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Uncertainty in forecasted environmental conditions for reliability analyses of marine operations

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ABSTRACT

Marine operations, e.g., the sea transport of heavy objects and the installation of offshore units and equipment, need to be planned and executed with proper consideration for environmental conditions and operational limits with respect to vessel motions and structural loads. Marine operations with a limited duration, usually less than 72 h, are typically designed as weather-restricted operations. The environmental design criteria are thus predefined, and the actual weather conditions are confirmed by weather forecasts issued immediately prior to the start of such an operation. Marine operations of longer duration are typically designed as weather-unrestricted operations, and the environmental conditions are calculated based on long-term statistics, possibly depending on the season. More detailed information about uncertainties in weather forecasts could increase the feasible duration of weather-restricted operations. The uncertainty inherent in weather forecasts, notably that in the significant wave height, is studied. Further, a method to assess the reliability of weather forecasts is described. Data from the Norwegian Sea are used to quantify the uncertainty in forecasted data. The probability of exceeding the design criteria used in the planning of a weather-unrestricted marine operation can be estimated based on forecast statistics. The corresponding uncertainty can be incorporated into structural reliability analyses.

1. Introduction

The work presented in this paper is part of a research project regarding the level of reliability inherent in marine operations. The uncertainty in the environmental conditions, and hence in the wave- and wind-induced load effects, that are considered in the planning of an operation is important with respect to the overall reliability level. The scope of this paper encompasses the study of methods to account for the uncertainty inherent in weather forecasts for marine operations. This is of interest, e.g., with regard to structural design for sea fastening (i.e., the design of structures to secure a transported object to the transport vessel), but the approach is more general. The marine operations considered herein are specially planned, non-routine operations of limited duration related to the load transfer, transport and installation of objects, typically in the offshore oil and gas industry. The need for special planning may arise because the transported object is large and/or heavy or has a high economic value or a long replacement time. Therefore, the consequences of severe damage to or total loss of such a transported object are large, involving economic loss and possibly pollution of the environment. Most likely, there will also be delays in the project, and some loss of reputation may be suffered by the companies involved. It is therefore necessary to quantify the uncertainties inherent in such an operation. The environmental conditions are important input for the planning of marine operations, particularly with regard to the motion analysis of floating vessels. Hence, the uncertainty in the environmental conditions and how it is accounted for in the planning/design exert a considerable effect on the safety level of such an operation.

Marine operations can be designed in accordance with several Standards and Guidelines. These operations are generally defined as either weather-restricted or weather-unrestricted operations, depending on their duration. For weather-restricted operations planned in accordance with DNV (2011) or GL Noble Denton (2013), the uncertainty inherent in the weather forecasts of the significant wave heights and wind speeds is accounted for by a so-called α-factor; see Eq. (2). For weather-unrestricted operations, the weather criteria cannot be based on forecasts but instead must be based on long-term statistical data on the environmental conditions.

The uncertainty in the forecasting of significant wave heights is quantified by comparing the forecasted wave heights with the

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actual waves at the location. Instead of observed/measured significant wave heights, hindcast data are used. The uncertainty is described by estimating the mean values and standard deviations of the difference and ratio between the hindcasted and forecasted wave heights. Data from the Norwegian Sea are applied to quantify the uncertainty in the forecasted data.

The objective is to incorporate the uncertainty resulting from weather forecasts into reliability analyses for marine operations. For most marine operations, the environmental loads govern the planning and structural design, and hence, the uncertainty in forecasted environmental conditions is important input for these analyses. The uncertainty in the forecasted significant wave height is studied in this paper. The intent is to address reliability analyses in a separate paper.

2. Planning of marine operations

2.1. Design standards for marine operations

Marine operations must be designed in accordance with certain standards/guidelines. We are aware of two such standards and two such guidelines:

- DNV-OS-H101, Marine Operations, General, DNV (2011).
- GL Noble Denton (2013), General Guidelines for Marine Projects.
- ISO 19901-6 (2009) Petroleum and natural gas industries. Specific requirements for offshore structures. Part 6: Marine Operations.
- London Offshore Consultants Limited, Guidelines for Marine Operations, LOC (1997).

A key parameter for a marine operation is the duration. It is defined as the best estimate plus an ample margin to account for inaccuracies in schedule and delays. This is the approach used in all referenced standards. Using the notation from DNV (2011), the operation reference period, T_R, is defined as follows:

$$T_R = T_{POP} + T_C \tag{1}$$

where T_{POP} is the planned operation period and T_C is the estimated maximum contingency time. (The estimated maximum contingency time is often between 50% and 100% of the planned operation period, unless more accurate information is known.)

2.2. Weather-restricted operations

If the duration of the operation is less than 72 h, then the operation can be defined as a weather-restricted operation. An operation can also be defined as weather restricted if it can be halted and the handled object brought into safe conditions during the same period. For a sea transport operation, this means that the route must be divided into several legs, and ports or areas of shelter along the transport route must be predefined. Updated weather forecasts are received regularly throughout the entirety of such an operation.

Traditionally, the maximum duration of a weather-restricted operation has been three days including contingency time, i.e., $T_R \le 72$ h. This limit is stated in ISO 19901-6 (2009), GL Noble Denton (2013), LOC (1997), NORSOK (2007). DNV (1996/2000) also adhered to this limit until 2011. In DNV (2011), however, the maximum operation period was increased to four days including contingency provided that the planned operation period is less than three days.

For marine operations in areas and seasons in which it can be demonstrated that weather forecasts are capable of predicting any extreme weather conditions over a longer period, the operation reference period may be increased accordingly. By contrast, in areas and/or seasons in which the corresponding reliable weather forecasts are not considered realistic, a shorter limit is to be applied.

If an operation is weather restricted, then the design environmental criteria are defined in an early phase of the project. Weather-restricted operations are beneficial because the owner, or his representative, may define the necessary environmental criteria (with the understanding that more strict environmental criteria may lead to more wait time before the operation can commence). The operation may commence when the weather forecasts indicate acceptable environmental conditions. The uncertainty in the weather forecasts and how to include this uncertainty in the planning of the operation thus become key issues.

To account for the uncertainty in weather forecasts, the operational environmental limits must be less than those considered in the design. According to DNV (2011) and GL Noble Denton (2013), the operational limit on the significant wave height can be expressed as

$$H_{s,oper} = \alpha H_{s,design} \tag{2}$$

where α is a parameter (≤ 1) that depends on both the duration of the operation and the level of forecasting and/or monitoring. In DNV (2011), α also depends on the significant wave height used in the design. The parameters for the base case, with one weather forecast available, are shown in Table 1. The α-factor can be increased if the wave height at the site of the operation is monitored and if there is a meteorologist on site (because the presence of a meteorologist will increase the confidence in weather forecasts at that location). In the DNV method, α accounts for the uncertainty in the weather forecast based on the planned duration ($T_{Dur} = T_{POP}$), but the forecasted wave height must be less than $H_{s,oper}$ for the operation reference period, T_R. In the GL Noble Denton method, α is based on the operation reference period ($T_{Dur} = T_R$). It should be noted that the safety formats (load and material factors) are somewhat different in the DNV and GL Noble Denton formulations and that the corresponding αs may not be directly comparable.

2.3. Weather-unrestricted operations

Operations with durations longer than three days are typically weather unrestricted. The separation between these two categories is important, as these two types of operations will be designed differently with respect to environmental loads.

Weather-unrestricted marine operations are not planned based on weather forecasts, because the duration of such an operation is longer than the duration over which weather forecasts are considered reliable. Instead, the environmental conditions used for planning must be based on long-term statistics. The environmental

Table 1
The parameter α as a function of operation duration from DNV (2011) and GL Noble Denton (2013) for the case of one weather forecast and no wave monitoring. In DNV (2011), the parameter definition is valid only for the North Sea and the Norwegian Sea and is given as a function of the design wave height.

T_{Dur} (h)	DNV			GL Noble Denton
	$H_s = 2$ m	4 m	$\ge$ 6 m	
12	0.76	0.79	0.8	0.69
24	0.73	0.76	0.78	0.65
48	0.68	0.71	0.74	0.59
72	0.63	0.68	0.72	0.54

loads will then be based on a set of conditions with a given (low) probability of being exceeded.

In the planning of an unrestricted operation, the environmental criteria for the design must be based on long-term statistics accounting for

- the geographical area,
- the season of the year and
- the duration of the operation.

The extreme values of the wave heights may be calculated based on scatter diagrams, e.g., those from BMT Ltd (1986) or DNV (2014). It should be noted that the scatter diagrams from DNV are based on visual observations of the sea and may therefore, to some extent, include the effects of heavy weather avoidance (i.e., the largest waves are never observed).

For commercial projects, more accurate data may be purchased, e.g., from Fugro Oceanor. Data from Fugro Oceanor are derived from hindcast models and are calibrated against satellite data and, where available, in situ wave buoy data (FugroOceanor, 2012).

A study by Shu and Moan (2008) of a VLCC (very large crude carrier) and a bulk carrier indicated that the use of data from Fugro Oceanor yielded amidships bending moments that were approximately 15% larger than those deduced from the scatter diagrams of DNV (2014).

Another alternative is the computer program Safetrans from Marin (2007), which contains a large environmental database and can provide wave statistics for certain transport routes and seasons.

3. Description of environmental conditions

3.1. Weather forecasts

Several global systems are available for weather forecasters, e.g., those from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the US-based National Centers for Environmental Prediction (NCEP).

The ECMWF system includes atmospheric variables, such as wind, temperature and precipitation, in addition to waves for offshore applications. The forecasts are based on the Ensemble Prediction System (EPS) (see, e.g., Saetra and Bidlot, 2004). The dynamical weather system is then simulated several times, each time changing the initial conditions slightly. The forecasters receive data from the ECMWF and perform their own evaluations and interpretations of the results, on which the weather forecasts are then based. The forecasts from different meteorologists may therefore differ for the same location and time.

For projects involving the installation of structures at offshore locations, weather forecasts are issued throughout the project period, which may be several years. In this paper, we will consider forecasted data for the Skarv oil and gas field, which is located 210 km west of Sandnessjoen, Norway, at a water depth of 350–450 m. The weather forecasts are provided by BP.

The forecasts include, amongst other information, the significant wave height H_s and the zero-crossing period T_z for wind-generated waves, swell and the total sea. The relation between these significant wave heights is $H_{s,total\ sea} = (H^2_{s,wind\ waves} + H^2_{s,swell})^{0.5}$. Only the total sea, i.e., the significant wave height resulting from both wind generated waves and swell, has been assessed in this paper. The lead time is defined as the numbers of hours from the time when the forecast is issued until the time for which it applies. The first set of forecasted values is for a three-hour lead time. Forecasted values are generally given every three hours for the first 72 h (for some forecasts, 69 h) and every six hours thereafter until the 168th hour. The data are for the year 2011 and include 1150 forecasts (generally three forecasts per day, with four forecasts for certain days).

3.2. Hindcast data

The formula given in Eq. (23) is a simple hindcast model, in which the significant wave height is estimated from the wind speed. This model does not, however, include the effects of wind

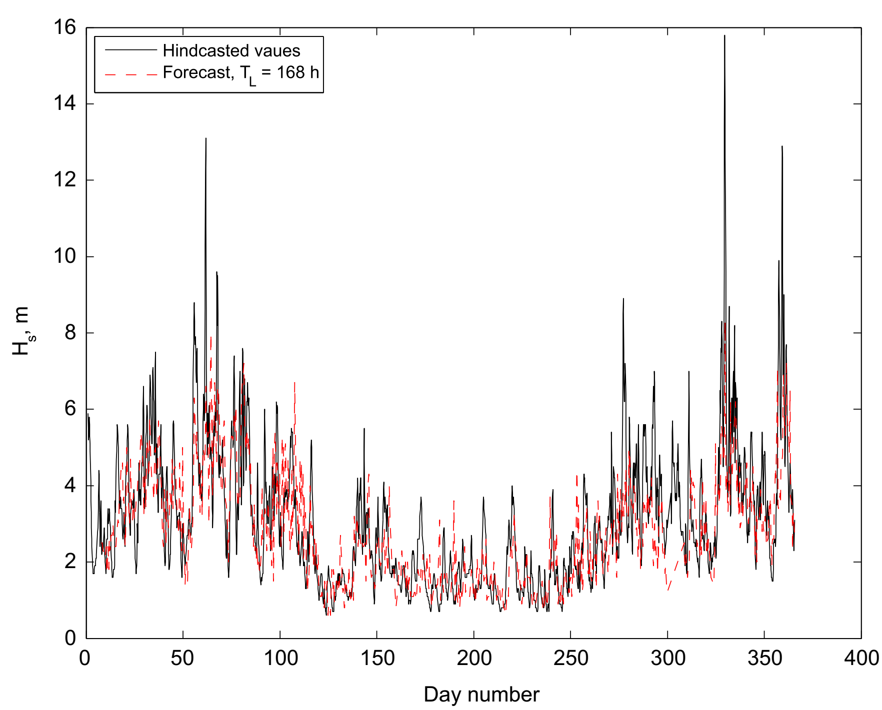

Fig. 1. Forecasted and hindcasted significant wave heights for a lead time of seven days.

fluctuations in time and space or any effects of the sea bottom topology, etc. A surface ocean wave model that does include such effects is used by meteorologists to hindcast wave data.

The hindcast data used in this study were provided by the Norwegian Meteorological Institute (DNMI, http://www.met.no). The data are based on the WAM Model of the Wamdi Group (1988). The quality of these hindcast data compared with the observed data is very good; see, e.g., Reistad et al. (2011). Therefore, in this paper, these hindcast data are used instead of observed data.

3.3. Comparing forecast and hindcast data

Forecasted and hindcasted wave heights are shown in Fig. 1. The figure shows the significant wave height in the year 2011 as a function of time in days (the first of January is day no. 1, and so on). The hindcasted significant wave height is shown in black. The forecasted significant wave height shown in red is given for a lead time of 168 h, i.e., these data represent the weather as forecasted seven days before (e.g., the wave height shown on day 30 is taken from the weather forecast issued on day 23, and so on). No details can be seen from the plot, but it is apparent that the trend is predicted quite well, even if the maximum significant wave heights (the peak values) are not forecasted. The maximum significant wave height at this location in 2011 was 15.8 m on day no. 329 (i.e., on 2011-11-25) at 18.00 h. In Fig. 2, the wave heights a few days before and after this date are shown together with the forecasted wave heights issued 72 and 168 h before. The maximum wave height was not captured in any of the forecasts, but the three-day forecast was, as expected, closer than the seven-day forecast.

The difference between the hindcasted and forecasted significant wave heights is also illustrated for two different lead times in Fig. 3 for one two-week period in June and one in December.

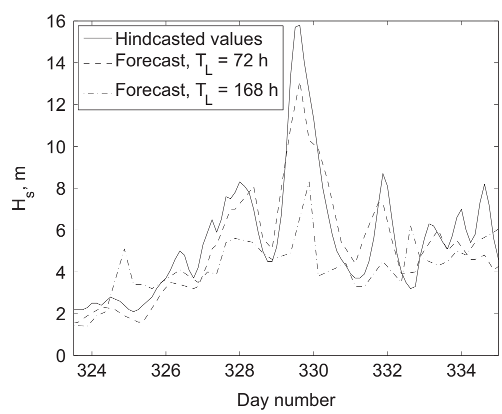

Fig. 2. Forecasted H_s values for lead times of three days and seven days together with hindcast H_s values for November 20 (day no. 324) to 30, 2011

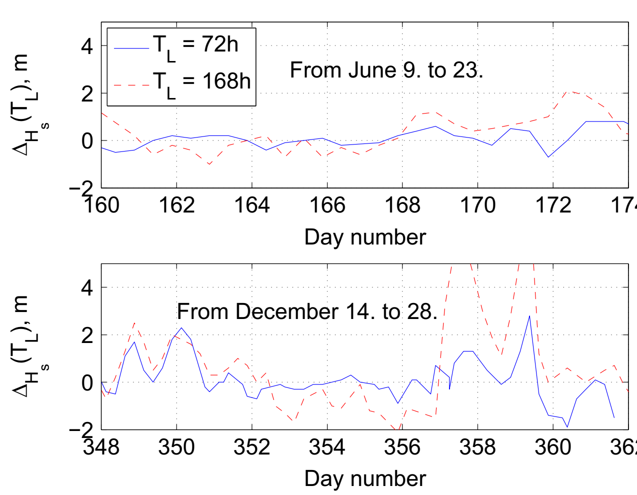

Fig. 3. The difference between hindcasted and forecasted significant wave heights ($\Delta_{H_s}(T_L)$ in Eq. (5)) for one two-week period in June and one in December 2011 for lead times of three and seven days

4. Model uncertainty in weather forecasts

4.1. Statistical models

The environmental conditions are an important input for marine operations. The significant wave height and wind speed are key information obtained from weather forecasts. For certain marine operations, the wave periods and wave directions may also be important. The uncertainties inherent in the environmental conditions predicted by forecasts, e.g., the significant wave height, can be quantified using two different mathematical models, one additive and one multiplicative model. The statistical parameters for these models are estimated based on hindcasted and forecasted data. The additive model is formulated as follows:

$$\Delta = Z_{true} - Z_{predicted} \tag{3}$$

where Δ is a stochastic variable. In our case, the predicted values are obtained from weather forecasts, whereas the true values are the hindcast data. In the multiplicative model, the stochastic variable χ is defined as follows:

$$\chi = \frac{Z_{true}}{Z_{predicted}} \tag{4}$$

Because the stochastic variable (Δ or χ) depends on the wave height, lead time (or forecasting period) and season, the mean value and the standard deviation of this variable are also functions of these parameters.

The statistical parameters necessary for a realization of the stochastic variable Δ (or χ) are calculated via the standard formulas using the software package (Matlab, 2010).

4.2. Uncertainty as a function of lead time

We now consider the significant wave height given in a weather forecast and define a stochastic variable $\Delta_{H_s}(T_L)$ as follows:

$$\Delta_{H_s}(T_L) = H_{s,hindcast} - H_{s,forecast}(T_L) \tag{5}$$

where T_L is the lead time. (A similar definition may also be used in the multiplicative model.) In Fig. 6, Δ_{H_s} is shown as a function of lead time.

The correlation between the forecasted and hindcasted significant wave heights is shown for several lead times in Fig. 4. As expected, the correlation is initially high and decreases with increasing lead time. In Fig. 5, the wave periods (spectral peak periods, T_p) are shown in a similar manner. It is apparent that the correlation between forecasted and hindcasted significant wave heights is higher than the correlation between forecasted and hindcasted wave periods. In fact, it seems preferable to use a fitted conditional probability distribution for the wave period but to base the wave height solely on the weather forecast.

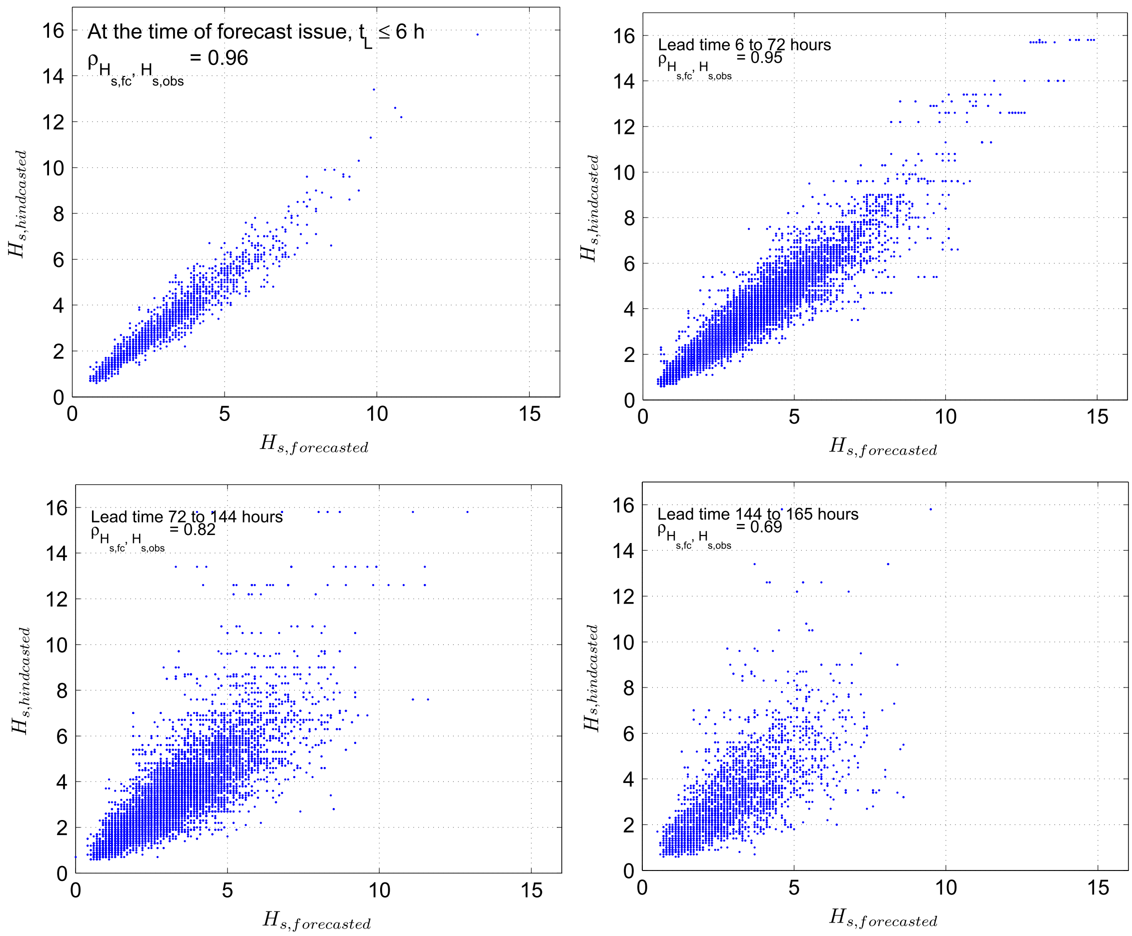

Fig. 4. Forecasted versus hindcasted significant wave height; note that for the longest forecast period, the largest waves are not forecasted

4.3. Uncertainty within a forecast period

In Eq. (5), the forecasting uncertainty is considered as a function of the lead time alone. For most marine operations, however, the primary concern is not whether a certain weather condition occurs exactly when forecasted but rather whether it occurs at all during the marine operation. Given the maximum wave height that is predicted to occur during a certain period, the probability that this wave height will be exceeded can be estimated.

A stochastic variable can be defined based on the additive model as follows:

$$\Delta_{H_{s,max}}(T_R) = H_{s,hc,max} - H_{s,fc,max} \tag{6}$$

where

$$H_{s,fc,max} = \max_{\tau}\{H_{s,forecast}(\tau)\} \quad \text{for } t \leq \tau \leq t + T_R \tag{7}$$

is the maximum forecasted significant wave height during the operation reference period and

$$H_{s,hc,max} = \max_{\tau}\{H_{s,hindcast}(\tau)\} \quad \text{for } t \leq \tau \leq t + T_R \tag{8}$$

is the maximum hindcasted significant wave height during the same period. Similarly, a stochastic variable can be defined based on the multiplicative model as follows:

$$\chi_{H_{s,max}}(T_R) = \frac{H_{s,hc,max}}{H_{s,fc,max}} \tag{9}$$

4.4. Quantification of model uncertainty

The methodology for estimating the uncertainty is as follows:

- Establish the observed data and weather forecasts for a certain period of time at a chosen location.
- Calculate $\Delta_{H_{s,max}}(T_R)$ from Eq. (6) and $\chi_{H_{s,max}}$ from Eq. (9).
- Calculate the statistical parameters.
- Choose the statistical distribution for the variables. For each data set, fit the distribution to the data.
- Extract percentile values for Δ_{H_s} and χ_{H_s} as functions of lead time and forecasted H_s, either based on the chosen statistical distribution or directly from the data sets.

The mean values and standard deviations for realizations of these stochastic variables (i.e., for the data from 2011) are shown in Figs. 7 and 8 for the additive and multiplicative models, respectively. (Note that whereas a perfect weather forecast would yield a mean value of 0 m for $\Delta_{H_{s,max}}$, the corresponding mean value would be equal to 1.0 for $\chi_{H_{s,max}}$.)

Figs. 7 and 8 present all-year data. However, the majority of marine operations are performed during the summer season, and therefore, seasonal data may be more relevant to use for analysing the uncertainties in weather forecasts. The data are therefore divided into two seasons: the summer season, from April to September, and the winter season, from October to March. (Data are often divided into four seasons or into monthly data, but because the data for only one year are considered here, only two seasons are defined.)

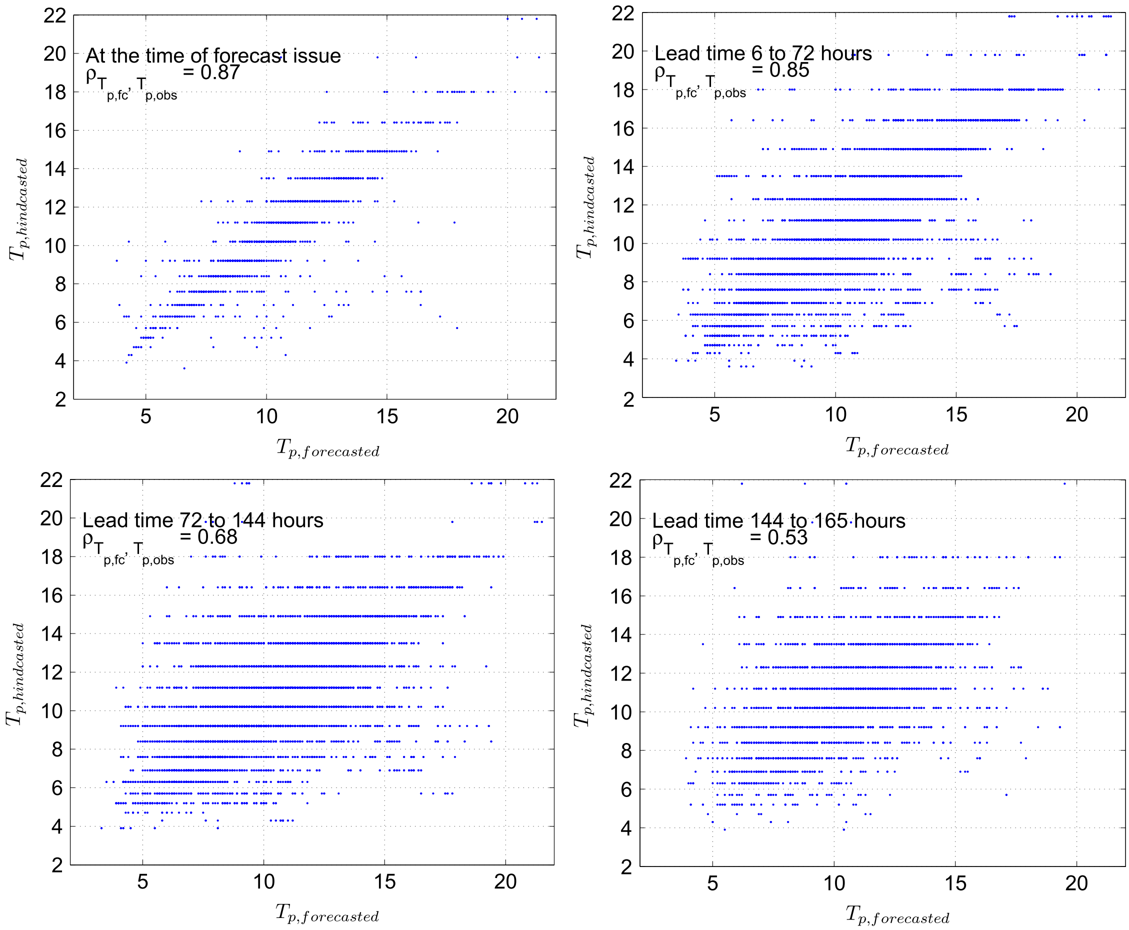

Fig. 5. Forecasted versus hindcasted peak wave periods

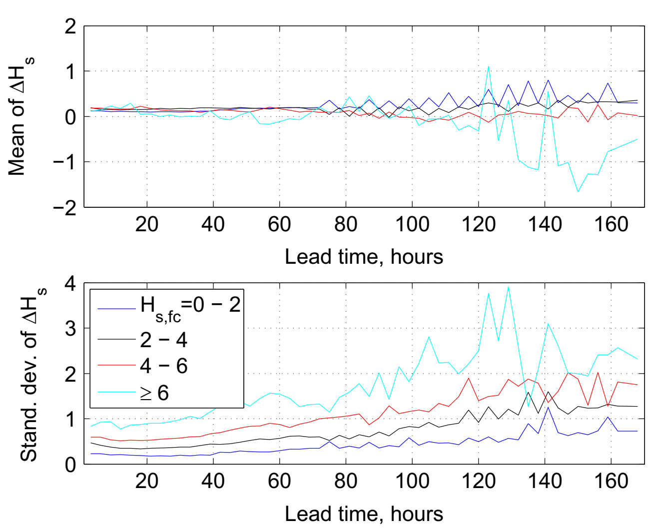

Fig. 6. Mean values and standard deviations of the stochastic variable Δ_{H_s} as a function of *lead time* for four groups of forecasted significant wave heights: 0–2 m, 2–4 m, 4–6 m and >6 m.

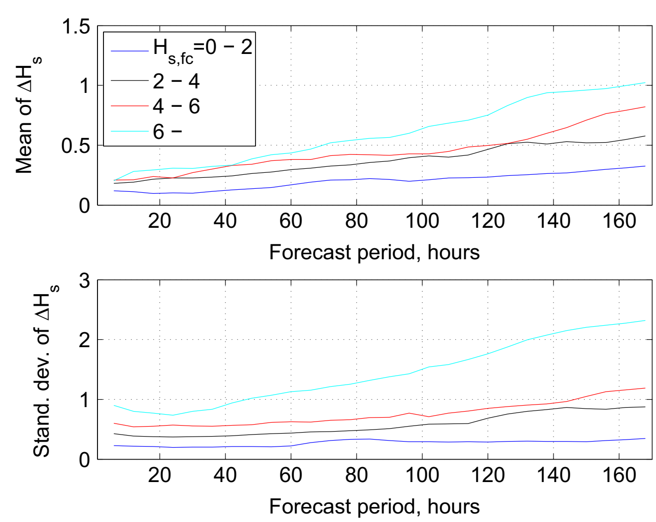

Fig. 7. Statistical parameters for the stochastic variable $\Delta_{H_{s,max}}$, based on the additive model, as functions of the *forecast period* for four groups of forecasted significant wave heights: 0–2 m, 2–4 m, 4–6 m and >6 m

In Figs. 9 and 10, the means and standard deviations of $\Delta_{H_{s,max}}$ are given for the summer and winter seasons for two groups of forecasted wave heights. The corresponding parameters for the variable $\chi_{H_{s,max}}$ are shown in Figs. 11 and 12.

It is evident that the means and standard deviations of $\Delta_{H_{s,max}}$ depend on the size of the forecasted significant wave height; this is particularly apparent from the all-year data presented in Fig. 7 and is, to some extent, also observed for the seasonal data presented in Figs. 9 and 10. In the groups corresponding to significant wave heights of 2–4 m and 4–6 m, the mean and the standard deviation are both larger during the winter season than during the summer season, except for H_s for the 4–6 m group for forecast periods of less than 50 h. (Notably, this variation could also, to some extent, be attributed to the fact that the forecasted wave

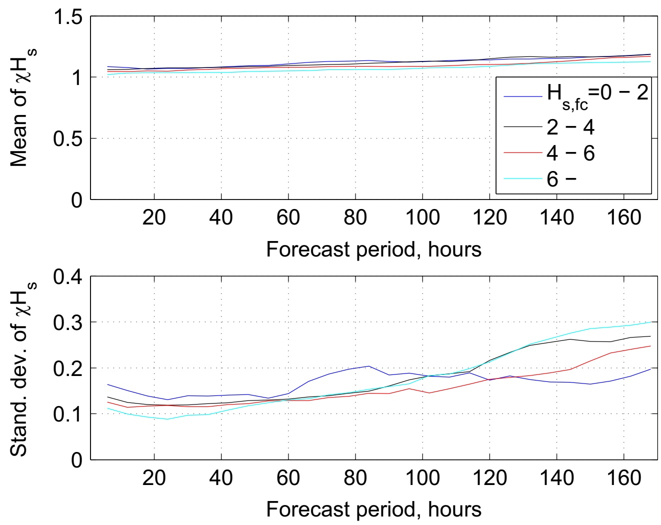

Fig. 8. Statistical parameters for the stochastic variable $\chi_{Hs,max}$, based on the multiplicative model, as functions of the *forecast period* for four groups of forecasted significant wave heights: 0–2 m, 2–4 m, 4–6 m and >6 m.

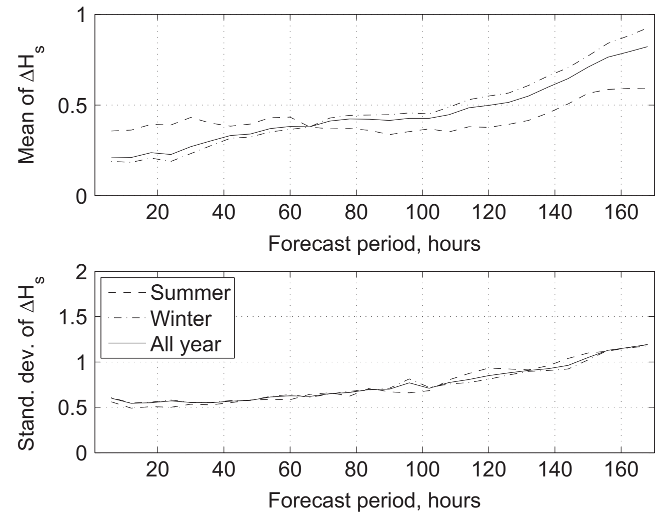

Fig. 10. Statistical parameters for the additive model as functions of the forecast period for the summer (April–September) and winter (October–March) seasons for forecasted wave heights between 4 and 6 m

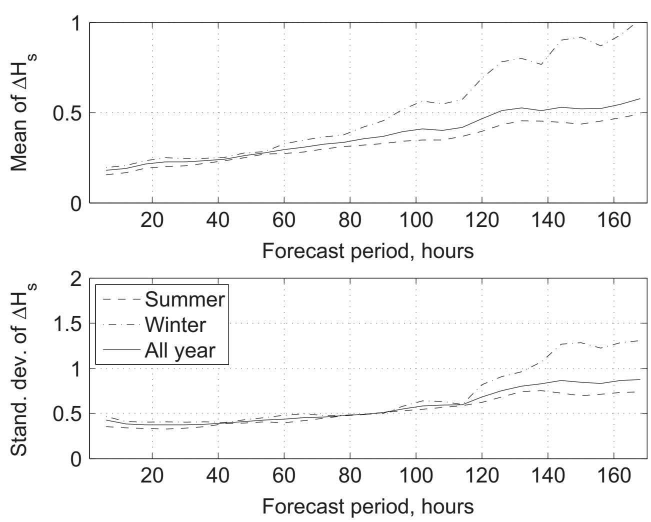

Fig. 9. Statistical parameters for the additive model as functions of the forecast period for the summer (April–September) and winter (October–March) seasons for forecasted significant wave heights between 2 and 4 m.

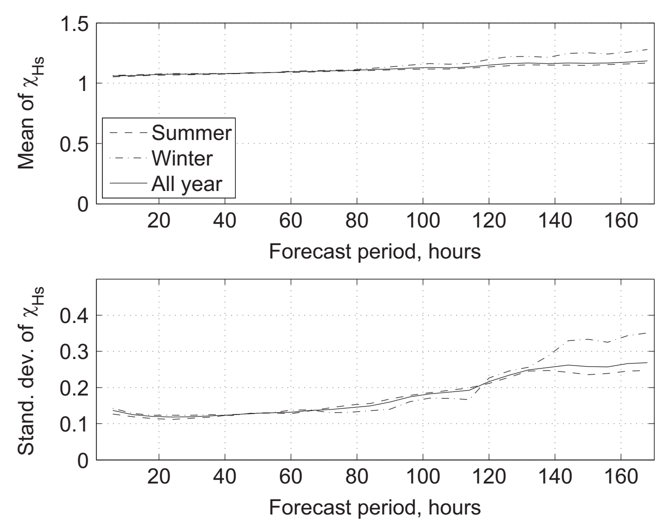

Fig. 11. Statistical parameters for the multiplicative model for the summer (April–September) and winter (October–March) seasons for forecasted wave heights between 2 and 4 m

heights are larger during the winter season and could thus reflect behaviour similar to that observed in Fig. 7 rather than an actual seasonal variation.)

The effects of the forecasted wave height and season are smaller for $\chi_{Hs,max}$. In Fig. 8, the mean values are essentially identical for all wave height groups, and the spread in the estimated standard deviation also appears not to depend on the forecasted wave height.

Based on the above findings, we choose to use the multiplicative model and to include all wave heights in a single group when performing the analysis. The behaviours of the statistical parameters in this analysis are shown in Fig. 13.

4.5. Uncertainty in point estimates

The uncertainties in the model parameter estimates are calculated via a bootstrap method using Matlab (2010). The 95% confidence interval for the mean value in Fig. 13 is found to be within $\pm 1\%$ of the estimates. For the standard deviation, the corresponding interval ranges from −5% to +10% of the estimates. For the skewness and kurtosis, the uncertainties are much larger. The 95% confidence interval varies with the forecast period, but it ranges from approximately −50% to +100% of the estimates (hence, single values in the confidence interval may be from 0.5 times to 2 times the corresponding estimates). It is well known that estimates of skewness and kurtosis suffer from a relatively large uncertainty for data sets of limited size. However, these parameters are used here only to identify a plausible statistical distribution to be fitted to the data set, and hence, the uncertainties are considered acceptable.

5. Statistical description of environmental conditions

5.1. Significant wave heights

A short-term sea state is described by a significant wave height and a wave period and possibly also by other wave spectral parameters (bandwidth parameter, doubly peaked spectrum, etc.).

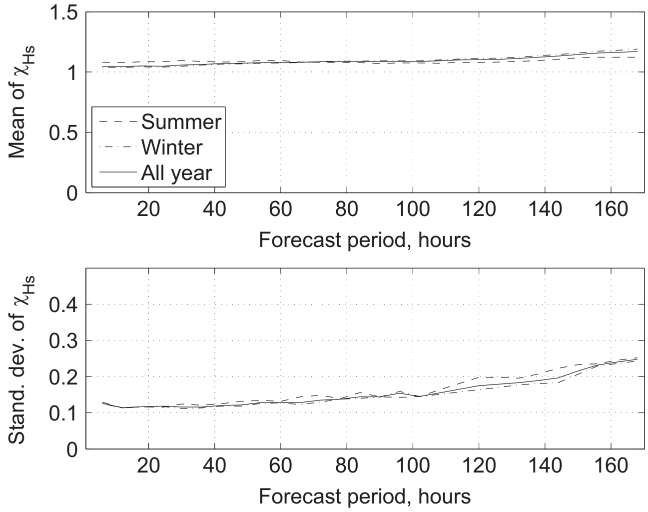

Fig. 12. Statistical parameters for the multiplicative model for the summer (April–September) and winter (October–March) seasons for forecasted wave heights between 4 and 6 m.

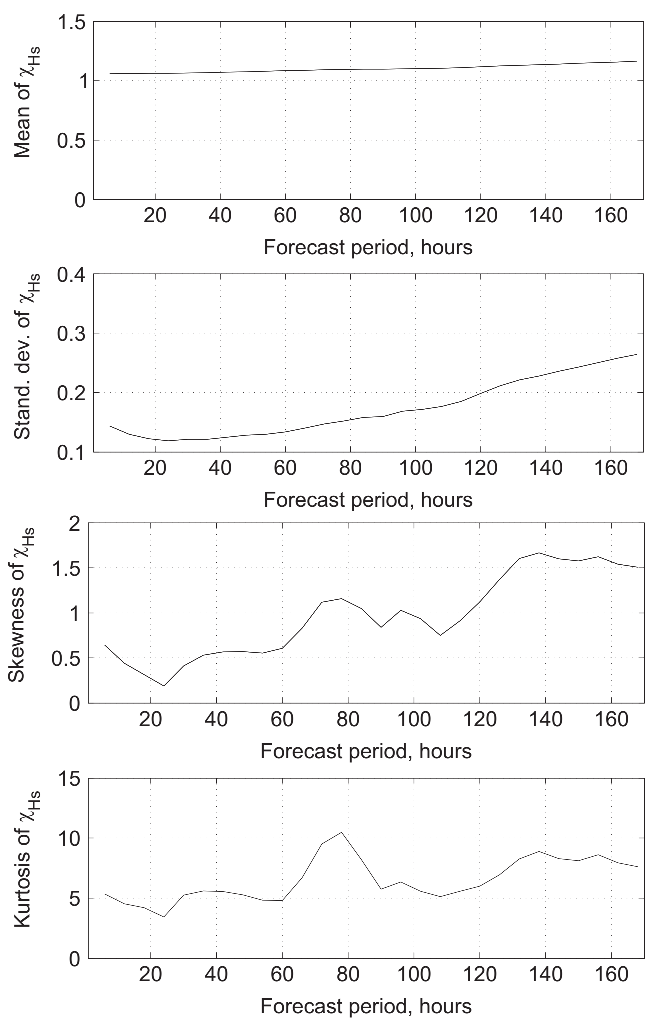

Fig. 13. Mean value, standard deviation, skewness and kurtosis of the stochastic variable $\chi_{Hs,max}$, based on the multiplicative model, as functions of the forecast period.

Given a forecasted significant wave height (i.e., the maximum predicted value during the forecast period) $h_{s,fc}$, the maximum significant wave height to be used in an operational design may be defined as a stochastic variable. In the additive model, this variable is defined as follows:

$$H_{s,max} = h_{s,fc} + \Delta_{Hs,max} \tag{10}$$

where $\Delta_{Hs,max}$ is defined in Eq. (6). The mean value and the standard deviation are equal to

$$\mu_{Hs,max} = h_{s,fc} + \mu_{\Delta Hs,max} \tag{11a}$$

$$\sigma_{Hs,max} = \sigma_{\Delta Hs,max} \tag{11b}$$

In the multiplicative model, the maximum wave height is expressed as follows:

$$H_{s,max} = \chi_{Hs,max} \cdot h_{s,fc} \tag{12}$$

where $\chi_{Hs,max}$ is defined in Eq. (9). The mean value and the standard deviation are equal to

$$\mu_{Hs,max} = h_{s,fc} \cdot \mu_{\chi Hs,max} \tag{13a}$$

$$\sigma_{Hs,max} = h_{s,fc} \cdot \sigma_{\chi Hs,max} \tag{13b}$$

It is evident from Fig. 13 that the skewness is positive and that the kurtosis is larger than three. Thus, the log-normal distribution may be suitable (see, e.g., Hahn and Shapiro, 1967, Fig. 6-1).

Under the assumption of a log-normal distribution, the probability density function for the maximum significant wave height during the operation reference period for a given weather forecast may be expressed as follows:

$$f_{Hs,max}(h_{s,max}) = \frac{1}{\sigma_{\ln Hs} h_{s,max} \sqrt{2\pi}} e^{-(1/2)((\ln h_{s,max} - \mu_{\ln Hs})/\sigma_{\ln Hs})^2} \tag{14}$$

where the mean value and the standard deviation of the logarithm of H_s are calculated as follows:

$$\mu_{\ln Hs} = \ln(h_{s,fc}) + \mu_{\ln \chi} \tag{15a}$$

$$\sigma_{\ln Hs} = \sigma_{\ln \chi} \tag{15b}$$

where $h_{s,fc}$ is given in meters and

$$\sigma_{\ln \chi} = \sqrt{\ln\left(1 + \left(\frac{\sigma_{\chi Hs,max}}{\mu_{\chi Hs,max}}\right)^2\right)} \tag{16a}$$

$$\mu_{\ln \chi} = \ln(\mu_{\chi Hs,max}) - \frac{1}{2}\sigma_{\ln \chi}^2 \tag{16b}$$

The cumulative distribution function is

$$F_{Hs,max}(h_{s,max}) = \Phi\left(\frac{\ln(h_{s,max}) - \mu_{\ln Hs}}{\sigma_{\ln Hs}}\right) \tag{17}$$

where $\Phi(\,)$ is the cumulative distribution function for the standard normal distribution.

5.2. Wave period

The wave period is given in the weather forecast and may be included in the analysis in a similar manner as is the wave height. However, because of the relatively low correlation between forecasted and hindcasted periods (see Fig. 5), this is not done here. The uncertainty in the wave periods can instead be accounted for using a statistical distribution that is conditional upon the

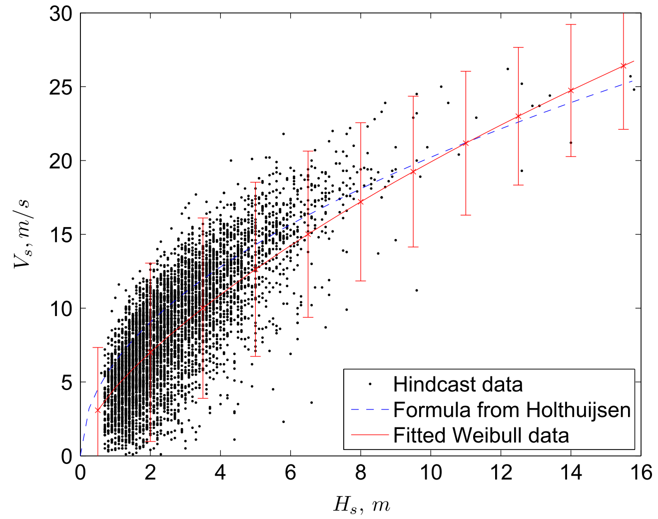

Fig. 14. Wind speed at a height of 10 m averaged over one hour versus significant wave height (hindcast data) at the Skarv field for 2010 and 2011, together with the wave-wind relation obtained from Holthuijsen's formula, Eq. (24), and the fitted Weibull distribution, i.e., the mean value from Eq. (20) with error bars of $\pm 2\sigma_{V|H_s}$ (see Eq. (21))

Table 2
Coefficients obtained by fitting Eq. (19) to the data from the Skarv field for 2010 and 2011.

Coefficient	Fitted value
c_1	1.23
c_2	0.55
c_3	1.17
c_4	0.00
c_5	5.19
c_6	0.61

Table 3
Mean wind speeds and standard deviations based on the conditional Weibull distribution (see Eqs. (19)–(21)) with coefficients from Table 2.

H_s (m)	$\mu_{V|H_s}$ (m/s)	$\sigma_{V|H_s}$ (m/s)
1	4.6	2.7
2	7.0	3.0
4	10.9	3.0
6	14.2	2.9
8	17.2	2.7
10	19.9	2.5
12	22.4	2.4
14	24.7	2.2

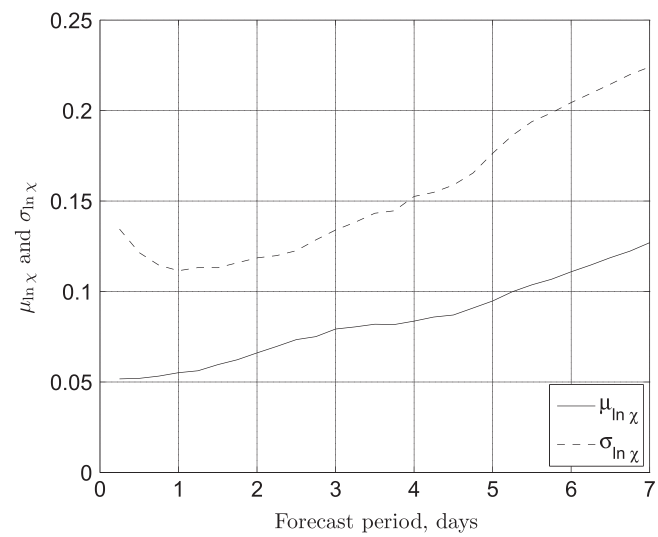

Fig. 15. Mean value ($\mu_{\ln\chi}$) and standard deviation ($\sigma_{\ln\chi}$) of the logarithm of χ in the multiplicative model, based on the previously mentioned Skarv data for all forecasted wave heights, as a function of the operation period.

significant wave height. The period may be described by a log-normal distribution, as shown by Bitner-Gregersen and Haver (1991). For design purposes, the distribution of the zero-crossing period, T_z, follows a log-normal distribution that is conditional on H_s:

$$f_{T_z|H_s}(t|h) = \frac{1}{\sigma_{\ln T_z} t\sqrt{2\pi}} e^{-(1/2)((\ln t - \mu_{\ln T_z})/\sigma_{\ln T_z})^2} \tag{18}$$

with parameters $\mu_{\ln T_z} = a_1 + a_2 h^{a_3}$ and $\sigma_{\ln T_z} = b_1 + b_2 e^{b_3 h}$ (see, e.g., DNV, 2014). The coefficients a_i and b_i, with $i = 1, 2, 3$, are estimated from real data.

For engineering purposes, the upper and lower bounds on the wave periods are given as functions of the significant wave height by, e.g., DNV (2011), GL Noble Denton (2013), and LOC (1997).

5.3. Wind speed

The wind speed may be treated in a similar manner as the wave heights, namely, by comparing forecasted values with observed values, resulting in a statistical description of the deviation. Alternatively, the wind speed can be inferred based on the joint probability density function of wind speed and wave height.

The significant wave height for wind-driven waves is typically conditional upon the wind speed, as the wind creates such waves; see, e.g., Johannessen et al. (2002).

However, in our scenario, the wind speed must be determined for a given significant wave height.

The joint probability distribution of wave height and wind speed is $f_{V,H_s}(v,h) = f_{H_s}(h) f_{V|H_s}(v|h)$, where the conditional distribution of the wind speed can be described by a two-parameter Weibull distribution; see Bitner-Gregersen (2005):

$$f_{V|H_s}(v|h) = k\frac{v^{k-1}}{V_C^k} e^{-(v/V_C)^k} \tag{19}$$

where the shape parameter is $k = c_1 + c_2 h^{c_3}$ and the scale parameter is $V_C = c_4 + c_5 h^{c_6}$. The coefficients c_i, $i = 1, 2, \ldots, 6$, are estimated from real data. The mean value of the conditional wind speed is

$$\mu_{V|H_s} = E[V|H_s] = V_C \Gamma\left(1 + \frac{1}{k}\right) \tag{20}$$

and the variance is

$$\sigma^2_{V|H_s} = V_C^2\left(\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right) \tag{21}$$

where Γ is the gamma function ($\Gamma(t) = \int_0^\infty x^{t-1} e^{-x}\,dx$).

In Fig. 14, the hindcasted significant wave height and the hindcasted wind speed at a height of 10 m averaged over one hour are plotted. Values are given for every three hours at the Skarv field in 2010 and 2011 (Table 3). In the same figure is also plotted the wind speed indicated by the conditional Weibull distribution from Eq. (19), which is plotted with error bars equal to $\pm 2\sigma_{V|H_s}$ (i.e., approximately the 95% confidence interval). The parameters used in Eq. (19) are given in Table 2.

Table 4
Select numerical values of $\mu_{\ln\chi}$ and $\sigma_{\ln\chi}$, from Fig. 15.

No. of days (–)	T_R (h)	$\mu_{\ln\chi}$ (–)	$\sigma_{\ln\chi}$ (–)
1	24	0.055	0.112
2	48	0.066	0.119
3	72	0.079	0.134
4	96	0.084	0.153
5	120	0.095	0.176
6	144	0.111	0.204
7	168	0.127	0.224

6. Environmental conditions for weather-unrestricted operations

6.1. Design environmental conditions

For weather-unrestricted operations, the environmental design conditions are based on long-term statistics, possibly accounting for seasonal variations. According to ISO 19901-6, weather-unrestricted operations may be planned using environmental criteria with return periods estimated as a multiple of the operation duration. A minimum of 10 times the duration of the operation may be used (ISO 19901-6, 2009). (However, for operations with durations of up to seven days, environmental criteria based on seasonal data with a return period of one year are recommended.)

An alternative is a method proposed by Lindemann (1986) for calculating the design significant wave height as a function of the duration with a defined exceedance probability of 10%. This method is used by DNV (2011).

6.2. Exceedance probabilities for the wave height

Consider a marine operation with a given duration and in a given season for which the long-term statistics for the geographical area yield a significant wave height for the design that is equal to $h_{s,d}$. Based on the log-normal distribution from Eq. (17), the probability that the actual (observed) significant wave height will be larger than the design value can be expressed as follows:

$$P_e = P(H_{s,max} \geq h_{s,d}) = 1 - \Phi\left(\frac{\ln(h_{s,d}) - \mu_{\ln H_s}}{\sigma_{\ln H_s}}\right) \tag{22}$$

$\mu_{\ln H_s}$ and $\sigma_{\ln H_s}$ are calculated from Eq. (15) for the maximum forecasted wave height, $h_{s,fc}$, during the operation period, T_R.

6.3. Simplified numerical values for the weather forecasting uncertainty

Using the expressions given in Eqs. (22) and (15), the probability of exceeding the design criteria over a period of several days can be estimated based on a given weather forecast. The mean and the standard deviation of χ are given in Fig. 13 for all-year data. In Fig. 15, the mean and the standard deviation of the logarithm of χ as calculated using Eq. (16) are shown. Select values of $\mu_{\ln\chi}$ and $\sigma_{\ln\chi}$ are given in Table 4.

6.4. Simplified design wind speed

A simple relationship between the significant wave height and the wind speed is given in Holthuijsen (2007, Section 6.3.2):

$$H_s = 0.24\frac{V^2}{g} \tag{23}$$

where V is the sustained wind speed (10-min average) 10 m above the sea surface. Similar expressions with slightly varying constants

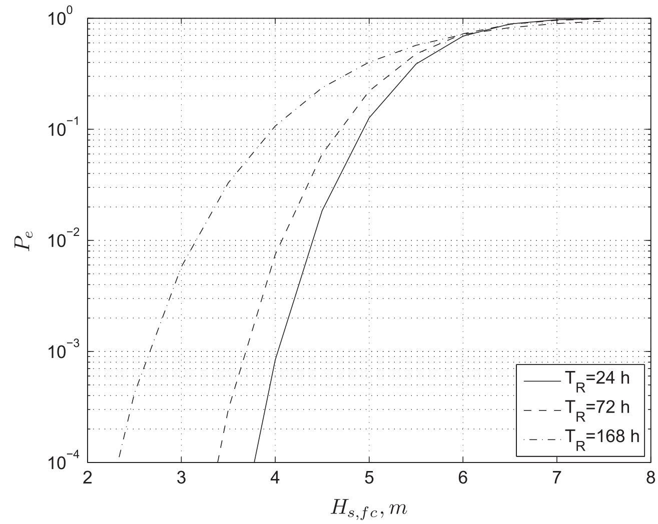

Fig. 16. Probability of exceeding H_s = 6 m as a function of the forecasted significant wave height for three operation reference periods: 24 h, three days and seven days

are also given by other authors, e.g., Gran (1992, Eq. 3.4.63), with a coefficient of 0.18 instead of 0.24 (for a wind speed V observed 10–20 m above the sea surface). Note that the spread (e.g., the standard deviation) of the H_s data is not described by this formula. Inverting Eq. (23) yields the wind speed as a function of the significant wave height:

$$V = \sqrt{\frac{H_s g}{0.24}} \tag{24}$$

The wind speed according to Eq. (24) is also shown in Fig. 14. (The wind speed in Eq. (24) is averaged over 10 min, whereas the hindcasted wind speed, which is approximately 10% lower, is averaged over one hour.) The significant wave height in Eq. (23) represents wind-generated waves. By contrast, the significant wave height assumed in long-term wave distributions describes the total sea, i.e., it also includes swells. This means that when the wind speed is calculated via Eq. (24) using a significant wave height from a long-term distribution representing the total sea, the wind speed will be overestimated.

In engineering, a simple method of calculating the wind speed corresponding to a specified significant wave height is useful for operation design. As a simplification, the wind speed may be taken to be a deterministic function of the wave height if a formula similar to Eq. (24) is fitted to the upper limit in Fig. 14 (i.e., to $\mu_{V|H_s} + 2\sigma_{V|H_s}$; see Eqs. (20) and (21)). The factor 0.24 is then replaced with 0.15; hence, $V_{one\ hour} = \sqrt{H_s g/0.15} \approx 8\sqrt{H_s}$. (A more sophisticated curve could also be used, but Eq. (24) is both simple and convenient and has the traditional form.) This formula could be used for planning operations in the Norwegian Sea, bearing in mind that it is based on two years of data. Because the formula is valid for wind speeds averaged over one hour, it should be transformed to correspond to the actual averaging time used in the case under consideration. A one-minute averaging time is often used, in which case the wind speed is approximately 20% higher than the one-hour wind speed (see, e.g., DNV, 2011). The one-minute design wind speed can thus be approximated as follows:

$$V_{one\ minute} \approx 10\sqrt{H_s} \tag{25}$$

where H_s is given in m and the wind speed is given in m/s. Note that this is merely an approximate formula for wind speed and is a function of the significant wave height only. The relation between wave height and wind speed at a certain location may depend on

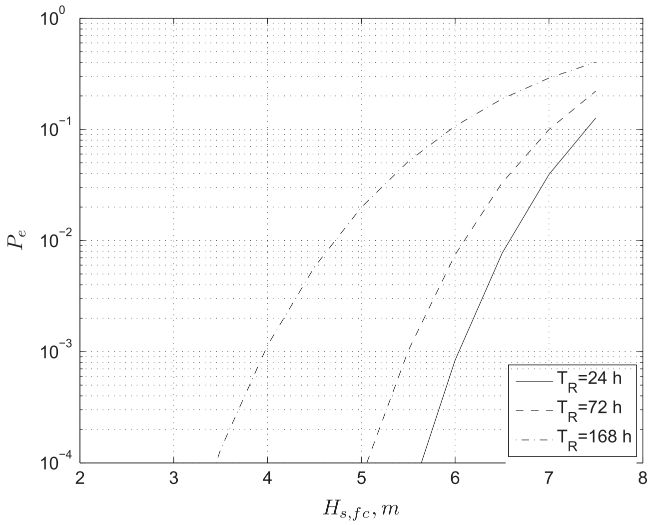

Fig. 17. Probability of exceeding H_s = 9 m as a function of the forecasted significant wave height for three operation reference periods: 24 h, three days and seven days.

the wind and wave directions, storm duration, fetch, water depth and possibly other covariates. However, Eq. (25) can be used for engineering or feasibility studies and is valid for deep water and unlimited fetch.

For structural reliability analyses, the conditional probability distribution given in Eqs. (19)–(21) may be used.

7. Reliability of a weather forecast

The probability of exceeding a certain significant wave height given a certain forecasted wave height and operation period can be estimated from Eq. (22).

In Fig. 16, the probability of exceeding a significant wave height of 6 m is plotted as a function of the forecasted wave height for three different operation periods. Similarly, the probability of exceeding a significant wave height of 9 m is plotted in Fig. 17.

It is observed that if the forecasted wave height is, e.g., 4 m, then the probability that the actual wave height will be greater than 6 m after 24 h is approximately 10^{-3}; after three days, it is approximately 10^{-2}; and after seven days, the probability of exceedance is 10^{-1}. The probability that the actual wave height will be greater than 9 m is negligible after either 24 h or three days. After seven days, the probability of exceeding a wave height of 9 m is approximately 10^{-3}. It is also apparent from Fig. 17 that if the forecasted wave height is 6 m, then the probability of exceeding a 9 m wave height after seven days is approximately 10^{-1}. Hence, the weather forecasts still provide interesting information even after one week. Because the results are sensitive to the tail of the distribution when extreme values are considered, the values here should be taken as examples only.

The primary concern in engineering is not the probability of exceedance but rather how to calculate a design wave height. The design wave height can be estimated for a given probability of exceedance and a forecasted wave height. By substituting Eq. (15) into Eq. (22) and solving for $H_{s,d}$, the maximum significant wave height can be calculated as follows:

$$H_{s,d} = h_{s,fc} \exp(\mu_{\ln \chi} + \sigma_{\ln \chi} \Phi^{-1}(1 - P_e)) \tag{26}$$

The probability of exceedance, P_e, should correspond to the safety format used in the design of the marine operation. The safety factors used in the structural design (typically load and material factors) will depend on the probability of exceeding a certain load level. A probability of 10% that the design wave will be exceeded is used in DNV (2011) for weather-unrestricted operations.

As an example, suppose that the maximum allowed forecasted significant wave height for a certain marine operation is 5 m. (Hence, the operation cannot begin before the forecasts indicate $H_s \le 5$ m for the entire duration of the operation.) Using the values from Table 4, the maximum significant wave heights obtained from Eq. (26) are 6.4 m for a three-day operation and 7.6 m for a seven-day operation, with P_e=0.1. (These would then be the characteristic values to be used in design.)

The ratio between the forecasted wave height and the design wave height for a three-day operation is 5/6.4 = 0.78. This value can then be compared with the values from the design standards. The ratio between the forecasted wave height and the design wave height for a 72-h operation is 0.72 according to DNV (2011) (for $H_{s,design} \ge 6$ m) and 0.54 according to GL Noble Denton (2013); see Table 1. Hence, these standards yield conservative results compared with our data set in this case.

For a seven-day operation period, no ratio is given by the design standards, but the ratio between the forecasted and design wave heights according to the results from Table 4 is 5/7.6 = 0.66.

In general, standards for marine operations do not allow the planning and design to be based on weather forecasts when the operation duration is more than three days unless it can be demonstrated that the relevant weather forecasts can predict any extreme weather conditions over a longer period. The method described in this paper may be used to assess the reliability of such weather forecasts, preferably based on a more extensive data set. Because only weather forecasts for a single location are included in the data set considered in this paper, the results cannot be directly applied elsewhere. However, they are considered to be representative of extratropical conditions.

Because only one year of data is included, there will be a rather large uncertainty in the calculated values; see, e.g., Moan et al. (2005).

8. Conclusions

The uncertainty in environmental conditions based on weather forecasts has been studied. Forecasted significant wave heights have been compared with hindcasted values using an additive and a multiplicative statistical model. In the additive model, the mean value and the standard deviation are more strongly dependent on the forecasted wave height than in the multiplicative model, making the latter the preferred model in this study.

The uncertainty in the forecasts increases with increasing lead time, reducing the correlation between the forecasted and hindcasted data. The correlation between forecasted and hindcasted data is lower for wave periods than for significant wave heights for the same lead time. Therefore, it is preferable to model the wave period conditionally upon the wave height.

The wind speed may be modelled using a Weibull distribution that is conditional upon the wave height. For marine operations in which the governing environmental load is caused by waves and the corresponding wind speed must be estimated, a simple engineering method is proposed. The relationship between wind speed and wave height was developed for wind-driven waves. Hence, if the waves in fact contain swells in addition to wind-driven waves, then the wind speed may be overestimated. Moreover, in sheltered water or other cases in which there may be high wind speeds but small or no waves, this method is not applicable. In such cases, it will be necessary to determine the wind speed using other methods, e.g., the return period approach based on the duration of the operation.

According to the design standards for marine operations, only operations with planned durations of less than three days are generally planned as weather-restricted marine operations, unless it can be demonstrated that the relevant weather forecasts are able to predict any extreme weather conditions over a longer period. In that case, the operation reference period may be increased. The data from the Norwegian Sea used in this paper do not reveal any specific limitations of the weather forecasts that would require a 72-h limit for weather-restricted operations. The method described in this paper may be used to assess the quality of weather forecasts for a period longer than three days based on forecasts for the area of interest.

The results may be used as input for structural reliability analyses of marine operations.

Although the statistical model described in this paper considers the significant wave heights, several other effects might have been included. Seasonal variations and the dependences of the forecasted wave height have been discussed to some extent, but other covariates may also influence the results. The wave and wind directions, water depth, geographical area, forecast provider or other covariate effects could be included in these analyses. To obtain the parameters for the engineering of an operation at a certain location, data reflecting the area of interest should be analysed.

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