AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2016JC012086

Special Section:
The Arctic: An AGU Joint Special Collection

Key Points:
- The significant wave height in polar lows is estimated using a parametric wave model
- A generalization of the fetch-limited wave equation in polar low is proposed
- The results show the possibility for large waves in polar lows
- There may be high uncertainties in wave forecasts in polar lows

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Citation:
Orimolade, A. P., B. R. Furevik, G. Noer, O. T. Gudmestad, and R. M. Samelson (2016), Waves in polar lows, *J. Geophys. Res. Oceans*, *121*, doi:10.1002/2016JC012086.

Received 23 JUN 2016
Accepted 10 AUG 2016
Accepted article online 13 AUG 2016

Waves in polar lows

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Abstract In a rather stationary fetch, one would not expect large waves in polar low situations. However, the picture changes when one considers a moving fetch. The significant wave heights that may be associated with the recorded polar lows on the Norwegian continental shelf from December 1999 to October 2015 are estimated using a one-dimensional parametric wave model. A comparison of the measured and the forecasted significant wave heights in two recent polar low cases in the Barents Sea is presented. The estimated significant wave heights show that the values could have been up to and above 9 m. The forecasted significant wave heights considerably underestimated the measured significant wave heights in the two recent polar low cases that are considered. Furthermore, a generalization of the fetch-limited wave equation in polar lows is proposed, which allows the wind field to vary in space and time, and is shown to give results that are consistent with the one-dimensional parametric model.

1. Introduction

A polar low is a small, but intense maritime cyclone that forms poleward of the main baroclinic zone [*Rasmussen and Turner*, 2003]. The horizontal extent of a polar low is approximately between 150 and 600 km. Although polar lows are usually short-lived (6–36 h), under stagnant weather systems, polar lows or a family of polar lows can persist for several days [*CCG*, 2012]. The polar lows are also known as Arctic hurricanes [*Emanuel and Rotunno*, 1989]. This is because, the spiral cloud bands of some fully developed polar lows often form a clear eye at the center of the cloud vortex similar to tropical cyclones (TC). Just as for TC, waves in polar lows are not well understood, mainly because of the limited amount of data, both on winds within polar lows and the complex nature of the sea. In recent times, more studies have been carried out on waves in TC, including studies by *Young* [1988], *Wu et al*. [2003], *Bowyer and MacAfee* [2005], and *MacAfee and Bowyer* [2005]. However, very little has been done on waves in polar lows.

The horizontal extent of polar lows are rather limited, therefore, wave growth during the outbreaks of polar lows would not be expected to be very large. However, if we take the influence of the moving fetch on wave growth into account, there is the possibility of large waves in polar low situations. It is yet to be verified whether the existing high-resolution wave forecast models, such as the WAM10 and the WAM4, can give reliable wave forecasts in polar low situations. WAM4 at 4 km resolution represents a higher resolution compared to WAM10 at 10 km resolution. The degree of the uncertainties in the models can be quantified using wave measurements and wave forecasts near polar low trajectories; however, this is rather difficult, because wave measurements in the regions prone to polar low occurrences are limited.

This paper is a novel approach to show how large waves can be in polar lows, motivated by the record of wind speeds in polar lows from December 1999 to October 2015, and the parametric wave equation proposed by *Dysthe and Harbitz* [1987]. In the estimation of wave heights in polar lows, 212 measured wind speed records that are associated with polar low occurrences were considered. The paper also presents two recent polar low occurrences in the Barents Sea, where the measured and the forecasted significant wave heights are compared.

2. Theoretical Background

In a stationary fetch situation, the duration of a wave component in the fetch area is related to the fetch length, F, by the wave group velocity, c_g. However, in a fetch moving in the direction of travel of a wave, the duration of a wave component in the fetch area is a function of the difference between the wave group velocity and the forward speed of the fetch [*Shemdin*, 1980]. Specifically in the case of polar lows, any wave component whose group velocity, c_g, is near the speed, V, of the polar low, will remain in the moving fetch for a long duration. This phenomenon is known as group velocity quasi-resonance, trapped fetch (commonly used by tropical cyclone modelers), dynamic fetch, or extended fetch.

A brief review of the basic wind-waves empirical relationships for stationary fetch situations is presented in section 2.1, while section 2.2 is a review of the adaptation of the relationships for application in moving fetch situations, such as for a translating polar low, as presented in the paper by *Dysthe and Harbitz* [1987]. In section 2.3, we present a generalization of the empirical relationships for the fetch-limited condition to include the extended fetch.

2.1. Empirical Relationships of Wind Waves

The deep water empirical relationships involving wind-wave variables are usually presented in nondimensional forms. For the fetch-limited condition, the relationships are [*Sverdrup and Munk*, 1947]:

$$\frac{gH_s}{U^2}=f_1(\chi) \tag{1}$$

$$\frac{c_p}{U}=\frac{gT_p}{2\pi U}=2\cdot f_2(\chi) \tag{2}$$

where g is the acceleration due to gravity, H_s is the significant wave height, U is the wind speed at 10 m height above the sea surface, c_p is the phase velocity, T_p is the spectral peak period, $\chi=gF/U^2$ is the nondimensional fetch, and F is the dimensional fetch. c_p is defined as the speed of propagation of the phase of any one frequency component of the wave, and is equal to the product of its frequency and wavelength.

Based on the Joint North Sea Wave Project (JONSWAP), the following expressions define $f_{1,2}(\chi)$ [*Hasselmann et al.*, 1973]:

$$f_1(\chi)=1.6\cdot 10^{-3}\chi^{\frac{1}{2}} \tag{3}$$

$$f_2(\chi)=0.023\cdot \chi^{\frac{1}{3}} \tag{4}$$

Equations (3) and (4) are derived from a combination of field and laboratory data. Contending that the balance of dynamical processes in the laboratory are rather different from those in the field, *Phillips* [1977] proposed an alternative to equation (4) that is based on field data alone, this can be written as:

$$f_2(\chi)=0.045\cdot \chi^{\frac{1}{4}} \tag{5}$$

It should be noted that the expressions are invalid for very long fetches, for instance, say for $\chi > 1.5\cdot 10^4$, when $c_p > U$.

The duration, t, in which waves are under the influence of the wind can be obtained from the following expression:

$$\frac{dF}{dt}=c_g\cong\frac{c_p}{2} \tag{6}$$

where c_g is the group velocity at which waves effectively progress in deepwater in the direction of the fetch. In dimensionless form, equation (6) can be written as:

$$\frac{d\chi}{d\tau}=\frac{c_g}{U}=f_2(\chi) \tag{7}$$

where $\tau=gt/U$ is the dimensionless time. Adopting equation (5) and substituting it into equation (7) yields the following expression for the wave characteristics χ, τ, starting at the origin:

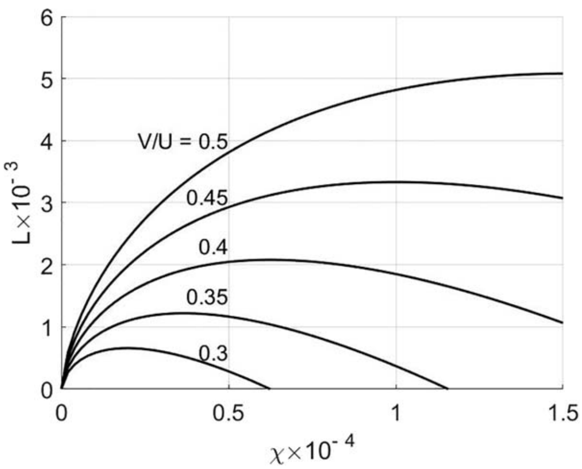

Figure 1. The nondimensional distance, *L*, of the wave from the front of the polar low, as a function of the nondimensional fetch, χ.

$$\tau = 29.63 \cdot \chi^{\frac{3}{4}} \tag{8}$$

2.2. Extended Fetch Concept in Polar Lows

The duration of a wave in a moving fetch such as in a polar low is frequency-dependent. The frequency-dependent fetch, $F(\omega)$, may be defined as:

$$F(\omega) = min\left\{ l\left|\frac{V}{c_g} - 1\right|^{-1},\ l_{\max} \right\} \tag{9}$$

where l is the polar low horizontal extent, and $l_{\max}$ is some limiting fetch, for instance, the maximum distance that a polar low is likely to travel along a relatively linear path. The $l_{\max}$ is around the resonance frequency, ω_0, whose group velcocity is equal to the propagation speed, V, of the polar low. The resonance frequency, ω_0, is defined as:

$$\omega_0 = \frac{g}{2V} \tag{10}$$

The use of equation (9) in equation (7) for the case $F(\omega = \omega_0) = l_{\max}$, that is, when $c_g(\omega_0) = V$, and the case $F(\omega)$, yields the polar low characteristics at the rear and the front, respectively, as:

$$\chi = \frac{V}{U}\tau \ \ and\ \ \chi = \frac{V}{U}\tau - \frac{lg}{U^2} \tag{11}$$

The nondimensional distance, *L*, which a wave component lags behind the front of the polar low, is obtained from equation (11) and equation (8) as:

$$L = \left(29.63 \cdot \chi^{\frac{3}{4}} \cdot \frac{V}{U}\right) - \chi \tag{12}$$

L as a function of χ for some values of *V/U* is shown in Figure 1. The solution of equation (12) shows that *L* has a maximum, L_0, at the fetch χ_0, where:

$$L_0 = 8.13 \cdot 10^4 \ \left(\frac{V}{U}\right)^4 \tag{13}$$

and

$$\chi_0 = 2.44 \cdot 10^5 \ \left(\frac{V}{U}\right)^4 \tag{14}$$

Mathematically, it can also be shown from equation (12), that the wave component will finally leave through the polar low front at a fetch $\chi_1 \cong 3.16 \cdot \chi_0$, where $L = 0$.

The conditions for an extended wave development in polar lows are summarized as follows [*Dysthe and Harbitz*, 1987]:

1. the existence of a straight polar low trajectory, l_{max}, considerably larger than the horizontal extent, l, of the polar low.
2. the ratio of the polar low speed, V, to the wind speed, U, in the direction of motion of the polar low, should satisfy:

$$0.25 < \frac{V}{U} < 0.5 \tag{15}$$

3. the horizontal extent of the polar low, l, should be greater than the maximum distance that the wave trajectory lags behind the front of the low; that is, it should satisfy:

$$\tilde{l} > L_o \ \ or \ \ l > 8.13 \cdot 10^4 \frac{V^4}{gU^2} \ \ (m) \tag{16}$$

where $\tilde{l} = lg/U^2$ is the dimensionless length of the polar low, and $8.13 \cdot 10^4 V^4/gU^2$ is the corresponding dimensional form of L_o.

If $l > 8.13 \cdot 10^4 V^4/gU^2$ (condition 3), the wave is contained by the moving fetch, up to the point where it leaves through the polar low front. In this situation, there is the possibility that the wave development will proceed past the resonance period, and maybe stop at the front, or at some maximum fetch, l_{max}. On the other hand, if $l < 8.13 \cdot 10^4 V^4/gU^2$, the wave will leave through the rear of the polar low, and the wave development is expected to halt before the peak frequency has reached the resonance frequency.

When an extended wave development takes place, the effective fetch is found to be between χ_0 and χ_1. Substitution of χ_0 and χ_1 into equation (1) gives a rough estimate of the wave height to be expected, as:

$$H_s(\chi_0) \cong \frac{0.8V^2}{g} \ \ and \ \ H_s(\chi_1) \cong \frac{1.4V^2}{g} \tag{17}$$

Although equation (17) shows that the expected H_s is independent of U, as earlier discussed, how far the wave development can go on, does depend on U. If conditions (1)–(3) are satisfied, a rough estimate of the significant wave height, H_s, at the end of the wave development is given by [*Dysthe and Harbitz*, 1987]:

$$H_s = \min\left\{ H_s\left(\tilde{l}_{\max}\right), 1.4\frac{V^2}{g} \right\} \tag{18}$$

where $\tilde{l}_{\max} = gl_{\max}/U^2$ is the dimensionless maximum fetch.

More details about this one-dimensional (1-D) parametric wave model for wave growth in polar lows can be found in the cited article. Interested readers may also look up *Bowyer and MacAfee* [2005], *MacAfee and Bowyer* [2005], for general information on extended wave development and the application to wave growth in TC.

2.3. Alternative Formulation of the Fetch-Limited Condition

Equations (1), (2), and (6) may be generalized to allow a spatially and temporally varying wind field $U(x, t)$ by treating the effective fetch, $F_e(x, t)$, as a slowly varying field variable that is determined by integration along the corresponding wave characteristics, where x represents the dimensional distance along the direction of wave propagation and of local wind. The effective fetch is the path length following the characteristic group velocity, c_g, of the wave field, and so satisfies the differential equation:

$$\frac{dF_e(x,t)}{dt} = c_g(x,t) \tag{19}$$

along the corresponding wave characteristics

$$\frac{dx}{dt} = c_g(x,t) \tag{20}$$

In the slowly varying approximation, the local group velocity, $c_g(x,t)$, and significant wave height, $H_s(x,t)$, are obtained from the fetch-limited condition, evaluated for the local wind and fetch:

$$\frac{c_g(x,t)}{U(x,t)} = f_2(\xi) \tag{21}$$

and

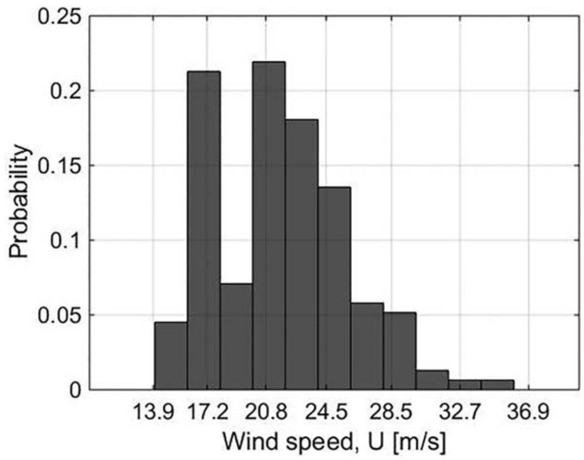

Figure 2. Histogram of the 155 wind speeds that are associated with polar lows on the NCS: December 1999 to October 2015.

$$\frac{g \cdot H_s(x,t)}{[U(x,t)]^2} = f_1(\xi) \quad (22)$$

where $\xi = g\ F_e(x,t)/[U(x,t)]^2$. Equation (21) completes the specification of the equations (19) and (20) for the effective fetch, while equation (22) allows the evaluation of the local significant wave height from the effective fetch and local wind. The physical basis of this formulation is a quasi-equilibrium approximation, in which the wave field is assumed to be in fetch-limited equilibrium with the local wind field, and the coupled fetch and wave field's area is allowed to evolve slowly—relative to an implied scale for adjustment to equilibrium—in response to the local wind along the wave-group characteristics.

To represent the spatial and time variation of the polar low field, the wind field $U(x,t)$ may for simplicity be taken to have a Gaussian form, with maximum wind speed U_0 and half-width λ_0, translating at the constant speed V:

$$U(x,t) = (U_0 - U_b)e^{-\frac{1}{2\lambda_0^2}(x-Vt)^2} + U_b \quad (23)$$

The small constant background wind, U_b, is included to avoid singularities in the arguments of f_1 and f_2 that could otherwise occur at points where $U = 0$; in the calculations described here, $U_b = 0.01$ m/s. The initial effective fetch field may be set to an arbitrary small positive constant, F_0, such as one-tenth of the polar low half-width:

$$F_e(x, t=0) = F_0 = 0.1\ \lambda_0 \quad (24)$$

Numerical solutions of equations (19)–(24) were obtained on a fixed spatial grid with grid spacing $\Delta x = 5$ km, using a simple, first-order, characteristic-based upstream difference scheme with time-step $\Delta t = 240$ s.

3. Application to Polar Lows on the Norwegian Continental Shelf

The 1-D wave prediction model described in section 2.2 is applied to records of polar lows on the Norwegian continental shelf (NCS). The aim is to give an estimate of the probable significant wave heights under the polar low conditions.

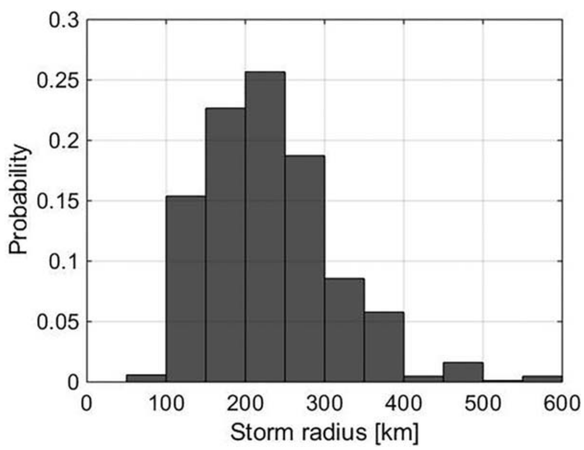

Figure 3. Histogram of storm radii associated with polar lows on the NCS: January 2002 to April 2011.

3.1. Important Parameters for Wave Height Estimation in Polar Lows

From section 2.2, the wind speed that is associated with a polar low, the polar low horizontal extent, the maximum or limiting horizontal extent, and the polar low speed, are the key parameters for the estimation of the wave height in the polar low. We considered a record of 212 polar lows that were identified by meteorologists at the Norwegian Meteorological Institute (MET, Norway) in Tromsø, from December 1999 to October 2015. The record shows the polar low positions, the time of observation which is in the early life span of the polar low, the maximum 10 min 10 m wind speed (U_{10}), and the minimum sea level pressure (MSLP). Out of the

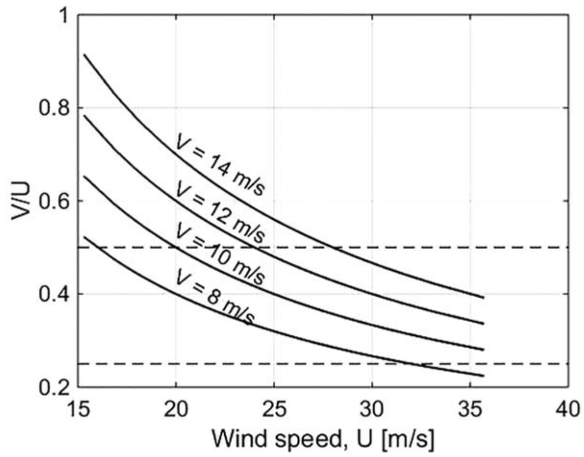

Figure 4. A plot of the ratio *V/U* against wind speed *(U)* for the 155 polar low cases: the boundary within which an extended wave development is possible is shown by the two horizontal dash lines.

212 polar low cases, there are only 155 cases with information about wind speeds. A histogram of the wind speeds is shown in Figure 2. The maximum wind speed in the 155 cases is 35.7 m/s, which corresponds to a typical hurricane wind speed. The minimum wind speed is 15.3 m/s, which is within the boundary of a near gale wind speed. The average wind speed is 21.8 m/s. A majority of the wind speeds fall between gale and storm wind speeds, with only a few exceeding violent storm wind speed.

General information about polar low horizontal extents are obtained from MET Norway polar low records from January 2002 to April 2011, the information is available in a database named STARS Data Set [*STARS-DAT*, 2013]. The records contain hourly positions of polar lows along their tracks of propagation. The positions are derived from the advanced very high-resolution radiometer (AVHRR) images by interpolation. An estimate of the radius of the storms that may be used to classify the sizes of the polar lows is provided in the database.

A histogram of the storm radii is shown in Figure 3. The minimum and the maximum storm radii over the period are 80 and 600 km, respectively. The average storm radius is 218 km. We can infer from the histogram that polar low storm radii below 100 km are rare, so also are polar low storm radii above 500 km. Since most polar lows are asymmetric in nature, the exact horizontal extent of the polar lows cannot be easily determined from this information. However, it can be inferred that a horizontal extent of 100–500 km is possible. This is in agreement with the work of *Fedor* [1984]. It can also be inferred that a maximum or limiting horizontal extent in the range of 600–1000 km is possible; *Dysthe and Harbitz* [1987] considered a maximum horizontal extent in the range of 500–800 km, this was based on the rectilinear paths of the tracks of polar lows given by *Wilhelmsen* [1985].

Information about polar low speed, V, is rather limited, as this is not often recorded. An average V of 10 m/s is considered reasonable judging from previous works. In this study, we considered an arbitrary V in the range of 8–14 m/s.

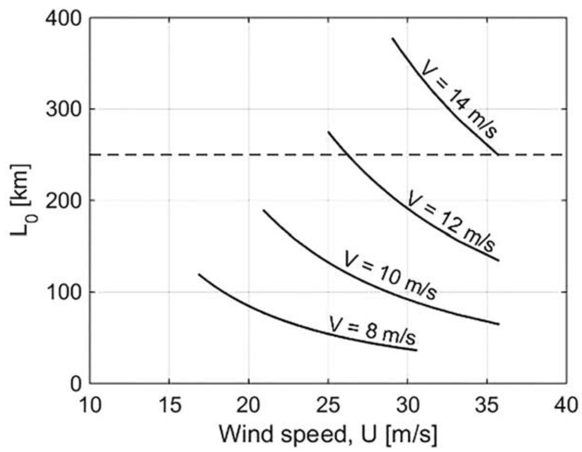

Figure 5. The maximum distance that the wave component lags behind the front of the polar low for the cases satisfying condition (2): cases below the horizontal dash line are those satisfying condition (3) for $l = 250$ km.

3.2. Determination of the Possibility of An Extended Wave Development

We assumed that the condition (1) for an extended wave development is satisfied for all the 155 polar low cases with U values. For the condition (2), the ratio V/U from equation (15) is plotted in Figure 4 for all the 155 cases and the arbitrary values of V. The boundaries within which the condition is satisfied are shown by the dashed lines. The figure shows that the condition (2) for an extended wave development is hardly satisfied when the polar low speed is 14 m/s, except at very high wind speeds. On the contrary, the condition is satisfied for most of the 155 cases, when the polar low speed is 8 m/s.

The condition (3) requires that $l > 8.13 \cdot 10^4 V^4 / gU^2$. The right hand side of this expression is computed for all the polar

Table 1. Summary of the Number of Cases Satisfying the Conditions of An Extended Wave Spectral Development Out of the 155 Polar Low Cases, for a Horizontal Extent of 250 km

	$l = 250$ km			
	$V = 8$ m/s	$V = 10$ m/s	$V = 12$ m/s	$V = 14$ m/s
Condition (2) only	145	84	40	6
Conditions (2) and (3)	145	84	18	1

low cases satisfying the condition (2). The estimated values are as plotted in Figure 5. For an average horizontal extent, l, of 250 km, Table 1 summarizes the number of cases satisfying condition (3) for the different values of V. For $V = 14$ m/s and $l = 250$ km, the condition (3) is barely satisfied in only one case. The condition is satisfied in only 18 out of the 40 cases that satisfied condition (2) for $V = 12$ m/s, and the condition can be said to be well satisfied for $V = 8$ m/s and for $V = 10$ m/s.

From the results of the analyses in this section, we conclude that extended wave development is possible in more than 50% of the recorded polar low cases, if an average polar low speed of 10 m/s is assumed, and in more than 90% of the cases if an average polar low speed of 8 m/s is assumed. For higher polar low velocities ($V > 12$ m/s), it will require very high wind speeds (say, $U > 30$ m/s) and larger polar low horizontal extent for all the conditions of an extended wave development to be satisfied.

3.3. Estimation of Wave Heights in Polar Lows

The significant wave height, H_s, at the end of the wave development is estimated from equation (18). The results are presented for $V = 8$ m/s, and for $V = 10$ m/s. We have considered a maximum horizontal extent, l_{max}, in the range of 600–800 km. In the calculations, we have taken the condition for validity of equations (3) and (5) into consideration, and only considered those cases in which $\tilde{l}_{\max} < 1.5 \cdot 10^4$.

The estimated H_s are presented in Figure 6. For $V = 8$ m/s, the limiting value from equation (18) is reached quickly as the l_{max} increases, and the maximum wave growth is limited to 9.13 m. For $V = 10$ m/s, the limit is not reached, signifying that it will take larger values of l_{max} and larger values of U for the waves to outrun the polar lows. The effect of an extended wave spectral development is seen in the estimated values of H_s. For instance, if the polar lows were stationary, l rather than l_{max} will be considered in the estimation of H_s. Therefore, the estimated H_s values would not be as high as the values that are presented in Figure 6.

While the presented values are not precise due to the assumptions and the simplified parametric model used, they give some insights into the possible significant wave height values in polar lows. It is clear that no marine operations can be conducted at such significant wave heights.

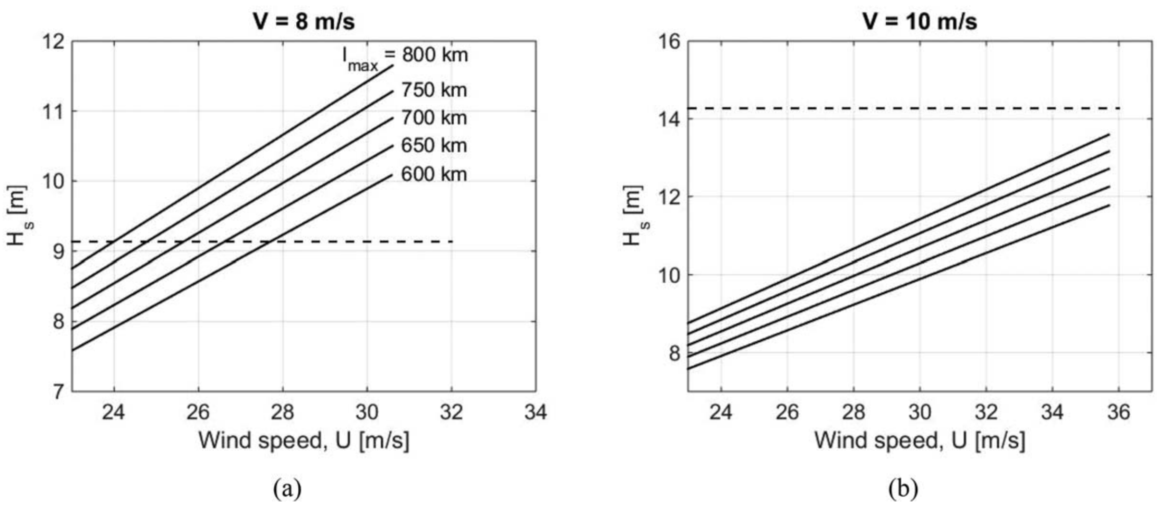

Figure 6. Estimates of the significant wave heights in polar lows for different values of l_{max}, the dash line represents the limiting H_s value.

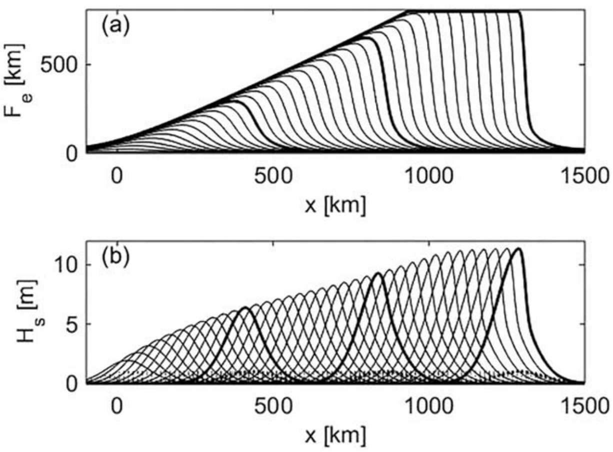

Figure 7. Profiles versus dimensional distance x (km) at hourly intervals of (a) effective fetch $F_e(x,t)$ (km) and (b) significant wave height $H_s(x,t)$ (m) from the slowly varying formulation in equations (19)–(24), with wind speed $U_0 = 25$ m/s, half-width $\lambda_0 = 75$ km, and translation velocity $V = 10$ m/s. The profiles at $t = \{12,24,36\}$ hours are emphasized (thick lines). In Figure 7b, the polar low profiles $U(x,t)/U_0$ are also shown (dashed lines), for reference, at the corresponding times.

3.4. Significant Wave Heights From the Alternative Formulation

The alternative formulation gives solutions for the significant wave height that are consistent with the calculations made in the previous sections. For example, with wind speed $U_0 = 25$ m/s, half-width $\lambda_0 = 75$ km, and translation velocity $V = 10$ m/s, the significant wave height reaches 9 m after 24 h, and the effective fetch reaches the imposed maximum $l_{max} = 800$ km after 28 h, at which time the low has propagated roughly 1000 km, 200 km greater than l_{max} (Figure 7). The half-width $\lambda_0 = 75$ km for these calculations was chosen to be somewhat smaller than half of the 250 km polar low width considered in the previous section, because appreciable wind velocities for the assumed Gaussian structure extend over a broader region than twice the Gaussian half-width (Figure 7b).

A broader set of results from the formulation in equations (19)–(24) can be summarized by computing the maximum significant wave height over the spatial profile at a fixed time for a range of values of wind speed U_0 and translation velocity V. Six values of the wind speed were considered, $U_0 = \{5,10,15,20,25,30\}$ m/s, and the maximum significant wave height was computed at $t = 24$ h for translation velocities in the interval $0 < V < 14$ m/s, and with fixed half-width $\lambda_0 = 75$ km. For $U_0 = 20$ m/s, the maximum significant wave heights exceed 5 m for essentially all $V < 9.5$ m/s (Figure 8). For $U_0 > 15$ m/s, the maximum significant wave heights increase sharply as V decreases through U_0-dependent critical values in the range 8–12 m/s. The imposed maximum effective fetch, $l_{max} = 800$ km, is reached by hour 24 at the point of maximum significant wave height for the simulations with $U_0 = 30$ m/s and $V \approx 10$ m/s.

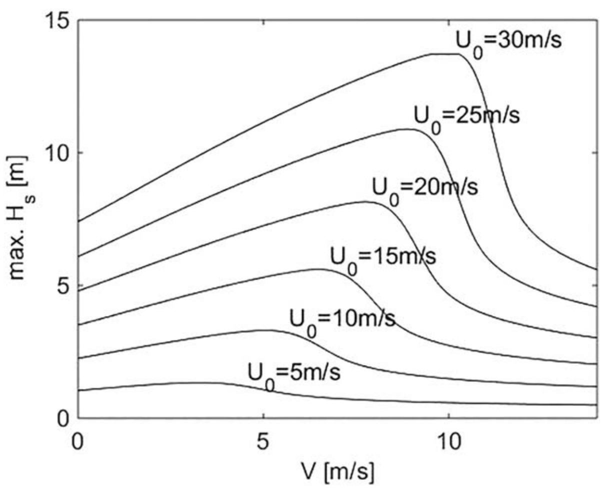

Figure 8. Maximum significant wave height max$\{H_s(x,t)\}$ (m) after 24 h versus polar low translation velocity V (m/s) for wind speeds $U_0 = \{5,10,15,20,25,30\}$ m/s, from the slowly-varying formulation in equations (19)–(24), for half-width $\lambda_0 = 75$ km.

4. Case Studies

Two recent polar low cases are discussed in this section, one from 13 December 2015 (case 1), and the second from 26 December 2015 (case 2). These cases are of interest because the polar lows traveled in close proximity to the location of the Goliat oil production platform (71.30°N 22.30°E) in the Barents Sea, and because it was possible to obtain metocean (meteorology and oceanography) parameters from the measuring instruments on the platform. The wind data are from one of the wind sensors on the platform, and the wave data are from the MIROS wave radar on the platform, the data are made available by the MET Norway, Bergen.

For case 1, three fully developed polar lows were observed. Two in the southwest

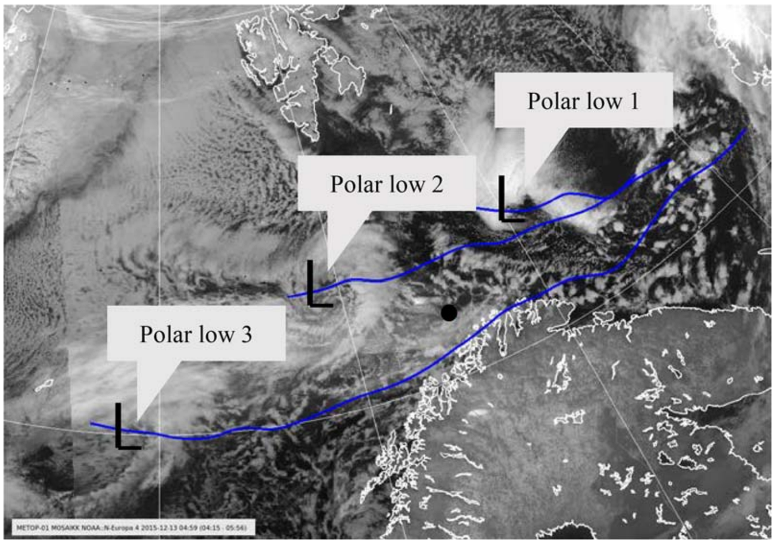

Figure 9. A satellite image showing the three polar lows of 13 December 2015: the blue lines shows the polar low trajectory, the platform location is indicated by the black dot.

sector of the Barents Sea, and the third in the northern Norwegian Sea, see Figure 9. The polar lows traveled easterly. Polar low number 3 traveled closest to the location of the Goliat platform. The center of the polar low was approximately 75 km from the location of the platform at 01 UTC on 14 December. A northwesterly storm of about 25 m/s that was associated with the polar low was observed at North-Troms and West-Finnmark, at the coast of Norway.

For case 2, the polar low originated near Bjørnøya (Bear Island in the Barents Sea) in the early hours of the 26 December. It followed a southeasterly trajectory, and it was later observed in the southwest sector of the Barents Sea, Figure 10. The center of the polar low was approximately 115 km from the location of the Goliat platform when the polar low was passing the platform area. A violent storm was recorded at the Slettnes Lighthouse, Norway, at about 16 UTC. This was attributed to the passage of the polar low.

4.1. Measured Metocean Parameters

The measured wind speeds, U, significant wave heights, H_s, and spectral peak periods, T_p, are presented in Figure 11 for the two cases. The figure shows these metocean parameters 1 day before the arrival of the polar lows and up to 1 day after they have passed the location of the Goliat platform. For the two cases under consideration, the measured maximum wind speeds from the wind sensors on the platform were around 16 m/s, higher wind speeds would be expected closer to the centers of the polar lows.

For case 1, Figure 11a shows an increase of about 2.73 m in the H_s in just 4 h. However, the T_p remains rather constant, and below the resonance period (equation 10) for an extended wave development. Although this case may not seem spectacular, the maximum observed H_s of 4.78 m would lead to a halt in activity and waiting on weather for most marine operations. In addition, the necessity to halt operation on a short notice could be a considerable concern.

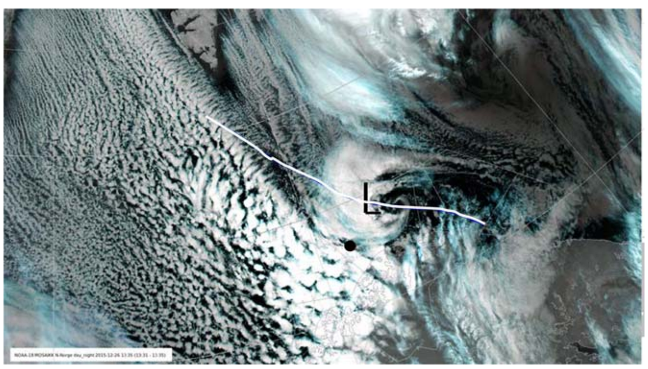

Figure 10. A satellite image showing the polar low of 26 December 2015: the white line shows the polar low trajectory, the platform location is indicated by the black dot.

Case 2 seems more interesting considering the larger waves shown in Figure 11b. However, there are no measurements for a long-time interval as shown in the figure. Figure 11b

10.1002/2016JC012086

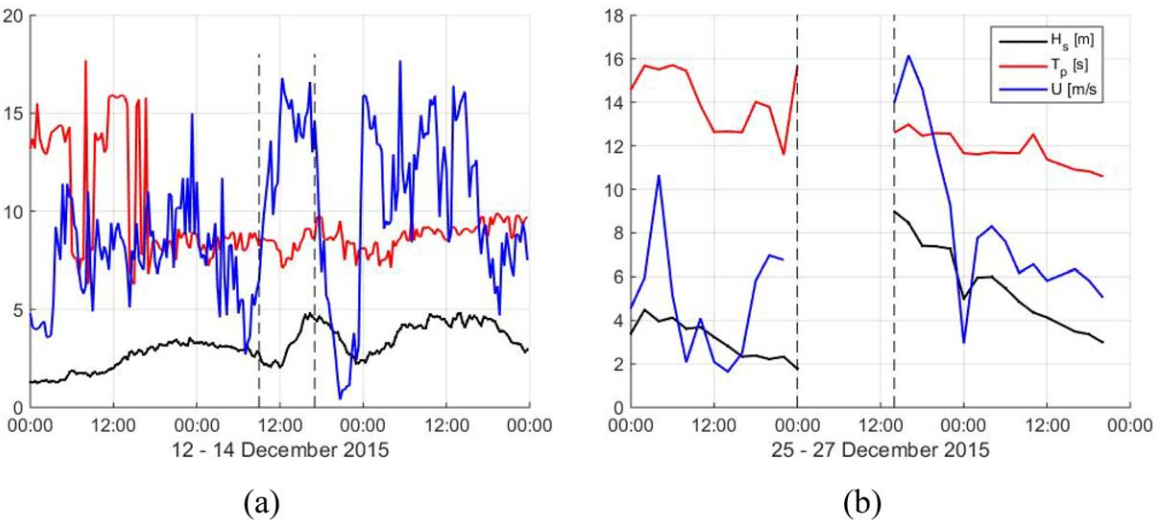

Figure 11. Time series of U, H_s, and T_p from one day before to one day after the polar lows have passed the Goliat platform: (a) the dashed lines represent the periods the polar lows were observed near the Goliat platform for case 1, (b) the dashed lines represent the periods the polars lows were observed near the platform for case 2, the data within this interval are missing and are shown as blank.

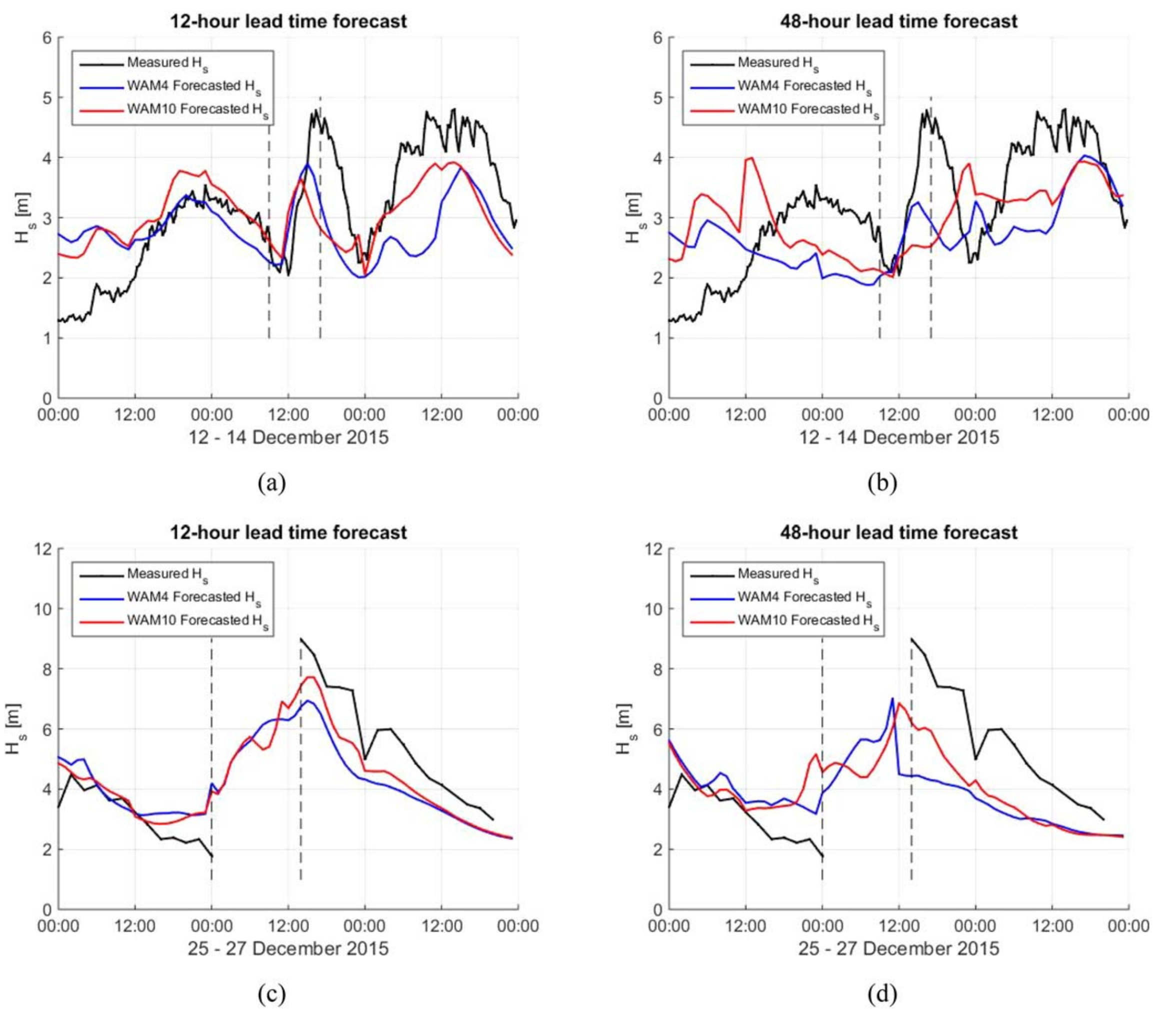

Figure 12. Comparison of wave forecasts and wave measurements at the location of the Goliat platform for the two polar low cases.

suggests that the H_s increased from 1.78 to 9.00 m between 00 UTC and 14 UTC. It should be noted that in a rather stationary fetch, a significant wave height of 9.00 m is not likely for a maximum wind speed of 16 m/s. The figure also shows that the T_p decreased from 15.66 to 12.6 s in the time interval, but a sharp increase is seen before 00 UTC on the 26 December. The values of the T_p are above the resonance period for an extended wave development in polar low, suggesting that the wave may have come into resonance, and probably continued developing.

4.2. Forecasted Significant Wave Height

The discussions in section 2 showed that the knowledge of the translation speed of a wave generating polar low is required to assess the moving fetch; this information is required in addition to the stationary storm factors of wind speed, duration, and fetch. There is a nonlinear relationship between these factors, making the forecasts of wave heights in moving fetch situations a complex problem [*COMET*, 2012]. According to *Bowyer and MacAfee* [2005], the extended fetch phenomenon has been known for generations, but may not always be well understood by forecasters. Therefore, the uncertainties in wave forecasts during polar low occurrences could be high.

The forecasted H_s in the time intervals shown in Figure 11 are compared with the corresponding measured H_s in this section. Wave forecasts from two wave models, WAM4 and WAM10, have been considered. Figure 12 shows how the wave forecasts compared with the wave measurements for a lead time of 12 h and a lead time of 48 h.

In both cases, the forecasted H_s underestimated the measured H_s. It is seen that the 12 h forecasts give a better prediction of the wave heights in polar lows than the 48 h forecasts. The advantage of the higher-resolution model (WAM4) over WAM10 is not obvious from the figure, but a higher-resolution model will be preferred over a lower one when dealing with a mesoscale phenomenon such as the polar low.

The degree of the uncertainty in the forecasted H_s during the two polar low cases is not a sufficient measure to generalize on the level of uncertainty in forecasted H_s during polar low occurrences. However, the observations from Figure 12 suggest that the uncertainty could be high. It is therefore not advisable to perform marine activities, including fisheries, anywhere within the horizontal extent of a polar low, and along the predicted track of the polar low.

5. Conclusions

The significant wave heights in polar low situations have been estimated using a 1-D wave prediction model. The polar low speed, its horizontal extent, and the wind speed are the important parameters that are used in the calculations. The study presented in this paper showed that large significant wave heights might be associated with the majority of the polar low cases that are recorded on the Norwegian continental shelf, depending on the polar low velocities.

The main advantage of the alternative formulation proposed in section 2.3 is that it generalizes in a straightforward way to the case of wind and group velocity vectors in two spatial dimensions. This offers the possibility of extending the present idealized modeling of polar-low wave-growth to include more realistic and detailed representations of polar-low surface wind fields. Such an approach would be similar in spirit to the method described by *Bowyer and MacAfee* [2005], *MacAfee and Bowyer* [2005] for the related problem of enhanced-fetch wave-growth for tropical cyclones, but arguably simpler in that it is amenable to direct numerical solution without iteration.

A comparison of the measured and the forecasted significant wave heights in the two recent polar low cases presented showed that the degree of uncertainty in the forecasts might be high. This knowledge may not be generalized from this study, considering that only two cases have been considered. In addition, the data used are rather limited; this may introduce further uncertainty into the comparison, therefore, the need for further collections of data. Nevertheless, it is recommended that marine activities should be suspended in areas and times where polar lows are likely to occur.

Weather forecasting is an integral part of marine operations, and marine activities in general. Therefore, more collaboration between engineers and meteorologist is required in order to increase the understanding of wave growth in polar lows and to improve the forecast accuracy. Further experimentations and more detailed data collection will be useful in improving the adopted model and the proposed alternative formulation that are presented in this study.

Acknowledgments
The authors would like to acknowledge the Research Council of Norway and the University of Stavanger (IN-10604), Norway, for providing the resources to prepare this paper. The authors also acknowledge the Norwegian Meteorological Institute for the data used in this study. In addition, we appreciate Magnar Reistad of the Norwegian Meteorological Institute, Bergen, for clarifying the source of the wave measurements used. The data used are available at the cited and listed references.

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