Ocean Waves Reanalysis of Operational Based Method
– Wave Forecast Error based on the encountered OCTOPUS wave database –

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Abstract
This research describes the local and seasonal wave forecast error of the encountered OCTOPUS wave database. The ocean waves reanalysis is performed with the NOAA wave hindcast, using the Climate Forecast System Reanalysis Reforecast wind and ice database. The hindcast that has been generated using the the wind wave model WAVEWATCH III, provides an accurate long-term wave records for an ocean waves reanalysis study around the Cape of Good Hope. Validation results for the combined sea and swell data have been presented using direct and statistical comparison methods. In general, the significant wave height seems to be representing the encountered wave climate. There are some concerns on the quality of the wave period due to the approximations to obtain the combined generalized JONSWAP spectrum.

Keywords: WaveWatch III; WAve Model; Reanalysis intercomparision; Cape of Good Hope; Copulas dependence measures; Goodness-of-fit; Pair-copulae; Conditional distribution; Wave Forecast Error; Bivariate offshore environment; Extreme value statistics.

1. Introduction
With continuous development in the Oil & Gas industry, there is an increase in the transport of heavier and larger structures. As these transports tend to reach the structural limits of heavy transport vessels there is a growing demand to perform more detailed transport analyses. Developments on the operational side are achieved by a motion monitoring project on the Dockwise vessels, gathering motion and weather data. This project increases insight in operational margins, the difference between measured and design conditions, during transports.

Concluded is that the recorded nowcast significant wave height, forecast based on the actual position, heading and speed, hardly ever exceeds 5.0m. Typically, the given operational margin for the higher design sea-states gives a significant wave height of at least 7.0m. For the lower design sea-states, a significant wave height of 4.5m, the operational margin is smaller and therefore sometimes exceeded. The aim of Dockwise is to reach a constant operational margin by increasing the design sea-state at the lower range and reducing the design sea-state at the higher range. (de Jonge, 2012)

A suitable method was developed and analyzed to implement the encountered wave environment into the design process. This Operational Based Method, which takes the weather routing capacity of the vessels into account, decreases the operational margin for the higher design sea-states. Lower design conditions are desirable for Dockwise in tendering contracts, as lower design sea-states and accelerations mean less chance of
damage for the cargo being transported. So, Dockwise is able to make more transports feasible depending on the limits of different areas and seasons. (Deelen, 2014)

The main objectives of this research are divided in research questions providing a handhold to realize these objectives. This thesis will investigate the wave forecast error, a method to implement this in the engineering design process and finally provide the operational margins for the obtained design sea-states.

2. Bad weather avoidance system

The OCTOPUS-Onboard system is a ship motion monitoring and decision support system installed on the Dockwise vessels. The system combines wave measurements, weather forecasts and navigation data like the voyage plan with ship characteristics, loading conditions and motion sensor measurements. This facilitates continuous monitoring as well as simulation and forecasting of the motion responses and performance.

The SPOS (Ship Performance Optimization System) provides the weather forecast for the OCTOPUS-Onboard system, taking wind and waves into account. The Nautical MeteoBase (NMB), of MeteoGroup, combines information from different weather models into a single forecast. MeteoGroup takes the advantages of each model, by monitoring and evaluating the output of these models on a continuous basis, with ongoing verification by global in-situ and altimeter stations, as input for the NMB. The weather data from the NMB sent to the Dockwise vessels is not adjusted on basis of observations, the observations are only used for biasing the model mix set-up for different combinations of time step, location and grid level. (Amarcon, 2015)

The SPOS provides the weather forecast for the OCTOPUS-Onboard system, making use of the ECMWF WAM model and multiple atmospheric models from the Nautical MeteoBase. For this research the choice has been made to only consider the encountered OCTOPUS wave database, also known as nowcast wave database SPOS(NOW), based on the actual GPS position, heading and speed. The forecast includes the significant wave height, mean period and wave direction divided in sea and swell. Furthermore, the wind speed and direction are included in the OCTOPUS database. The research boundary for this ocean waves reanalysis will be expanded with the area around Cape of Good Hope. Since, the forecast skills in the Southern Hemisphere can be somewhat less because of these strong currents and bottom topography. (Magne, 2014)

3. Historical ocean wave data

The wave hindcast dataset is using the WAVEWATCH III (WW3) model. The model has conducted a wave climatology with the Climate Forecast System Reanalysis Reforecast (CFSRR) wind and sea-ice database, an atmospheric reanalysis in which numerical models using data assimilation techniques, from the Environmental Modeling Center at the National Centers for Environmental Prediction (NCEP). Its solution will not
describe reality unless a perfect knowledge about the initial and boundary conditions is present. The main driving force for third generation wave models are the wind fields. (Chawla, 2012)

A sensitivity analysis is performed with altimetry measurements (Ash, 2015) to identify seasonal biases, temporal discontinuities and spatial error trends in terms of wave height. This will present the reliability and accuracy of the NOAA WAVEWATCH III CFSRR hindcast for the area around Cape of Good Hope. Altimeters provide a direct estimate of $H_s$, especially in the Southern Hemisphere where limited in-situ validation data is available. The limitation of the satellite data when trying to validate a specific location and time interval. This disabled a direct comparison with the encountered OCTOPUS wave database. To facilitate a direct comparison with the NOAA hindcast significant wave height $H_s$, the temporal and spatial resolution is interpolated.

The aim of this sensitivity analysis was to verify if the NOAA hindcast dataset provides accurate long-term wave records for an ocean waves reanalysis study around the Cape of Good Hope. It is possible, through a probabilistic approach, further analyze the seasonality for this area and implement the error dependence. Since this research aimed to describe and implement the wave forecast error of the encountered OCTOPUS wave database, there will not be any further statistical analysis on these sensitivity results. This does not preclude the need for correction since the dataset has its own limitations for this area of interest. So, the results of this $H_s$ error analysis will be taken into account and provide a starting point. Buoys and satellite altimetry measurements provide the most comprehensive information, only there is not enough available data to develop an ocean waves reanalysis based on these sources.

4. Ocean waves reanalysis

The procedure to investigate the wave forecast error and the influence on the resulting design wave height and accelerations is presented in Figure 2.

With the use of MatLab scripts, these wave processing and grid interpolation have been built to rerun all the sailed voyages stored in the OCTOPUS database. In this paragraph the error statistics are presented for the statistical sea-state information, $H_s$, $T_p$, $W_s$ and $W_d$, obtained with a validation study between the encountered OCTOPUS wave database (labeled “SPOS”) and the NOAA WaveWatch III CFSRR hindcast dataset (labeled “NOAA”). The combined wave direction, $D_p$, will be left out of this comparison because the motion response calculations are performed for all directions wherein the maximum is taken into account.

Although there is a slight underestimation in SPOS for the wave height, the RMSE is around the 60cm while the scatter index is about 25%. The scatter index for the wind speed is around the 30%. Since, wave model accuracy depends critically on the accuracy of the surface winds, a 10% error in the estimated surface wind speeds can lead to 10-20% errors in $H_s$ and 20-50% errors in wave energy.

The peak period statistics show an increased absolute bias and decreased correlation coefficient although the scatter index remains quite similar. This has to do with the uncertainties about the shape of wave spectra examined by Haver and Moan. (Haver, 1985) The within OCTOPUS database stored wave peak period is obtained from the combined directional frequency spectrum. Statistical uncertainty is related to the estimation of a spectrum from a wave record. Thus, whenever a sea-state is defined by a significant wave height and an average period, there are two main uncertainties; degree of development and existence of combined wave systems.
Figure 2: Analysis sequence to obtain Wave Forecast Error
Using the peak frequency as a parameter to describe the degree of sea development has been explored by Hasselmann in the JONSWAP project. The other main source of uncertainty for the value of the wave peak period parameter is the representation of combined wave systems. The fitting procedure of the double peaked spectra gives average values of these parameters. Shown is that $H_s$ is independent on whether the sea-state was dominated by the swell or the sea component. (Soares, 2011) Thus, for the wave peak period the representation of combined wave systems also involves the error in relative intensity of each of the two wave systems.

The seasonal statistical metrics of area 90 gives a similar impression. The wind speed predictions around Cape of Good Hope having the same seasonal variability, so this trend would also be expected for the significant wave height since this is the main input. Especially, the significant wave height during the winter season of area 90 gives an unexpected deviation. This is related to the fact that during the winter season these strong westerly winds meet the Agulhas current and cause for an unpredicted upwelling. This upwelling has a negative influence on the statistical error for the significant wave height and wave period. However, the expected correlation between the $H_s$ and $W_s$ will never show exactly the same trend, despite the fact that the $W_s$ is the main input for this wave model. This area around Cape of Good Hope is a swell-dominated region, which means that these waves are calculated depending on the accuracy of the wind predictions of the surrounding areas. The higher statistical error for the wind direction can be related to the fact that these westerly winds pass over the irregular land surface at the southern tip of Africa. Irregularity as land contours, hills and mountains change the predicted wind direction.

It is necessary to use multivariate models in order to capture the dependencies between these datasets. Linear correlations are the correct dependence measures to use for multivariate normal distributions, but not for other joint distributions. To achieve this, an approach based on copulas is proposed, a tool for modelling dependence of several random variables. The main purpose is to describe the interrelation of several random variables. The copula based dependence measures, rank correlation and tail dependence, will be discussed in the next paragraphs. Copulas were first introduced in financial context (Genest, 2007), avoiding that the individual behaviour of the variables must be characterized by the same parametric family.

Since the design sea-states are made up of a combination between the significant wave height and wave period, the wave forecast error has to describe both parameters. In addition to the wave height forecast error, a method to describe and implement the wave period forecast error will be provided in the paragraph below.

To evaluate the wave period forecast error the wave steepness parameter will be used, describing the wave period as a function of wave height and steepness. Despite the fact that the correlation coefficient between these wave period parameters does not indicates any consistency, the wave steepness probability distributions show similarities. So, for the wave period forecast error there will be a descriptive analysis in the next paragraph to find a way to describe the error limits and implement this into the design method. Based on the wave steepness distributions, a design method including these physical behaviour of waves will be introduced to find an alternative description of the extreme wave heights and periods.

5. Wave forecast error

The data considered for the wave forecast error consist of the significant wave height ($H_s$) and the wave zero crossing period ($T_z$) for 6 consecutive years, starting in 2008 and ending in 2013, between the SPOS nowcast and NOAA hindcast wave data of area 90.

The wave forecast error can be generated per interval of the SPOS nowcast wave height. This
can also be accessed per wave, but due to the amount of data is the wave forecast error implement for a certain interval. The construction is based on a conditional probability density function, to implement a conditional coverage, such that an interval represents the true encountered wave height distribution. This probability density function, including the additional coverage, will be inverted to a set of wave heights for a certain interval. Taking the 95% confidence range of this conditional coverage gives the wave height forecast error for this certain interval, this will be carried out for the entire range. After that the Weibull fitting process will be elaborated, to estimate the parameters of this cumulative distribution function including the local wave forecast error.

A marginal distribution for the conditional distribution including the wave forecast error is necessary, since the DoSuite method and the Operational Based Method use this 10-year return period based on the POT approach. A choice has to be made which POT percentage is used for the further analysis. This is done for the yearly and seasonal wave data varying the POT values between the 50%-1%.

The period in which the highest waves encountered by the Dockwise vessels shifted from Mar-May (autumn) to Sep-Nov (spring). According the GWS wave data for area 90 spring season is one of the heaviest seasons, which now corresponds to the SPOS wave data including the wave forecast error. For Mar-May and Sep-Nov there is a decreasing 10-year return period visible for the lower POT values. The other seasons show the opposite movement and the POT values below the 3% for Yearly and Jun-Aug shows greater variability. However, there is no reason to assume that these 10-year return Hs are realistic, because the tail shows no convergence. Therefore, these values will be left out the further analysis. The difference by varying the POT percentages are respectively between the 0.05 - 0.80m as depicted in Table 1.

<table>
<thead>
<tr>
<th>Season</th>
<th>Max Hs [m]</th>
<th>Min Hs [m]</th>
<th>Difference [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly</td>
<td>7.9631</td>
<td>7.6536</td>
<td>0.3095</td>
</tr>
<tr>
<td>Mar-May</td>
<td>7.4167</td>
<td>6.6669</td>
<td>0.7558</td>
</tr>
<tr>
<td>Jun-Aug</td>
<td>6.2600</td>
<td>6.2326</td>
<td>0.0274</td>
</tr>
<tr>
<td>Sep-Nov</td>
<td>8.2990</td>
<td>7.5020</td>
<td>0.7970</td>
</tr>
<tr>
<td>Dec-Feb</td>
<td>5.4790</td>
<td>5.3471</td>
<td>0.1319</td>
</tr>
</tbody>
</table>

Table 2: Difference in 10-yr return design wave height

Despite the fact that the correlation coefficient between the wave period parameters do not indicate any consistency, the wave period forecast error will be, according a descriptive analysis, be described by an upper and lower bound to take into account. To account for the wave period forecast error, it is assumed that the maximum error in wave period and highest encountered wave height will occur at the same time. The design sea-states including the wave height forecast error move one second to the left and right, to describe and implement the influence of the wave period forecast error with an upper and lower bound.

6. Bivariate statistical analysis of long-term wave climates

The analyses are based on a bivariate description of offshore wave conditions. The design sea-states can be evaluated by using the scheduled route, in combination with the encountered OCTOPUS wave scatter diagrams including the local and seasonal wave forecast error. In the estimation of extreme limit states of oceanographic data, wave heights and wave periods, a probabilistic approach is adopted. The bivariate models within this paragraph, to correctly describe the data and their behaviour when used for extrapolation to extreme events, have nothing to do with this modelling dependence tool and are an independent probabilistic approach. The first method, the Operational Based Method (Deelen, 2014), will fit the marginal distribution of the significant wave height with a Weibull distribution. Combined with the conditional distribution of the wave period to the significant wave height on top. The second method includes the physical limitations of waves, introduced by Vrijling and Bruinsma (Vrijling, 1980), contains a marginal PDF for $H_s$ and for the wave steepness $S_p$.
Both methods are tested on yearly wave data of the Cape of Good Hope, area 90. Figure 3 presents the JPDF contour lines and design sea-states from the different bivariate models. The models have been compared to their ability to correctly describe the extrapolation to extreme wave data. It appeared to be difficult to judge the goodness-of-fit of the implementation of the wave period forecast error for the OBM method. Within the wave steepness model the marginal steepness distribution, describes the wave period as a function of wave height and steepness, is not being influenced to a forecast error. When the OBM method will be judged visually, in taking the wave period forecast error into account as a fixed factor on top of the sea-states. It seems to be, with regard to the wave period, that this OBM design method is fitted relatively close to the bivariate steepness model data.

Figure 3 shows also the conventional DoSuite design sea-states representing the highest being obtained from the Cargo Securing Manuals. A design sea-state with a significant wave height of 10.17m and zero-up crossing wave periods of 8.70, 9.70, 10.70 and 11.70 seconds. The design sea-states are evaluated by using the scheduled route, in combination with a different statistical wave database, the GlobalWave Statistics environmental database.

Table 2 shows difference between the 10-year design sea-states from the OBM method including the wave forecast error and without according Deelen.

<table>
<thead>
<tr>
<th>Season</th>
<th>Season</th>
<th>10-yr return [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Yearly</td>
<td>27.65</td>
</tr>
<tr>
<td>Autumn</td>
<td>Mar-May</td>
<td>19.39</td>
</tr>
<tr>
<td>Winter</td>
<td>Jun-Aug</td>
<td>27.38</td>
</tr>
<tr>
<td>Spring</td>
<td>Sep-Nov</td>
<td>35.92</td>
</tr>
<tr>
<td>Summer</td>
<td>Dec-Feb</td>
<td>23.43</td>
</tr>
</tbody>
</table>

Table 2: Increase design sea-states for combined sea & swell of area 90

7. Conclusions & recommendations

Both transverse- and vertical design accelerations will be increased due to the influence of the wave forecast error on the design sea-states from the Operational Based Method. The maximum observed difference for the yearly transverse design accelerations is 24.30% and for seasonal transverse design accelerations 37.03%. The vertical design accelerations increase relatively more than the transverse design accelerations. The maximum observed difference for the yearly vertical design accelerations is 31.06% and for seasonal vertical design accelerations 36.97%.

The minimum operational margin from the Operational Based Method, defined as the difference between the design acceleration according the Operational Based Method and the measured accelerations, of both the transverse- and vertical accelerations will be increased, due to the influence of the wave forecast error on the design sea-states. For the yearly transverse design accelerations, the minimum operational margin changed from -0.7% to 16.18%. The minimum operational margin of the seasonal transverse design accelerations changed from -9.5% to 15.57%. For the yearly vertical design accelerations, the minimum operational margin changed from 29.33% to 40.37%. The minimum operational margin of the seasonal vertical design accelerations changed from -5.38% to 15.49%.
Both transverse- and vertical design accelerations show a positive operational margin when comparing the design accelerations with the measured accelerations, except for one voyage. For this particular voyage the masters decisions have a large influence on the operational margin. It is advised to investigate these sheltering and weather routing events, for insight in the masters decisions to avoid bad weather and on the other hand the influence on the wave forecast error modelling.

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