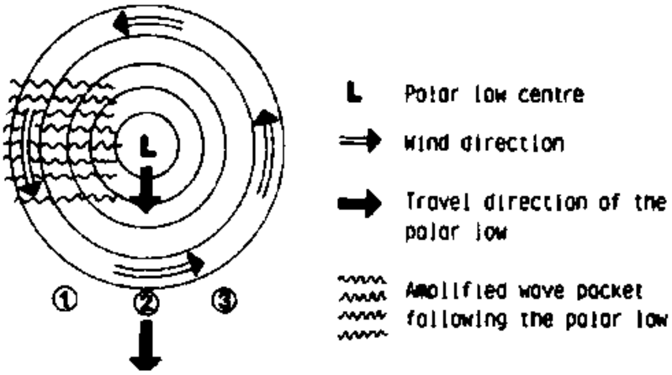


Figure 8: Simplified model of wave generation under a polar low [23], [19].

In the past many people, especially fishermen, lost their lives due to the strong winds and big waves that can develop so quickly and unexpected in the northern part of Norway. Petter Dass (1647 – 1707) a Norwegian poet made one of the first written notes about severe weather in northern Norway. He wrote about a storm with sudden, strong northerly winds that killed around 500 fishermen from one village out at sea. This storm was probably a polar low due to the very sudden strong northerly winds. [28]

Even if the waves are not amplified, as described above, polar lows can still have severe consequences for Marine Operations due to the sudden increase in wind speed and wave height. For example a wind speed of 35m/s leads to a significant wave height of 5.5 m over a fetch length of 100km [26]. Gunnar Noer, a meteorologist from the Norwegian Meteorological Institute, said in an interview in Mai 2012 that he recently found a polar low case where the wave height increased from 3 to 6m within an hour [Gunnar Noer, DNMI, personal communication, Mai 2012]. Depending on the operation a typical limit for carrying out a marine operation could be 3m maximum wave height. Furthermore also the wind speed can be critical for Marine Operations. High wind speeds can for example be very dangerous when it comes to lifting operations.

In Europe polar lows develop mainly in the Norwegian Sea and the Barents Sea but under special circumstances they can also be observed much further south in the North Sea and even in the Mediterranean [19]. Figure 9 shows all polar lows that were registered by the Norwegian Meteorological Institute from 1999 to 2010, in Appendix 2 a list of these polar lows is enclosed. The triangles mark the points where the polar lows were discovered first. The genesis area corresponds well to what Wilhelmsen found in his study about gale-producing polar lows in the period 1987-82 (Figure 10) [24]. His study included only polar lows with surface winds of near gale force (15m/s) or greater.

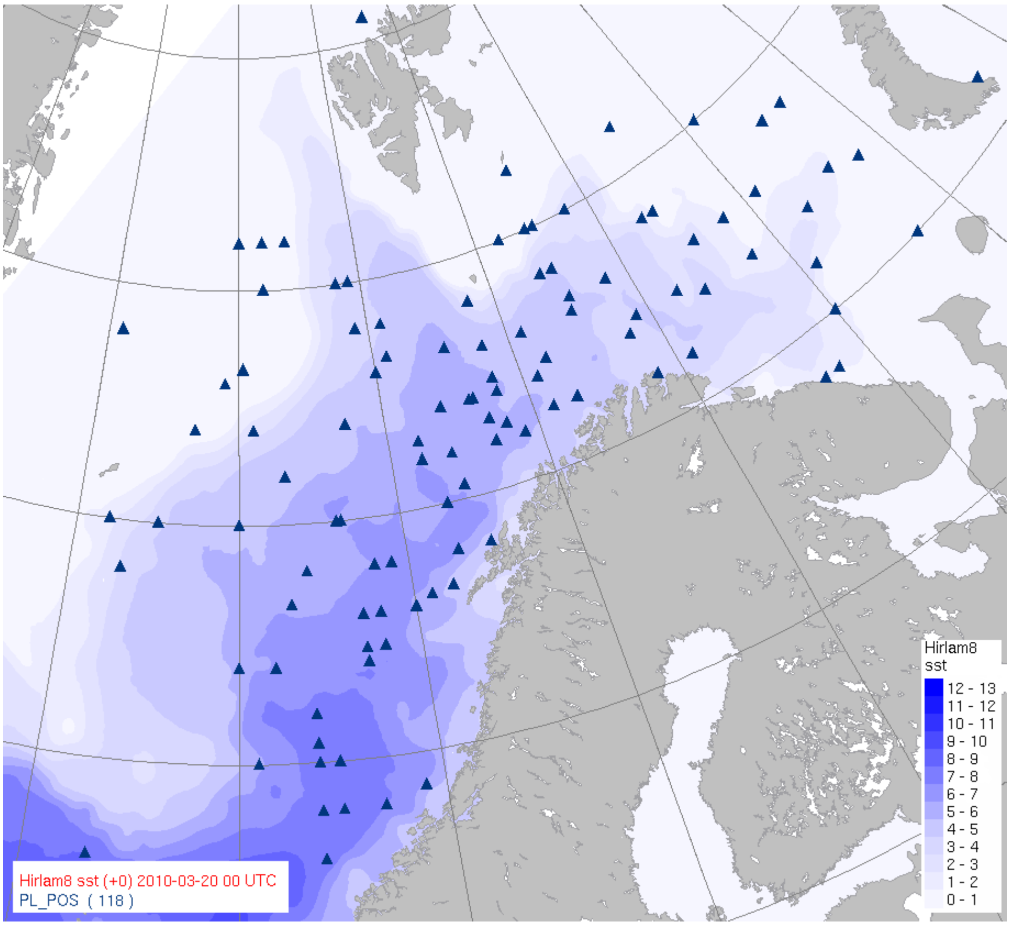


Figure 9: Polar lows registered from the Norwegian Meteorological Institute in Tromsø from 1999 to 2010 [22]. Illustration: Gunnar Noer/met.no

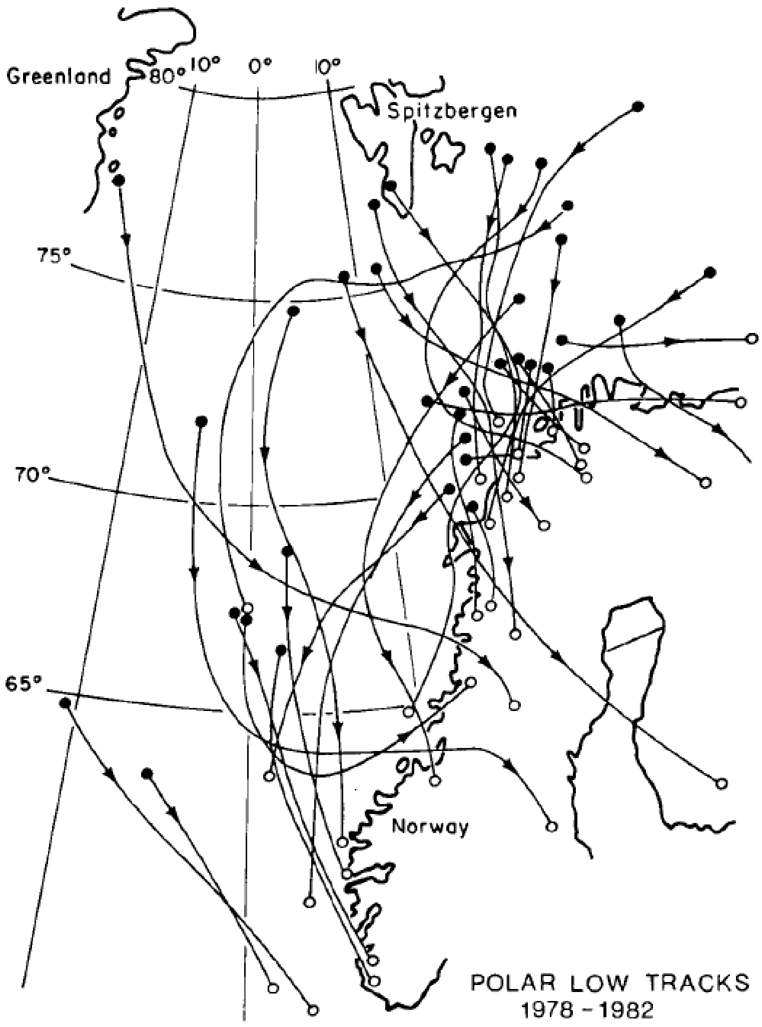


Figure 10: The tracks of polar lows for the period 1978-82 [24]

Figures 11 and 12 show the monthly frequency of polar lows for the period 1999 to 2008 and 1978 to 1982 for the Norwegian and the Barents Sea. Figure 12 shows only gale-producing polar lows just like Figure 10. From both frequency distributions it can clearly be recognized that polar lows are not present during the summer months and that most polar low events happen from November to April. What is noticeable is that February seems to be a month with less polar lows than in the two busy months January and March.

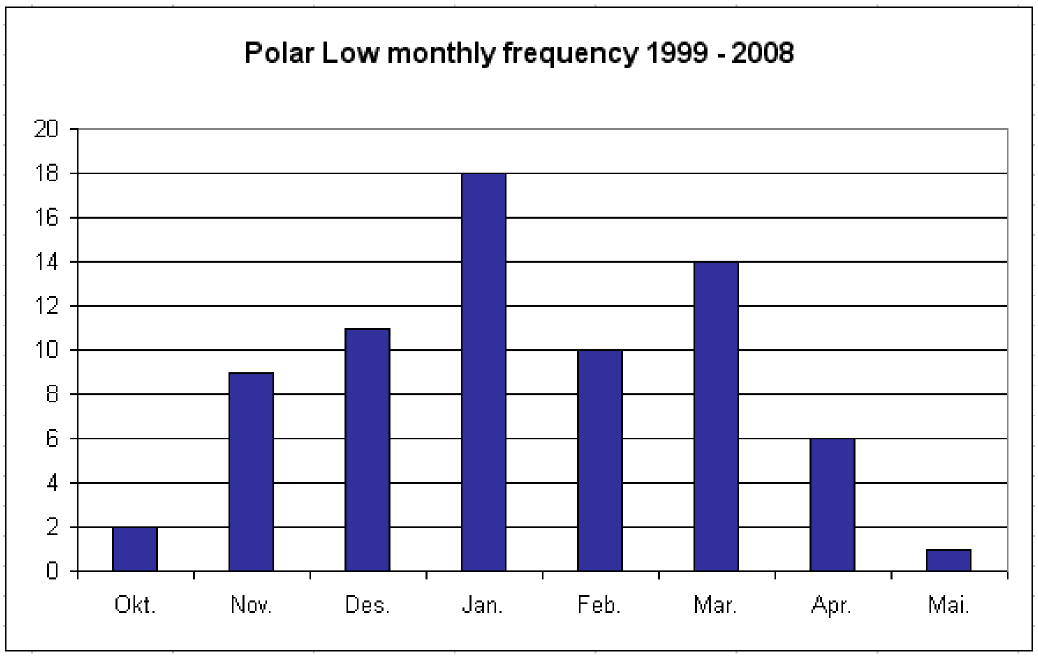


Figure 11: Frequency distribution of polar lows from 1999 to 2008 for the Norwegian Sea and the Barents Sea [22]. Illustration: Gunnar Noer/met.no

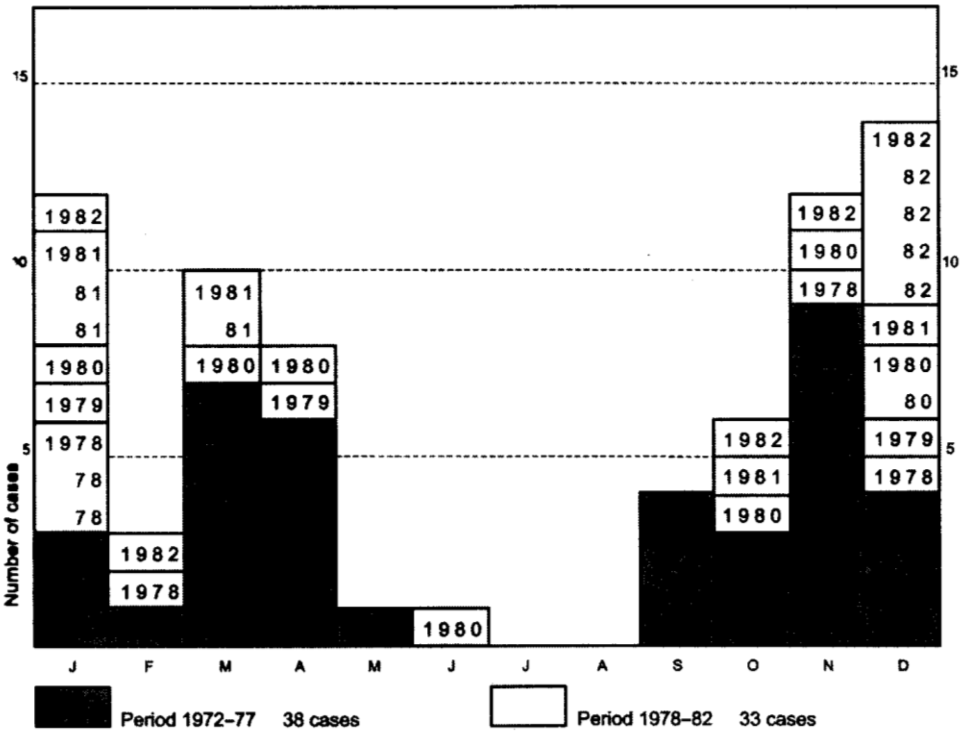


Figure 12: Frequency distribution of the occurrence of gale-producing polar lows for the period 1972-82 (71 cases in 11 years) in the Norwegian Sea and the Barents Sea [24]

As noted earlier polar lows are difficult to forecast. That is due to the small scale and the quick development. It was basically impossible to forecast them before the availability of satellite images because there were only few observation stations in the Barents Sea and the lows could easily pass in between them [22]. Satellite images are still a valuable tool in forecasting polar lows. They are used to perform “nowcasting” as it is called. That means that the movement of polar lows is forecasted a few hours ahead with the help of satellite images. This method works well for about 6 hours ahead and can be used up to 12 hours ahead or more in some cases [19]. Furthermore forecasters can use historical maps like that in Figure 10 to forecast likely tracks of polar lows.

Numerical weather prediction analysis and forecast systems became much better in forecasting polar lows throughout the past decades but can still be considered as poor due to various reasons. For example the resolution of the models is often not high enough to predict a polar low and in situ data as input data to the models are lacking. Still models can be very helpful in evaluating where and when polar lows might develop because it is known which weather situations are likely to lead to polar lows [19]. Lystad et al. [25] divided polar lows into four different groups which reflect the weather situations during which these storms can develop: polar lows developing during major cold air outbreaks, polar lows developing in troughs behind a synoptic-scale low, the comma cloud type of polar lows and mesoscale baroclinic waves. Gunnar Noer said in an interview that for a polar low to develop a cold air outbreak and a cold upper trough around 500–400 hPa are necessary [Gunnar Noer, DNMI, personal communication, Mai 2012]. These conditions can be forecasted quite well. He also mentioned that a study showed that in around 25% of the cases where the weather conditions are favourable, polar lows develop.

The Norwegian Meteorological Institute issues polar low probability forecasts for which the predictability of the weather conditions, that are necessary to produce a polar low, is used. In 2008 they issued this probability forecast for the Thorpex program. Thorpex is a project to improve weather forecasting. Table 9 shows polar low probability levels as they were defined for the Thorpex polar low probability forecasts. The table shows probabilities and associated weather conditions, as well as how far into the future these conditions are predictable. The predictability time span is based on experience and varies depending on model performance and e.g. the size of the polar low [Gunnar Noer, personal communication, June 2012]. [27]

Table 9: Polar low probability forecasts [27]

Polar low probability	**Conditions**	**Actual probability of polar low**	**Predictability of conditions**
Low	Non favourable synoptic scale (either no CAO or no cold core, or non of both)	Polar low has never been seen	7 days
Moderate	Favourable synoptic scale conditions (CAO and cold core)	25%	7 days
High	- CAO, cold core and model development of polar low in the MSLP - Polar low observed	?	- 36 hours - 12 hours

4. REVISED ALPHA FACTOR – JOINT INDUSTRY PROJECT

In 2005 a joint industry project was started to revise and refine the alpha factor, which was introduced by DNV in 1996. The participants were BP, Heerema, Norsk Hydro, Shell, Statoil, Stolt Offshore, Subsea 7, Technip and Total. The resulting alpha factors from this JIP were used as basis for the alpha factors in DNV's Marine Operations standard from 2011 [1]. [29]

DNV found it necessary to perform this study because it could be expected that the weather forecasts had improved since the middle of the 90's. Furthermore, the basis of the old study was small with respect to the amount of data and the geographical spread of observations. Only 8500 data sets (observation and corresponding forecast value) from two locations in the North Sea were available. In the 2005 JIP 160000 data sets from three forecasting organisations and various locations, as shown in Figure 13 were used. The forecasting organisations that provided data were DNMI, UK MetOffice and Storm (now StormGeo). The reason for using data from different organisations was to have a wide geographical spread of locations, to be able to compare the forecasts of different organisations and to have a variance in applied numerical models. Thus alpha factors should be developed that do not depend on the forecasting organisation used. [29]

In order to identify the uncertainties in the forecast, measured and forecasted wave heights were compared. The significant wave height was chosen as assessment parameter because for the typical marine operation it is the most influencing parameter. [29]

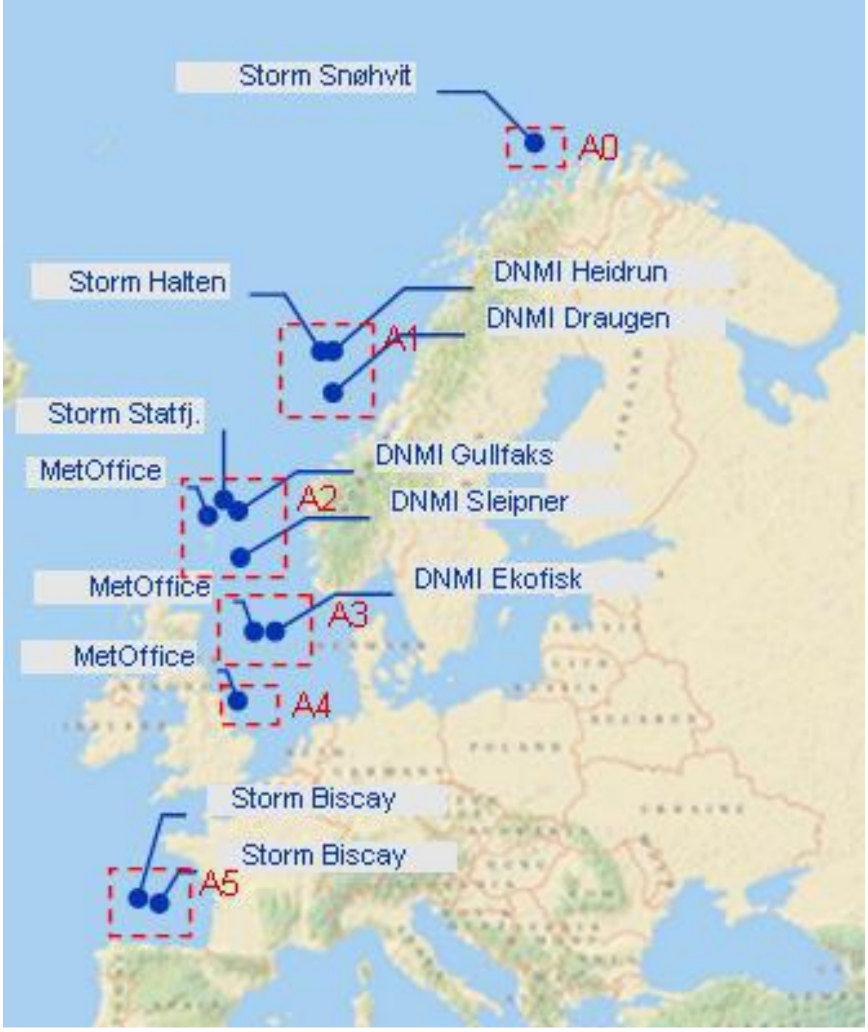


Figure 13: Locations for data collection in the JIP [29]

4.1. Calculation of the α-factor

This chapter will explain how the calculations of the alpha factor were done in the DNV JIP project. For this chapter the Excel spreadsheet that was used for the calculation, the Technical Report of the JIP project [29] and further literature were considered. The text below complements the explanations in the Technical Report [29]. The alpha factors are estimated by the following relation:

$$\alpha = \frac{H_{\max}}{H_{\max\_WF}} \tag{6}$$

The maximum wave height is the wave height with a 10^{-4} probability for exceedance during a certain period. For the calculation of the α-factor (see equation (6)) the forecasted significant wave height is used to calculate the forecasted maximum wave height (H_{max}) (see 4.1.2). This is divided by the maximum wave height taking into account the bias and the variance in the forecast (H_{max_WF}).

4.1.1. Calculation of bias and variance of the deviation between forecasted and measured significant wave height

Measured and forecasted significant wave height data were used to calculate error values (H_{error}) according to equation (7) for each forecasted and measured significant wave height pair.

$$H_{error} = H_{forecast} - H_{observed} \tag{7}$$

$H_{forecast}$	forecasted significant wave height
$H_{observed}$	measured significant wave height

The error values were stored in scatter tables. Each scatter table included the data from a specific forecasting organisation, a specific area in the North Sea and a specific forecasting period. The forecasting period refers to how far into the future the forecast applies. The error values H_{error} were categorised in error groups of width 0.5m. That means for example that all error values from 0.25m to 0.75m were put into the error group 0.5m. In the scatter tables the data were arranged according to the wave height and the error group. For each scatter table bias and standard deviation were calculated for each wave height group. Bias and standard deviation were then plotted in two figures (see Figures 14 and 15). They include bias and standard deviations from all scatter tables, thus from all providers and all locations.

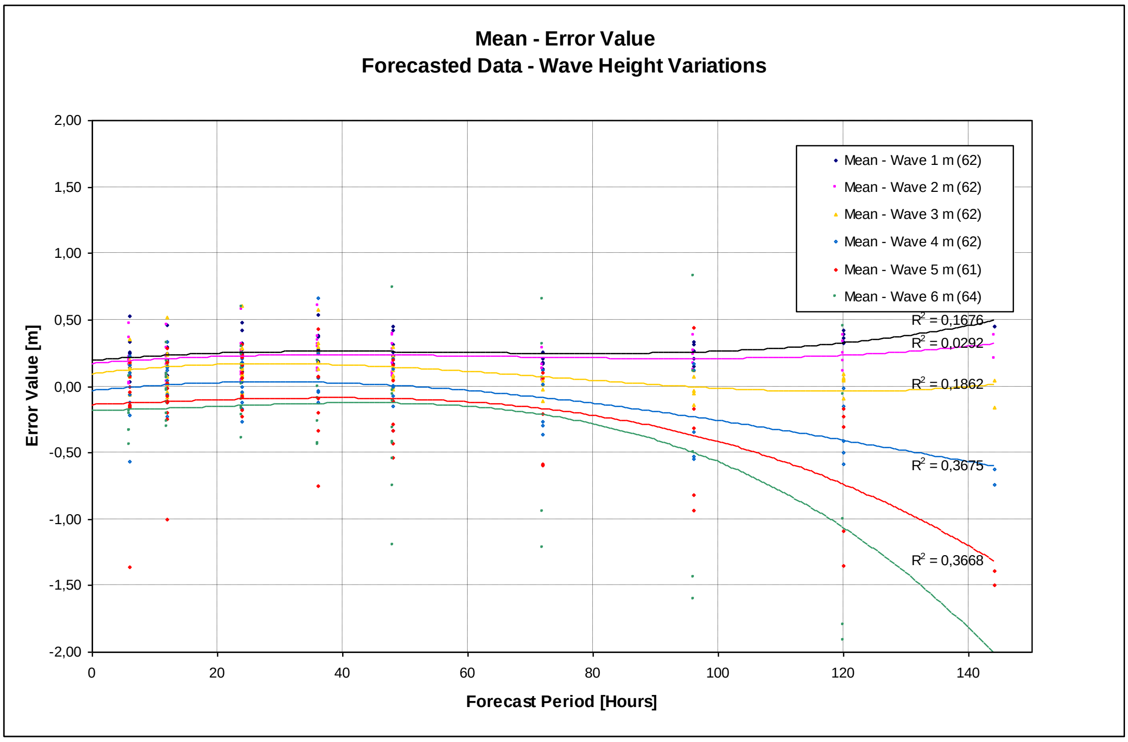


Figure 14: Bias of deviation between forecasted and measured wave height [29]

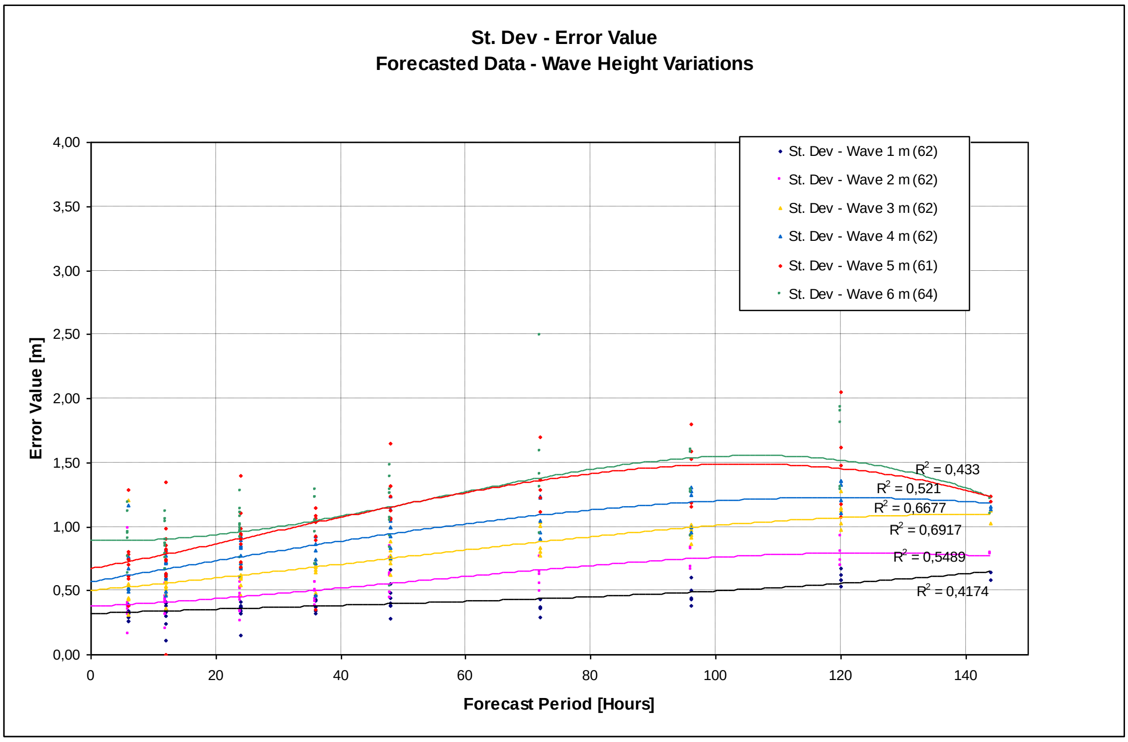


Figure 15: Variance of deviation between forecasted and measured wave height [29]

The values for bias and variance for each forecasting period and wave height were then taken according to the trend lines (third degree polynomials) in the two figures and are summarised in Table 10.

Table 10: Bias and standard deviations for difference between forecasted and measured significant wave height for all forecasting periods and wave heights

Mean Values	Forecast Periods [Hrs]								
Obs. Group Hs [m]	6	12	24	36	48	72	96	120	144
1	0.22	0.24	0.26	0.27	0.27	0.25	0.26	0.32	0.50
2	0.19	0.21	0.23	0.24	0.24	0.23	0.21	0.25	0.30
3	0.13	0.15	0.18	0.18	0.15	0.08	0.00	-0.03	0.00
4	-0.02	0.02	0.03	0.03	0.01	-0.08	-0.24	-0.40	-0.60
5	-0.13	-0.12	-0.10	-0.09	-0.09	-0.16	-0.37	-0.74	-1.35
6	-0.18	-0.17	-0.15	-0.13	-0.13	-0.21	-0.60	-1.15	-2.00

St. Dev, Values	Forecast Periods [Hrs]								
Obs. Group Hs [m]	6	12	24	36	48	72	96	120	144
1	0.33	0.34	0.36	0.37	0.39	0.43	0.48	0.55	0.65
2	0.39	0.42	0.45	0.50	0.54	0.66	0.75	0.79	0.78
3	0.53	0.56	0.62	0.68	0.75	0.87	0.99	1.08	1.10
4	0.62	0.66	0.76	0.85	0.94	1.08	1.18	1.23	1.18
5	0.73	0.78	0.90	1.04	1.15	1.36	1.47	1.45	1.24
6	0.80	0.83	0.94	1.05	1.16	1.37	1.52	1.52	1.24

4.1.2. Calculation of the forecasted maximum wave height H_{max} and the maximum wave height taking into account the uncertainty in the weather forecast H_{max_WF} (equation (6))

In the JIP project the maximum wave height during a given period is defined to be the wave height with a 10^{-4} probability for exceedance during this period. The probability distribution of the highest wave height can be found by using the fact that if the largest of the individual wave heights is smaller or equal to H then all wave heights must be less than or equal to H:

$$P\left(H_{highest} \leq H\right) = P\left(\max\left(H_1, H_2, \ldots, H_n\right) \leq H\right)$$

$$= P\left(\left(H_1 \leq H\right) \cap \left(H_2 \leq H\right) \cap \ldots \cap \left(H_n \leq H\right)\right)$$

Assuming independence between the events:

$$P\left(H_{highest} \le H\right) = P\left(\left(H_1 \le H\right) \bullet \left(H_2 \le H\right) \bullet \ldots \bullet \left(H_n \le H\right)\right)$$
$$P\left(H_{highest} \le H\right) = \left[F\left(H\right)\right]^n \tag{8}$$

$H_{highest}$	highest wave height
$P(H_{highest} \le H)$	cumulative probability distribution of highest wave height
$F(H)$	cumulative probability distribution of wave height
n	number of waves

According to the Coastal Engineering Manual [15] the wave height probability distribution F(H) can be described by the following Rayleigh distribution:

$$F\left(H\right) = 1 - \exp\left[-\frac{H^2}{H_{rms}^2}\right] \tag{9}$$

H_{rms}	root-mean-square of all measured wave heights

With use of equation (11) the probability distribution for the highest wave height (8) can be expressed by equation (10) which is the probability distribution that was used in the JIP project in order to calculate the maximum wave height.

$$P\left(H_{highest} \le H\right) = \left[1 - \exp\left[-\frac{H^2}{8m_0}\right]\right]^n \tag{10}$$

m_0	zero order moment of wave spectrum

$$4.00\sqrt{m_0} = 1.416 H_{rms} \qquad \text{(see [15])} \tag{11}$$

The zero order moment can be expressed in terms of the significant wave height by the following relation according to the recommended practice from DNV [17].

$$m_0 = \frac{H_S^2}{16} \tag{12}$$

In the JIP project the calculation of the number of waves n was done according to equation (13)

$$n = \frac{t_F}{T_P} \tag{13}$$

t_F	forecasting period
T_P	peak wave period

The wave spectrum was defined to be according to the JONSWAP spectrum with the average peak enhancement factor from the JONSWAP experiment data γ=3.3 [17]. The relation between the peak wave period and the zero up-crossing period can be expressed by the following relation:

$$\frac{T_Z}{T_P} = 0.6673 + 0.05037\gamma - 0.006230\gamma^2 + 0.0003341\gamma^3 \tag{14}$$

(see [17])

With γ equal to 3.3 equation (14) can be rearranged:

$$T_P = T_Z / 0.7777 \tag{15}$$

T_Z	zero up-crossing wave period
γ	peakness parameter for Jonswap wave spectrum

T_Z was also defined according to the “Rules for Planning and Execution of Marine Operations” [18]. It was chosen to be the median of the zero up-crossing period interval (16) that should be considered for design purposes, but with the use of the significant wave height H_S instead of the characteristic significant wave height $H_{S,C}$.

$$H_{S,C}^{0.52} \le T_Z \le 13 \tag{16}$$

$H_{S,C}$	characteristic significant wave height, significant wave height with defined probability of exceedance

The forecasted maximum wave height H_{max} was then found as the wave height with a probability of 10^{-4} of being exceeded within the forecasting period (equation (17)) by using the forecasted significant wave height H_{S_F} in equation (12). In order to obtain the forecasted significant wave height $H_{S\_F,}$ the (true) significant wave height H_S (any wave height for which an alpha factor should be calculated) was converted with the bias from Table 10.

$$1 - P\left(H_{highest} \leq H_{\max}\right) = 10^{-4} \tag{17}$$

The maximum wave height taking into account the bias and the variance in the forecast H_{max_WF} was found according to equation (18)

$$1 - P\left(H_{highest} \leq H_{\max\_WF}\right) = 10^{-4} \tag{18}$$

The probability distribution $P(H_{highest} \leq H_{max\_WF})$ requires intergration over a joint probability distribution because the uncertainty of the true significant wave height and the probability of the maximum wave height being H for given significant wave height H_S have to be taken into account. Joint probability density functions can be calculated the following way:

$$p\left(H, H_S\right) = p\left(H \middle| H_S\right) \bullet p\left(H_S\right) \tag{19}$$

$p(H,H_S)$	joint probability density function of the wave height H and the significant wave height H_S
$p(H|H_S)$	conditional probability density function of the wave height H
$p(H_S)$	probability density function of the significant wave height H_S

The probability density function for the (true) significant wave height $p(H_S)$ is assumed to be normal distributed with the mean taken as the forecasted significant wave height corrected for the bias and the standard deviation taken according to Table 10. The conditional probability density function of the wave height $p(H|H_S)$ is obtained from equation (10). The cumulative probability distribution for the highest wave height $P(H_{highest} \leq H)$ becomes:

$$
\begin{aligned}
P\left(H_{highest} \leq H\right) &= \int_0^H \int_0^\infty p\left(H, H_S\right) dH_S \, dH \\
P\left(H_{highest} \leq H\right) &= \int_0^H \int_0^\infty p\left(H \middle| H_S\right) \bullet p\left(H_S\right) dH_S \, dH
\end{aligned}
\tag{20}
$$

By integrating, the value of H_{max_WF} is determined as the upper threshold level for the integral that gives the exceedance probability specified in equation (18).

5. ANALYSIS

5.1. Data

The analyses are performed on a sub set of data that was used in the Revised Alpha Factor – Joint Industry Project (see part 4). The data are the measured and forecasted wave height data for the Snøhvit gas field, which is located in the Barents Sea (see Figure 16). The forecasting organisation StormGeo provided the wave height forecasts. The forecast data recorded are from the ECMWF (European Centre for Medium-Range Weather Forecasts) model and from a forecaster. Here the data from the forecaster are used as was done in the JIP. Forecasted wave heights are available for forecasting periods of +12h, +24h, +48h, +72h, +96h and +120h. Forecast and actual wave height data were recorded at 00:00 and 12:00 UTC. The data provided are from end of December 2004 to end of October 2005, i.e. around 3650 data sets (forecasted wave height and corresponding measured wave height) should be available theoretically. In practice it is only around 2900 data sets.

Figure 16: Location of the Snøhvit gas field

5.2. Calculation of alpha factors for the Barents Sea

The analysis is supposed to evaluate whether different alpha factors than the ones used in the DNV Marine Operations standard [1] for the North Sea and Norwegian Sea are necessary for operations in the Barents Sea. The reason for this would be that the uncertainties in the weather forecast are potentially bigger than further south. The error could very well be bigger as the “mobility of weather systems is generally greater in the north, leading to somewhat larger errors due to the difficulties which the models sometimes experience in specifying the intensity and rapidity of developments” [30]. Furthermore seasonal variations of the forecast uncertainty are probable because in winter there are generally more storms and more quickly changing weather situations than in summer. These variations might make it necessary to develop alpha factors depending on the season.

5.2.1. Method

Generally the same calculation method is used as in the Revised Alpha Factor – JIP (see part 4) except for the method to calculate the bias and the variance of the error value (difference between forecasted and measured value). No advantage of finding variance and bias in the relatively complicated way described in part 4.1.1 could be found. Therefore both are computed directly.

The error values (difference between forecasted and measured wave height) are computed with equation (7):

$$H_{error} = H_{forecast} - H_{observed}$$

$H_{forecast}$	forecasted significant wave height
$H_{observed}$	measured significant wave height

These error values are then divided according to their date into winter and summer. Winter is defined to be from November to April and summer from May to October. Furthermore the data are arranged in wave height groups (0-1m, 1-2m, ...) and forecasting periods. Bias and standard deviations are calculated according to equations (21) and (22).

$$\overline{H}_{error} = \frac{1}{j} \bullet \sum_{i=1}^{j} H_{error,i} \tag{21}$$

$$\sigma = \sqrt{\frac{\sum \left(H_{error} - \overline{H}_{error} \right)^2}{j-1}} \tag{22}$$

$\overline{H}_{error}$	mean error value
σ	standard deviation

The standard deviations and the bias for the different seasons, wave heights and forecasting periods are then used to calculate alpha factors. That is done according to 4.1.2 and equation (6). Only 50% of the overestimation of the waves is considered, meaning that the positive bias implemented is considered to be 50% of the actual bias for the calculation of the alpha factor. By using only half of a positive bias the resulting alpha factor will be lower compared to using the full positive bias value. This introduces additional safety for alpha factors that are based on a positive bias value. The alpha factors developed for the marine operations standard [1] were calculated in the same way. Alpha factors are only computed for values of standard deviations and bias that are based on at least 10 data sets.

5.2.2. Results and discussion

Table 11 shows bias and standard deviation of the Snøhvit error values for the whole year. Figures 17 and 18 show the same graphically. The bias shows that relatively large waves are often underestimated and there seems to be no clear correlation between the bias and the forecasting period. Furthermore for large waves the bias values are spread out quite a lot. A reason for this might be that there is quite a limited amount of data available in these wave height groups. For the wave height group of 4-5m there are only 20 data sets. It is also apparent that especially for the two longest forecasting periods, namely +96 hours and +120 hours, the wave heights from 3m to 5m have a much lower bias than for the other forecasting periods. They are underestimated by around half a meter. If these results reflect a systematic underestimation, it could be dangerous for relatively long weather restricted marine operations in case the uncertainty in the weather forecast is not accounted for properly.

As expected the standard deviations for all groups show a clear dependency on the forecasting period, the longer the forecasting period the bigger the standard deviation. That is natural as the weather forecast is more uncertain for longer forecasting periods. Furthermore the standard deviation increases with increasing wave height, which can be expected as well. It is noticeable, though, that the standard deviation increases quite drastically from the wave height group 3-4m to the wave height group 4-5m for all observation periods.

Table 11: Bias and standard deviation of Snøhvit error values

Bias

Obs. Group Hs [m]	12	24	48	72	96	120
1	0.18	0.18	0.23	0.20	0.25	0.36
2	0.03	0.03	0.07	0.13	0.12	0.12
3	0.06	0.05	0.09	0.04	-0.04	0.11
4	-0.23	-0.18	-0.15	-0.30	-0.53	-0.56
5	0.17	0.23	0.10	-0.04	-0.43	-0.39

St. Dev, Values

Obs. Group Hs [m]	12	24	48	72	96	120
1	0.31	0.34	0.42	0.38	0.42	0.56
2	0.42	0.52	0.60	0.63	0.82	0.69
3	0.61	0.77	0.95	0.96	1.02	1.35
4	0.70	0.90	1.11	1.24	1.29	1.45
5	1.39	1.45	1.68	1.89	1.96	2.28

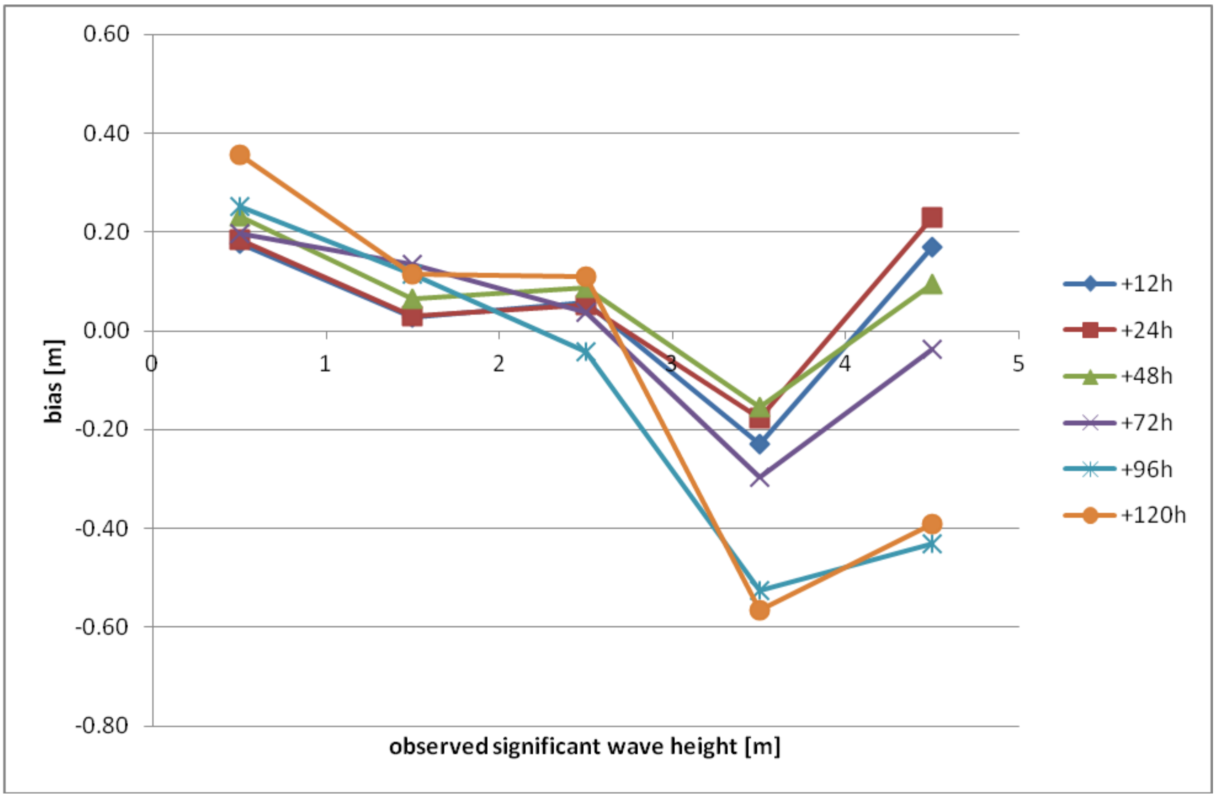


Figure 17: Bias of Snøhvit error values

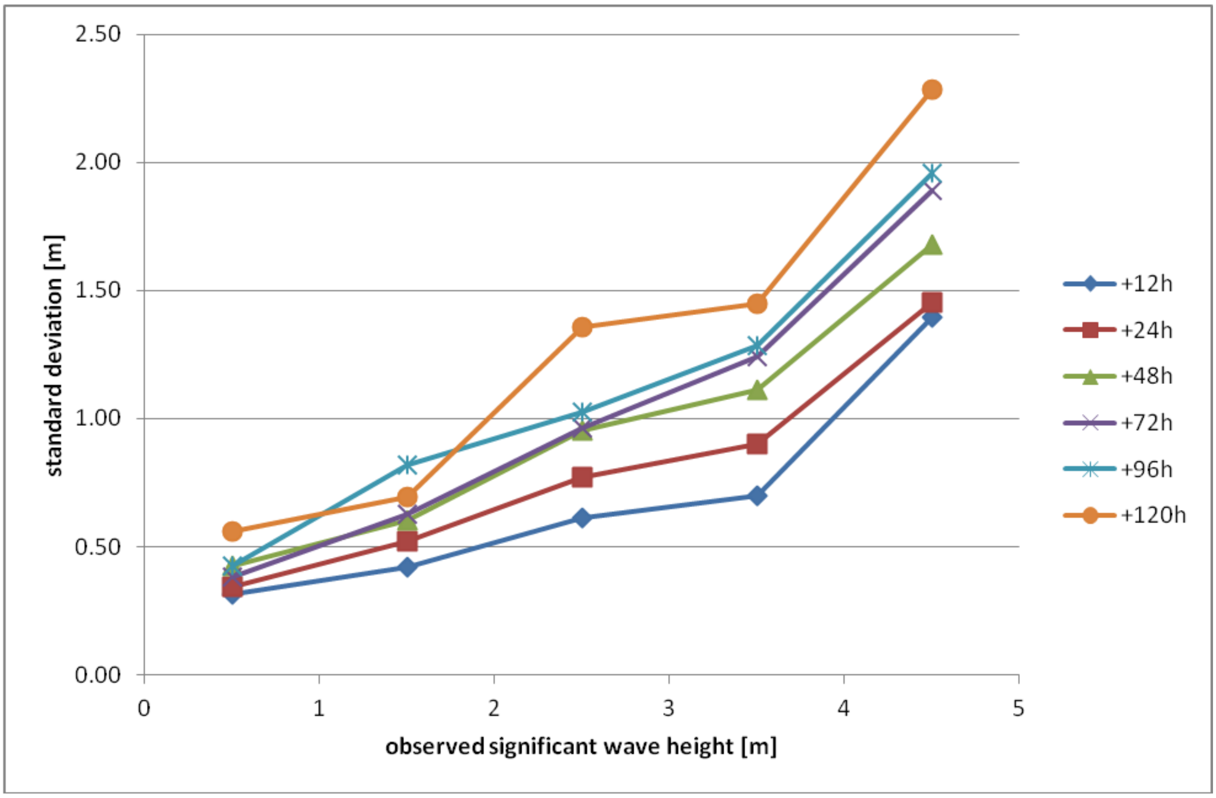


Figure 18: Standard deviation of Snøhvit error values

Tables 12 and 13 show bias and standard deviations of the error values for summer and winter and Figures 19 and 20 show the results graphically. The differences between winter and summer standard deviations are shown in Figure 21. The bias seems mostly to be bigger in winter than in summer. The seasonal dependency of the standard deviation is not that clear. For the wave height group 1-2m the standard deviation is bigger in winter than in summer but for higher wave heights it is mostly the other way round. This higher variability of the error value in summer than in winter indicates that the uncertainty of the weather forecast is higher in summer. The calculated alpha factors (Table 14) also reflect this.

Table 12: Bias and standard deviation of Snøhvit error values in winter

Bias

Obs. Group Hs [m]	12	24	48	72	96	120
1						
2	0.12	0.16	0.10	0.24	0.26	0.31
3	0.06	-0.03	0.14	0.09	-0.01	0.17
4	-0.20	-0.21	-0.17	-0.25	-0.45	-0.39
5	0.08	0.14	0.37	0.51	-0.16	-0.17

St. Dev, Values

Obs. Group Hs [m]	12	24	48	72	96	120
1						
2	0.44	0.57	0.64	0.68	0.82	0.81
3	0.58	0.58	0.77	0.82	0.98	1.48
4	0.71	0.80	1.10	1.20	1.40	1.62
5	1.10	0.92	1.26	1.59	1.83	1.66

Table 13: Bias and standard deviation of Snøhvit error values in summer

Bias

Obs. Group Hs [m]	12	24	48	72	96	120
1	0.18	0.19	0.23	0.18	0.22	0.34
2	-0.04	-0.07	0.04	0.06	0.01	-0.02
3	0.06	0.14	0.03	-0.02	-0.08	0.05
4	-0.27	-0.13	-0.12	-0.36	-0.65	-0.82
5	0.26	0.30	-0.12	-0.49	-0.66	-0.59

St. Dev, Values

Obs. Group Hs [m]	12	24	48	72	96	120
1	0.32	0.35	0.43	0.37	0.39	0.56
2	0.39	0.46	0.57	0.58	0.80	0.56
3	0.66	0.93	1.13	1.10	1.07	1.22
4	0.69	1.06	1.16	1.32	1.10	1.12
5	1.70	1.79	1.96	2.06	2.11	2.80

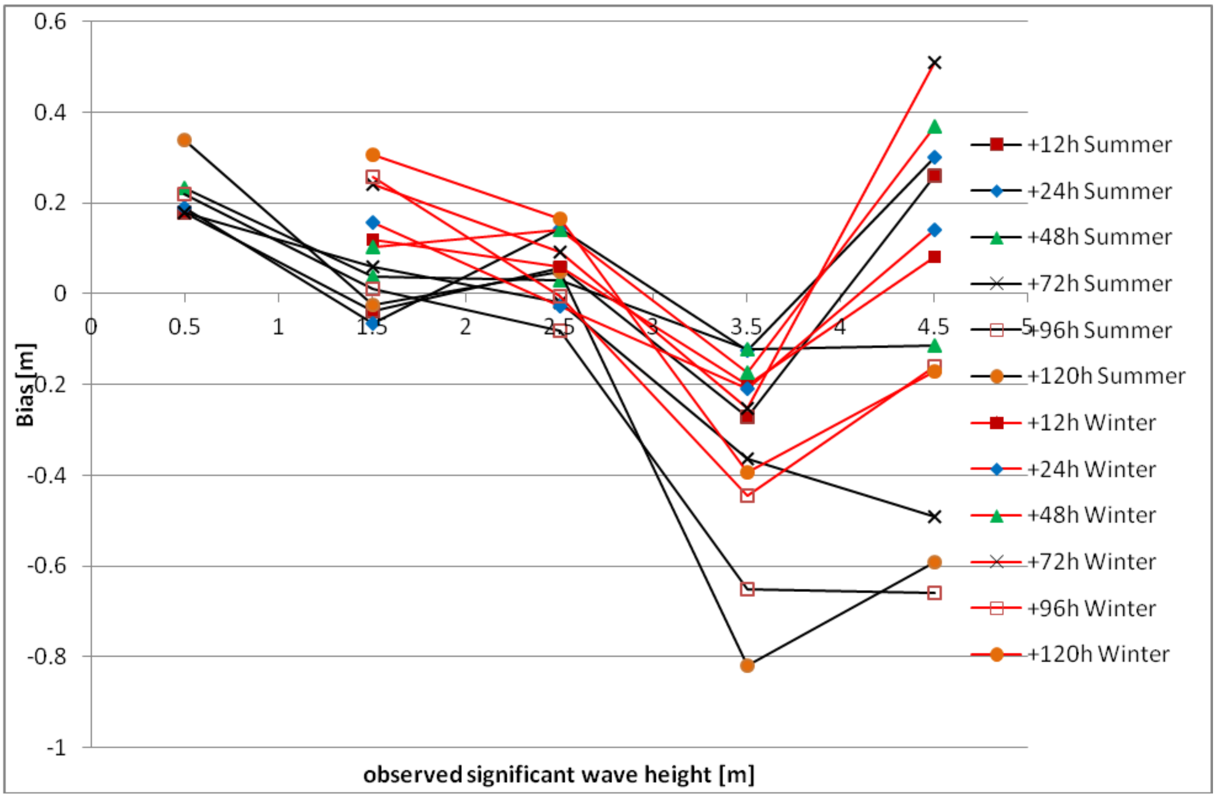


Figure 19: Bias of Snøhvit error values for summer and winter

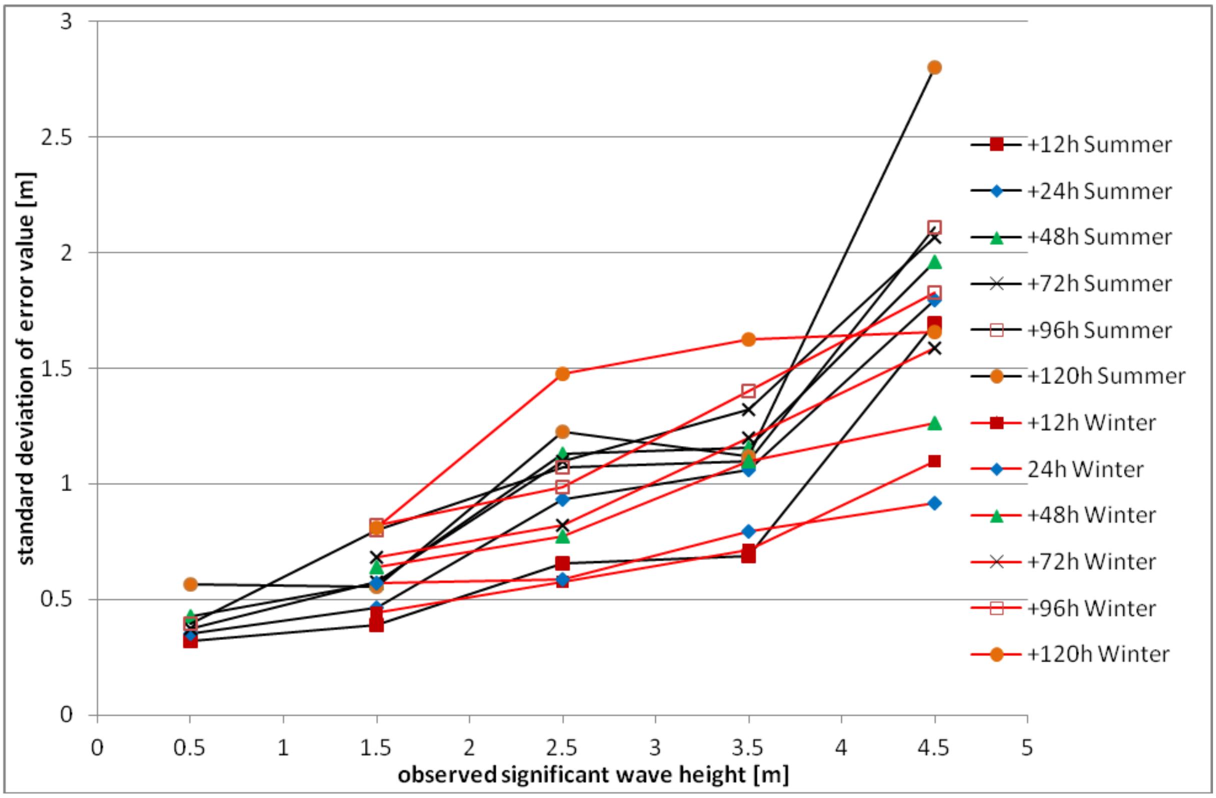


Figure 20: Standard deviation of Snøhvit error values for summer and winter

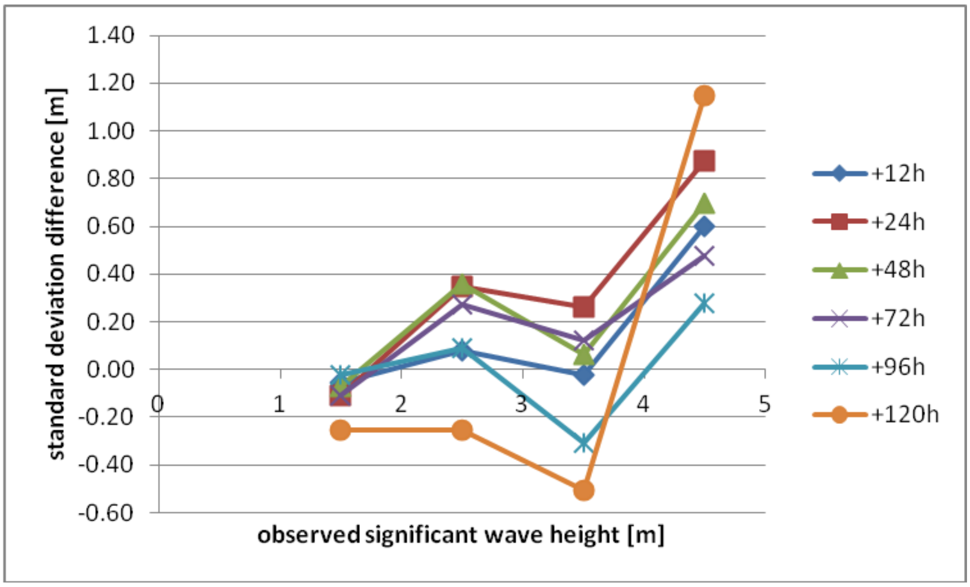


Figure 21: Difference in error value standard deviations between winter and summer (summer-winter)

The alpha factors that result from the above mentioned values of standard deviations and bias are tabulated in Table 14. Figure 22 shows the difference in the alpha factors from winter and summer. In most cases the alpha factor is higher in winter than in summer. This is due to the fact that the standard deviation is often lower in winter than in summer. It means that the uncertainty in the weather forecast is less in winter than in summer. This is unexpected as generally the weather in winter is more variable than in summer and therefore less predictable. There are, however, possible reasons why the uncertainty is bigger in summer than in winter. It might, for example, be that that particular winter was subject to long stable weather periods and that the summer was possibly characterised by many storms. Another reason could be that the numerical model which the forecasts are based on is better suited for winter than for summer. Anyhow, the data base is too small to give further indications on this matter. Data from multiple years are needed to verify whether the uncertainty in the weather forecast really is higher in summer. Thus it would be possible to indicate whether the forecasting model used by StormGeo is really better in summer than in winter. Furthermore data from more forecasting organisations that use different forecasting models are needed for comparison.

Table 15 shows the differences between the alpha factors from Snøhvits “all year data” and the alpha factors that served as basis for DNV’s Marine Operations standard [1].The here calculated alpha factors are considerably smaller in wide ranges, especially for the wave height group 3-4m. This means that the uncertainty in the weather forecast could be considered higher for Snøhvit than for the North and Norwegian Sea for which DNV’s alpha factors apply. This has, however, to be seen in the light of the fact that the amount of data was very limited in the study performed here. Furthermore the data of only one weather forecast provider were used compared to three in the JIP.

Table 14: Alpha factors (W - Winter, S - Summer, Y - All Year)

		Obs. Group Hs [m]				
Forecast period	Season	0-1m	1-2m	2-3m	3-4m	4-5m
12h	W		0.73	0.76	0.73	0.72
	S	0.65	0.73	0.72	0.73	0.63
	Y	0.66	0.73	0.74	0.73	0.66
24h	W		0.65	0.73	0.7	0.77
	S	0.62	0.67	0.62	0.63	0.63
	Y	0.63	0.66	0.67	0.67	0.65
48h	W		0.61	0.67	0.61	0.69
	S	0.56	0.63	0.54	0.6	0.61
	Y	0.56	0.62	0.6	0.61	0.63
72h	W		0.6	0.64	0.57	0.66
	S	0.58	0.63	0.54	0.53	0.56
	Y	0.59	0.61	0.59	0.55	0.62
96h	W		0.54	0.58	0.5	0.61
	S	0.58	0.52	0.54	0.53	0.55
	Y	0.56	0.52	0.56	0.51	0.58
120h	W		0.55	0.47	0.47	0.62
	S	0.48	0.62	0.51	0.5	0.56
	Y	0.49	0.57	0.49	0.47	0.58

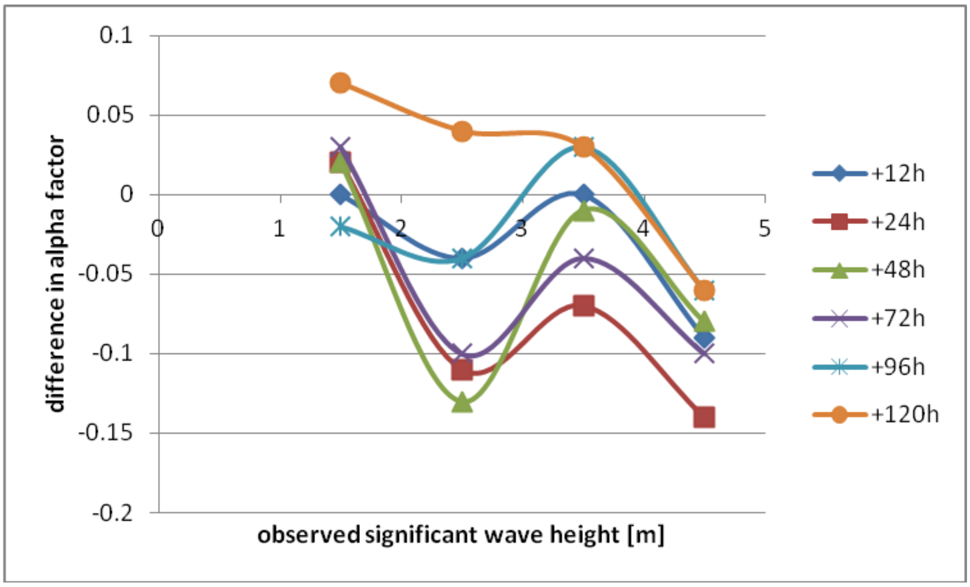


Figure 22: Difference in winter and summer alpha factors (winter-summer)

Table 15: Difference between calculated alpha factors for Snøhvit and alpha factors that were used as base for the marine operations standard [1] (standard-Snøhvit)

Obs. Group Hs [m]	12h	24h	48h	72h	96h	120h
0-1	-0.01	0.01	0.03	-0.03	-0.04	0
1-2	0.03	0.08	0.06	0	0.04	-0.02
2-3	0.03	0.08	0.08	0.03	0.02	0.05
3-4	0.06	0.08	0.07	0.08	0.06	0.07
4-5	0.12	0.09	0.05	0.01	0.01	-0.03

5.3. Effects of polar lows on the forecast uncertainty

Polar lows pose a huge threat to marine operations in the Barents Sea as mentioned before. Therefore an evaluation of the influence of polar lows on the weather forecast uncertainty is tried in this analysis.

All polar lows from January to October 2005 that possibly could have had an effect on the wave height at Snøhvit are searched for with the help of the list of polar lows from Appendix 2 and the map of these polar lows (Figure 9). The problem hereby is that the map only shows the positions in which the polar lows were discovered first. They travel generally southwards but knowing the paths of the polar lows would make the analysis easier. It is non-essential, though, that the low travels directly above the location of Snøhvit because waves can travel out of the storm area. For all six polar lows that possibly could have had an influence on the wave height at Snøhvit (Table 16), the data are scanned for big differences between forecasted and measured wave heights around the dates of the polar lows.

Table 16: Polar lows that could have had an effect on the sea state at Snøhvit

Date	Time (UTC)	Latitude	Longitude
01.03.2005	15:00	76N	35E
07.03.2005	07:00	72N	18E
17.03.2005	01:40	72N	48E
02.04.2005	09:00	75N	24E
26.04.2005	17:00	74N	25E
12.10.2005		76N	00E

No case with unusually big differences between forecasted and measured wave heights could be found for any forecasting period. This is probably due to the limited amount of data. There are only six polar lows that might have had an influence on the sea state at Snøhvit during the measurement period. That is not much considering that it is not known which way the low pressures travelled. Furthermore wave height measurements and forecast data from Snøhvit are only available for 00:00 and 12:00 UTC. That means that even if the sea state was influenced by a polar low still the probability that it “slipped through” the measurements is relatively big.

6. CONCLUSIONS AND RECOMMENDATIONS

Today's knowledge about weather forecasting indicates that using the alpha factors for the North and Norwegian Sea, that are recommended by DNV [1], is not sufficient to account for the forecast uncertainty inherent to the Barents Sea.

Seasonal variations of the alpha factors can be expected. The alpha factors for summer and winter, which were calculated in section 5.2, show that the uncertainty in the weather forecast is higher during summer than during winter. This is not what is expected because in general unstable quickly changing weather conditions are more difficult to predict than stable weather conditions. In winter there are generally more storms, thus quickly changing conditions. The results might be due to the lack of data. In order to achieve statistically meaningful results data from several years and possibly different forecast providers are necessary. The potential for continuing this study exists as Statoil, the Norwegian Coastal Administration and the Norwegian Radiation Protection Authority deployed three buoys in the Barents Sea that collected amongst other data also wave heights from 2007 to 2010 [Einar Nygaard, Statoil, personal communication, April 2012]. The positions of the three buoys are shown in Figure 23. For this study it was, however, not possible to find a forecasting company that could provide the necessary forecast data to compare measured and forecasted wave heights.

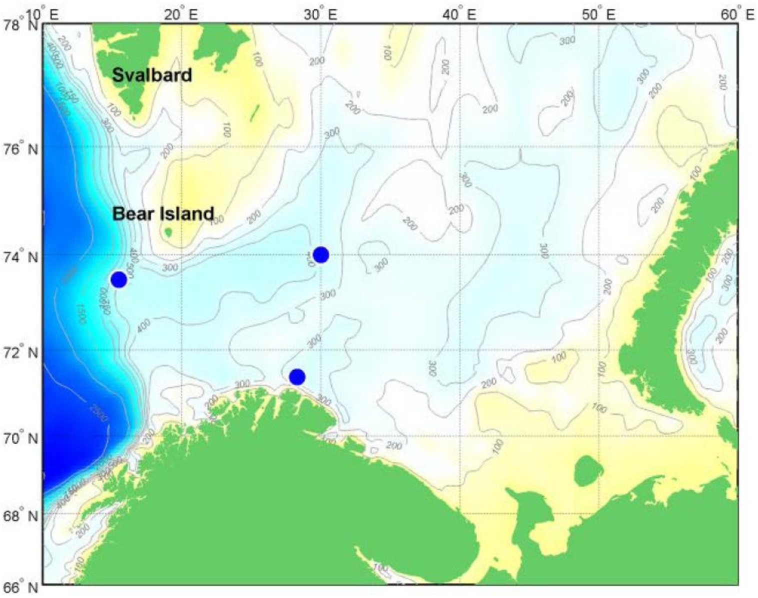


Figure 23: Positions of buoys in the Barents Sea [32]

The alpha factors that were calculated with the all year data indicate that the forecast uncertainty in the Barents Sea is higher than in the North and Norwegian Sea (see section 5.2.2). This is especially the case for waves between 3m and 4m. It has to be mentioned again that the amount of data on which the calculated alpha factors are based is small, thus the results have to be considered with care. Anyhow, 2-4m wave height is the interval in which many marine operations are accomplished, thus with the current knowledge as background it should be considered to use the alpha factors calculated in this thesis rather than DNV's alpha factors for the North Sea and the Norwegian Sea in order to be on the safe side.

Even alpha factors developed especially for the Barents Sea are not sufficient to account for the forecast uncertainty in that region during the winter season. The relatively frequent occurrence of polar lows during the winter period calls for extra measures to reduce the risk for marine operations. Alpha factors that are sufficient in order to perform work in this region can only account for the forecast uncertainty connected to well predictable weather phenomena and not to strong storms, that can build without much indication where and when, within hours. Polar lows can potentially lead to situations with high waves that "come out of nowhere". As noted in section 3, a case was observed by Gunnar Noer in which the wave height increased from 3m to 6m within an hour due to a polar low. If alpha factors would be developed to also take care of these situations they would probably be so low that performing weather restricted marine operations is impossible because no sufficiently long weather window could be found. This shows that alpha factors cannot account for uncertainties in the weather forecast connected to polar lows.

It is necessary though to deal with the threat of polar lows in some way. A good way of treating this uncertainty is using polar low probability forecasts. As described in section 3 the Norwegian Meteorological Institute issues these forecasts. It should be a requirement for weather restricted operations in the Barents Sea that are planned to be done in winter, to use polar low probability forecasts. There are, however, no guidelines yet on how to treat the different probability levels. One way might be to perform no marine operation if there is a moderate probability for polar lows. Another approach could be to make the decision whether marine operations are allowed in case of moderate probability for polar lows dependent on the time it takes to stop the operation in case the polar low probability becomes high. For this approach it is, however, necessary to gather more data on how far ahead a high probability forecast can be issued. The minimum length of time needs to be longer than the maximum time for halting a marine operation because any risk of a polar low at a site during a marine operation is unacceptable. Anyhow, it would be very useful in all cases to be able to stop a marine operation as fast as possible. This might reduce project time, because some marine operations that are only possible to be done in summer could with a reduced halting time also become possible in winter.

In order to assess the risks connected to marine operations in the Barents Sea during winter fully, it is, however, necessary to know how high the waves that develop in polar lows are. Theoretical and practical studies about waves in polar lows exist (see [23],[25],[26]) but especially studies in which wave heights were measured are quite limited and more knowledge about this is needed. With respect to marine operations also a study about wave height forecast uncertainty in polar low events, like attempted in section 5.3, is necessary.

Generally it will probably not be avoidable that marine operations in the Barents Sea during the winter on average will be more costly than further south. That is because more waiting on weather can be expected than in the Norwegian and North Sea. One reason is that weather windows are probably on average shorter than further south because “the mobility of weather systems is generally greater further north” [30]. Furthermore if the alpha factors for the Barents Sea really need to be smaller than in the North and Norwegian Sea this reduces the chances of finding a weather window further. Another reason is the frequency of occurrence of polar lows.

An example from Snøhvit illustrates that the companies have to be prepared financially to perform marine operations in the Barents Sea because long waiting on weather time has to be expected: In October, November 2004 the reel lay vessel CSO Apache was supposed to lay 17 km of pipeline at Snøhvit. Two trips were expected to be needed with estimated offshore work time of 12 days for the first trip and 18 days for the second trip. The acceptable operational wave height was 2.5m to 3.0m and the start of installation work typically required 2-3 days of acceptable weather. The first trip took 12 days but the second one 30 days and even then the work could not be completed. The remaining work was postponed to 2005. Forecasted potential of polar lows in November 2004 introduced this delay during the second trip. [Ove Tobias Gudmestad, UIS, personal communication, June 2012]

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Appendix 1

Duration of sea states for Åsgard where the significant wave height is below the specified values [14].

	2m				3m			
Month	Mean (h)	Stdev. (h)	Max (h)	# events	Mean (h)	Stdev. (h)	Max (h)	# events
1	42	44	247	3,4	73	84	425	5,1
2	45	44	323	3,9	80	96	610	4,7
3	54	59	430	4,2	99	124	976	5,1
4	69	60	321	4,9	156	221	1841	4,7
5	104	106	642	5,3	288	301	1536	3,5
6	112	122	1034	5,0	376	414	1790	2,9
7	136	142	745	4,7	451	451	1852	2,4
8	131	127	823	4,4	327	274	1224	2,5
9	71	71	441	4,9	126	138	867	4,9
10	52	55	341	4,2	75	93	771	5,9
11	38	38	255	4,0	63	68	400	6,0
12	38	36	243	3,2	58	65	443	5,6
Year	75	92	1034	49,5	126	207	1852	47,0
	4m				5m			
Month	Mean (h)	Stdev. (h)	Max (h)	# events	Mean (h)	Stdev. (h)	Max (h)	# events
1	112	137	759	5,2	178	400	4984	4,8
2	143	216	2104	4,2	229	453	4487	4,0
3	183	282	2089	4,7	392	717	4795	3,8
4	414	656	3852	3,5	996	1230	4559	2,2
5	768	909	3746	2,3	1614	1303	3839	1,6
6	1028	886	3137	1,7	1770	1036	3147	1,3
7	981	701	2579	1,5	1653	626	2757	1,1
8	603	430	1835	1,7	963	516	2013	1,3
9	252	258	1595	3,3	403	371	1784	2,4
10	134	184	1488	5,3	237	267	1491	4,0
11	111	130	761	5,4	200	219	1086	4,0
12	80	93	555	6,7	142	190	1361	5,5
Year	200	389	3852	36,5	317	633	4984	25,4
	6m				7m			
Month	Mean (h)	Stdev. (h)	Max (h)	# events	Mean (h)	Stdev. (h)	Max (h)	# events
1	307	683	5757	4,0	566	1144	6698	2,9
2	549	1073	5616	2,9	960	1614	6326	2,2
3	882	1534	5601	3,0	1994	2405	7759	2,1
4	2263	1860	5246	1,6	3567	2029	7480	1,2
5	2822	1298	4713	1,1	3299	1714	6760	1,2
6	2531	930	3969	1,1	3204	1093	6016	1,0
7	2066	634	3249	1,0	2707	825	5296	1,0
8	1353	556	2505	1,1	1963	825	4552	1,0
9	653	490	1804	1,8	1166	789	3808	1,3
10	435	376	1494	2,5	747	623	3088	1,8
11	328	349	2175	3,0	566	525	2344	2,1
12	275	339	1865	3,8	439	515	2283	2,7
Year	544	1030	5757	15,5	961	1594	7759	9,0

Appendix 2

Dates, time and positions of first observations of polar lows over the Nordic seas between 2000 and 2010 [31].

Date	**Time (utc)**	**Lat.**	**Long.**	**Remark**	**Min.SLP (hPa)**	**Max wind (kt)**
19.12.99	1340	72N	18E		989	45
22.01.00	0250	72,5N	29E	Old Erik	990	42
31.01.00	0610	65N	04E	Cirrus on top	978	50
08.03.00	1900	69N	4E		992	35
24.03.00	1230	72N	21E	Most beautiful	997	35-40
01.01.01	1500	75N	22E	**		
04.02.01	1540	62,5N	03W	Pre Mike		
05.02.01	1600	65N	01E	The Mike Low	998	35
02.03.01	0600	75N	41E	**		
19.03.01	1400	75N	08E	**		
24.03.01	0730	74,5N	09E	Marginal	1020	40
10.04.01	0650	71N	02E	Baroclinic	1000	58
27.10.01	1700	74N	09W	**		
01.11.01	0200	71N	19E	The Torsvåg case, Cirrus outflow	992	50
04.11.01	1900	67N	02E	**		
09.11.01	1700	74N	25E	**		
12.11.01	0700	67,5N	07E		990	45
31.12.01	0400	73N	38E	Dual **		
12.01.02	1200	73N	21E		979	35
19.01.02	0400	70N	47E		989	35
22.01.02	1100	75N	28E	Dual systems	985	50
23.01.02	1200	71N	17E	Multiple	978	35
26.01.02	0600	72N	12E	Most beautiful		
19.02.02	1300	74N	34E	Most beautiful	968	55
22.02.02	0000	74N	33E	Dual **		
23.02.02	1140	67,5N	07E		958	45
01.03.02	1200	68N	10E	The polar storm **		50
09.03.02	1100	70N	05W	**		
20.05.02	1436	7320N	1530E	Dual systems	1010	35
19.12.02	1200	74N	47E	Ivans low **		
20.12.02	1200	6820N	1100E		999	30
31.12.02	1100	73N	38E	Multiple **		
16.01.03	1400	72N	0730E			
17.01.03	0000	73,5N	25,5E	Slow moving	985	35
23.01.03	1500	73N	10E	Multiple **	995	53
29.01.03	0700	73,5N	0,5E	Reversed shear	997	50
30.01.03	0700	64N	05E	**		35
11.03.03	0000	72N	16,5E		979	45
23.03.03	0300	68,5N	12,5E	Comma in SW		45

24.10.03	0600	71,5N	18E	Reversed shear	990	45
05.12.03	1320	72N	14E	Reversed shear	990	40
08.12.03	1320	71N	31E	Reversed, secondary	985	44
17.12.03	1300	72N	38E		988	45
27.12.03	1200	73N	18E			38
29.12.03	1200	69N	13E	**		54
27.01.04	0900	71N	12E	Widespr. conv., -50@500hpa	988	45
30.01.04	0700	70N	08W	Short lived	**	
06.02.04	1300	71N	12E	**		
21.02.04	1000	68,5N	03E	Neutral (no) shear	990	55
01.03.04	1200	70N	06,5E	Direct shear, fast moving, dual	999	44
27.03.04	1200	65N	05E	**		53
30.03.04	1800	69N	09E	**		
15.11.04	1400	70N	00E	Dual, neutral, secondary	1002	42
16.11.04	0120	69N	15E	Reversed, secondary	982	44G72
16.11.04	1600	69N	37E	Reversed	987	40
18.11.04	0400	74N	45E	Dual **		
23.11.04	1200	72,5N	46E	Small **		
10.12.04	1700	63N	04W	Secondary, direct shear	1003	50
18.12.04	0700	70N	06E	Secondary, reversed, Radar, Soundings	981	52
13.01.05	1640	68N	07E	Primary, neutral, poor models	1002	55
18.01.05	1800	72N	03W	Large system **		
23.01.05	1320	67N	13E		1003	43
27.02.05	0500	69N	37E	**		
01.03.05	1500	76N	35E	**		
07.03.05	0700	72N	18E	The Brümmer case		35
15.03.05	0900	64N	04E	Direct, primary	999	48
17.03.05	0140	72N	48E	Direct/neutral		
02.04.05	0900	75N	2430E	Secondary, strong reversed.	994	70
26.04.05	1700	74N	25E	Cirrus shield **		
12.10.05		76N	00E	**		50
23.11.05	1500	74N	18E	Double-system/Comma in SW		44
29.11.05	1700	66N	04E	Sounding LDWR, Radar		50
19.12.05	03-06	Vest-	Finnmark	Small (130km)		36
29.01.06	15-21	Hopen		Shear vorticity (Bear Island-Spitsbergen)		35
06.03.06	18-24	Lofoten -	Vesterålen	From a CB-cluster		30G48
20-22.03.06		67N	00E	Multiple, widespread conv. JM sound.1005		40
29.10.06	1200	72N	16E	Primary, good models	992	38G54
08.11.06	1800	63N	07W		998	45
22.12.06	12-18	7150N	17E	Secondary, baroclinic, poor mod.	979	48G61
26.12.06	03-18	7230N	18-22E	Secondary, inst. Occ., reversed	977	49G63

21.01.07	0600	73N	41E	Primary, Stockman, widespread	993	50
22.01.07	1500	76N	04E	Primary, direct, widespread		
26.01.07	04-12	7030N	1430E	Primary, cold, cirrus shield, case	974	51
27.01.07	0000	Vest-	Finnmark	Primary, cold, cirrus shield	982	51
05.02.07	00-06	6430N	09E	2 small polar lows	994	41
13.02.07	0600	7130N	23E	Small PL	1004	40
06.04.07	00-24	7330N	11E	Strong PL, long life time, baroclinic	986	53
29.04.07	01-05	Berlevåg-	Vadsø	Baroclinic PL	1001	51
03.09.07	0500	64N	07E	Season start !	993	40
11.12.07	1930	71N	31E			35
25.01.08	1700	6730N	08E	Comma		35
31.01.08	04-24	74N	11E	Primary		40
14.02.08	2330	69N	38E	Primary, Reversed ?	1012	45
29.02.08	1030	74N	24 E	Dual	950	40
02.03.08	2100	75/69N	09/10E	Dual, small		35
04.03.08	0130	71N	03E	The Thorpex Low	990	45
16.03.08	0830	7140N	12E	Baroclinic		35
18.03.08	1500	7330N	2830E	Dual, reversed		35
20.03.08	0700	72N	43 E			35
04.04.08	0100	72N	01E	Primary, reversed		45
24.04.08	1200	71N	41E			40
27.10.08	2300	6540N	04E	Secondary, reversed, NE of Scotland		50
17.11.08	0700	75N	25E		990	35
18.11.08	0200	75N	02E		980	40
18.11.08	2030	71N	14E	Baroclinic,	971	55
20.11.08	0600	69N	08E	Secondary, reversed, good models	967	65
28.11.08	0900	70N	00E	Secondary, reversed, dual	988	40
29.11.08	1900	73N	01W	Convergence, baroclinic	1004	35
30.12.08	1200	72N	34E	Marginal	995	40
07.01.09	0300	72N	28E	Multiple		50
15.01.09	0100	76N	53E	*		
16.01.09	1200	71N	57E	Baroclinic, Kara Sea	990	40
05.02.09	0300	72N	03W		1008	33
05.02.09	1800	69N	40E	Small, dual	1010	30
07.02.09	1800	72N	43E	Dual	1005	
25.02.09	2100	7130N	22E	*		
26.02.09	1800	70N	13E	Dual, reversed, Baroclinoc	985	40
27.02.09	1800	7230N	3230E	Neutral, baroclinic	1000	30
27.03.09	2300	69N	07W		995	35
02.04.09	0900	73N	3530E	Baroclinic, reversed	1008	35
05.04.09	0000	72N	43E	Baroclinic, reversed	990	40
05.04.09	0700	73N	25E	Cirrus waves on top !	1008	30

08.01.10	1200	8030N	1630E	Small, N of Spitsbergen, conv.		30
29.01.10	1800	68N	08E	In SE off Scandinavian mainland		45
30.01.10	1800	62N	04E		977	36
02.02.10	1600	61N	02E	Convective, marginal	990	35
16.02.10	0900	71N	04E	No observations		
23.02.10	1800	67N	17W		1011	55
02.03.10	0800	6330N	04E	Small, dual, U~20, B, Neutral, Florø	1005	39
04.03.10	1800	73N	42E	Small	1000	40
10.03.10	1600	76N	41E		985	35
12.03.10	1200	72N	19E	Multiple	991	35
14.03.10	1200	73N	16E	No observations	996	
19.03.10	1200	7430N	18E	Dual	994	35
21.03.10	0300	67N	12E	Short lifespan, Neutral, U~20	995	39
24.03.10	1800	72N	18E	Comma, later PL	1012	
27.03.10	0100	7230N	1930E	Baroclinic, reversed, U~20	1005	35
23.04.10	0900	71N	02E	Baroclinic, reversed	1005	35
31.05.10	1800	7030N	1930E	One fatality, baroclinic, neutral	1008	40