Is Wave Height Necessary to Determine Ship Performance in Calm Water from Measurements?

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Abstract

In order to monitor the performance of a vessel in calm seas it is important to ensure that the operational parameters are not biased by weather conditions. This paper makes a comparison between the relationship of true wind speeds obtained from on-board anemometer measurements and hindcast MetOcean data with the wave heights obtained from the MetOcean data. The insights obtained from the correlations between wind and waves is used to make a comparison calm water model derived from 'wind-wave' filtering and data filtered using only the wind speed. Finally, the increase in shaft power with respect to wind speed and wave heights for discrete intervals is presented. The results presented indicate that an average decrease of 4-5% in shaft power is seen when including an additional wave filter in the calm water model. However, this discrepancy improves when a stricter wind speed filtering is used.

1. Introduction

The powering performance of a ship is influenced by several factors, amongst which the operational conditions and the environment are of key importance. A ship in service predominately operates in stochastic weather conditions which can have a significant effect on the power requirements and the fuel consumption. However, the performance of a ship in calm water is vital to understanding performance against guarantees, monitoring coating and propeller performance as well as benchmarking energy-saving technologies. Sea trials to achieve the guarantee speed as per the contract specification are carried out in, or more usually corrected to, a calm water condition.

In order to monitor the performance of a vessel in calm seas it is important to ensure that the operational parameters are not biased by weather conditions. This is usually achieved by either filtering or normalising measured data, or a combination of both, to derive a calm water model, *Dinham-Peren and Dand (2010), Webb and Hudson (2015)*. Weather, or MetOcean, data (wind speed, wave height and their directions) may be obtained using hindcast models, measured at the site (shipboard instruments and/or wave buoys) or remote sensing by satellites. MetOcean data from hindcast modelling typically not only include the combined wave height but also primary and secondary swell and the wind-generated wave data. Automatic high-frequency data acquisition systems installed on-board ships now enable ship operators to obtain operational data of high quality, which not only facilitates monitoring performance more precisely but also in identifying changes in performance in smaller time periods, *Aldous et al. (2015)*. The performance prediction can be improved significantly by combining automatic data acquisition with MetOcean datasets to model the weather effects more accurately, *Bos (2016)*. However, more often than not the MetOcean data comes at considerable cost, which might not be affordable to the ship owners and operators.

Onboard a vessel the wind speed is either estimated visually by the Master or determined using an anemometer, but presently, wave measurements are practically impossible to obtain routinely from the available onboard instruments. Anemometer measurements are considered more reliable than visual estimations, although uncertainties do exist in readings from the anemometer, *Taylor et al. (1995)*. The errors in wind speeds measured by an on-board anemometer due to flow caused by the ship's superstructure can be as high as 30% for a tanker in a head wind condition, *Yelland et al. (2001)*. When comparing measured data to forecast (or hindcast) data, a higher wind speed will usually be recorded because the location of the ship's anemometer is generally much higher than the reference height of 10m used as a MetOcean standard. However, there are established relationships which can be applied to correct the anemometer measurements to a required reference height. Ocean waves are generated primarily due to the transfer of energy from the wind blowing on the ocean surface. The combined wave height or significant wave height of all the component sea states measured at a site exhibits a strong correlation with the wind speeds measured, *Khristoforov et al. (1994)*, and consequently it is likely to be possible to derive a correlation between the true wind speed from anemometer measurements and significant wave heights.

This paper attempts to find a relationship between the true wind speeds derived from onboard anemometer measurements and wave heights obtained from hindcast MetOcean data, including both the combined and the component sea-states. The hindcast datasets also incorporate the true wind speed and direction which is also used to deduce correlations with the wave heights. The correlations thus obtained between wind and waves are used to filter the high frequency data obtained from a merchant vessel to calculate the calm water powering. A comparison will be made between the accuracy of the calm water model derived from the deduced ‘wind-wave’ relationships and the MetOcean wave data directly. The analysis presented in this paper will provide insights into the accuracy and differences in calm water power models when the MetOcean data are not available. The independent effect of wind and wave on the power vs speed curves is also investigated.

2. Methodology

This section provides a brief description of the methodologies used to derive the relationship between wind and wave using on-board anemometer measurements and MetOcean data, respectively, together with the data filtering applied to derive the calm water model. Firstly, the nature of data acquired from the automatic data acquisition system on the vessel and MetOcean data from hindcast modelling are reported.

2.1 Ship Data Acquisition

High-frequency continuously monitored data was obtained for three sister merchant ships along with the weather data from a MetOcean hindcast model. The data logger installed on board recorded the shaft parameters at a sampling frequency of 1 Hz and averaged over 5 min intervals. The wind speed and direction were measured using an on-board anemometer. The total period of the measured data for the three ships was different with the maximum being two years and one month and the minimum being six months. The ship with maximum data was only considered for this study due to the quantity of data. The raw data for this ship yielded a total of 155814 data points. Fig.1 shows the operational profile of the vessel with reference to the ship speed, draft, trim and the significant wave height from the MetOcean dataset. The encountered significant wave heights mainly fall in the range of 1 to 3 m and the number of data points for a wave height ≤2.0 m is 63385 which comprises 41% of the total dataset.

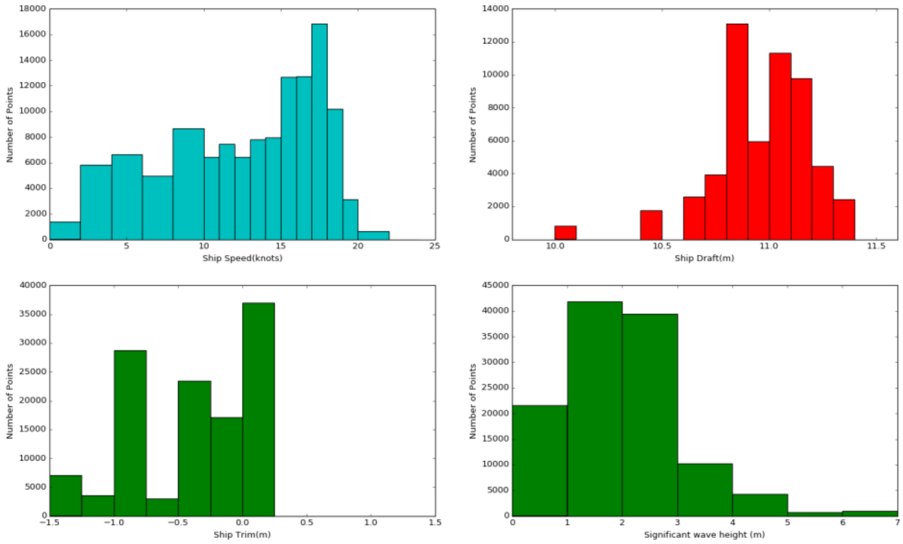

Fig.1: Histograms of ship speed, draft, trim and significant wave height during the analysis period
The apparent wind angle and the wind speed recorded using the anemometer are presented in Fig.2. The apparent wind is a relative effect which arises due to the combined effects of the true wind and the vessel speed. In section 2.2 the method to translate the apparent wind to true wind using the ship's speed and heading are described.

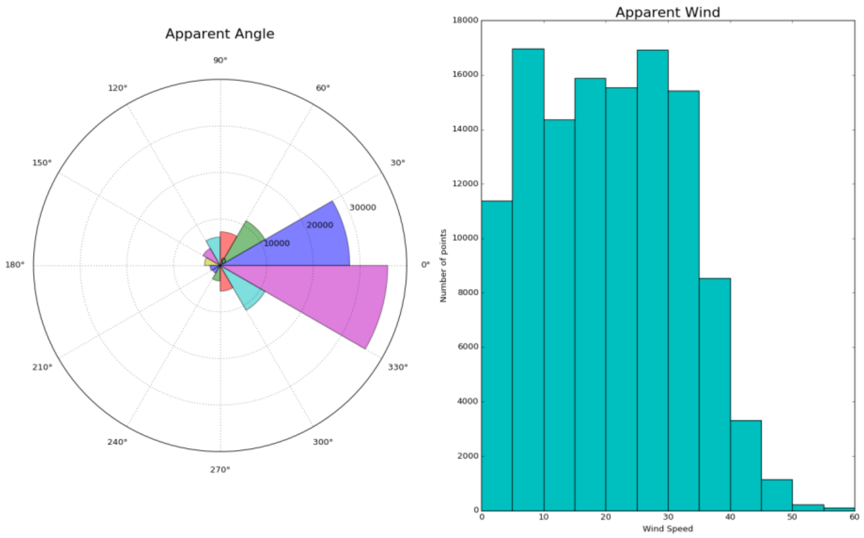

Fig.2: Apparent wind direction and wind speed experience by the vessel

2.2 MetOcean data and True Wind Speed

The MetOcean data obtained include primary swell, secondary swell, wind wave, combined wave, and true wind, which are shown as a block diagram in Fig.3. The primary and secondary swell are the components of the sea state in which the waves are not generated by local winds but rather remote from the location of interest and then travel towards it, whereas the wind wave consists of locally generated wave systems.

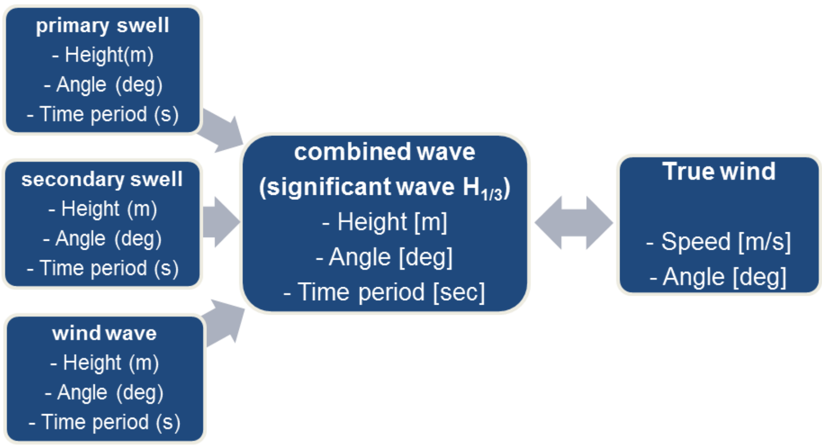

Fig.3: Schematic diagram of the hindcast weather dataset

In general, the primary, secondary and the local wind wave are related to the combined or significant wave height by the formula given below, *Barth and Eecen (2006)*. This relationship was verified, shown in Fig.4, for the data set obtained and the results are in good agreement. The comparison between the significant wave height from the MetOcean data and calculated using the formula are almost linear, as illustrated in Fig.4.

$$H_{1/3} = \sqrt{((1^{\circ})^2 + (2^{\circ})^2 + (wind)^2)}$$

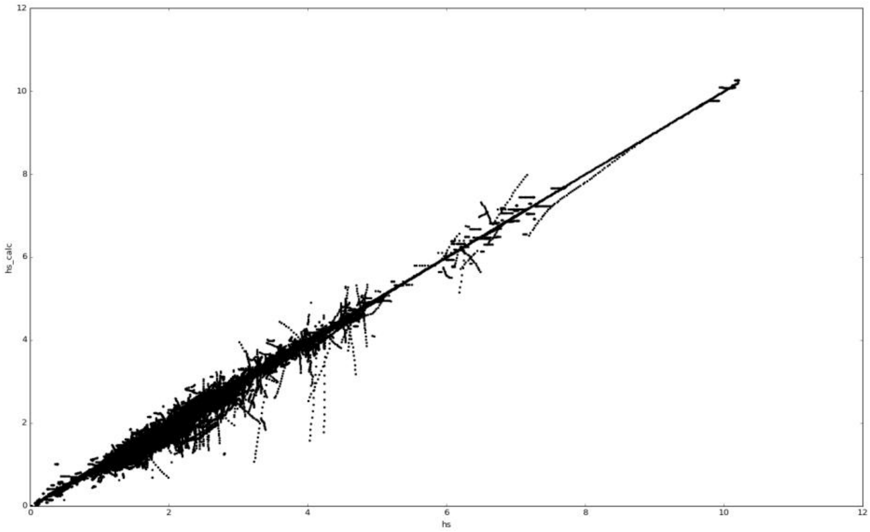

Fig.4: Significant wave height from MetOcean data vs that calculated using the component sea states

True wind speed and direction were determined by eliminating the influence of the ship speed from the apparent wind measurements using the relationship given below. The true wind angle and speed is also obtained from the hindcast weather data, where the angle of zero degrees indicates true north. For comparison, the true wind angle from the anemometer was corrected using the ship heading angle (ship data) and compared to the true wind angle from the MetOcean data.

The true wind speed and angle determined using the relationship are shown in Fig.5. The true wind speed histogram resembles a normal distribution curve, with most wind speeds recorded below 20 m/s.

$$V_{true} = \sqrt{{V_{apparent}}^2 + {V_{Ship}}^2 - 2V_{apparent}V_{Ship}}$$

$$\alpha = \text{accros}\left(\frac{V_{apparent}\cos(\beta) - V_{ship}}{\sqrt{{V_{apparent}}^2 + {V_{Ship}}^2 - 2V_{apparent}V_{Ship}}}\right)$$

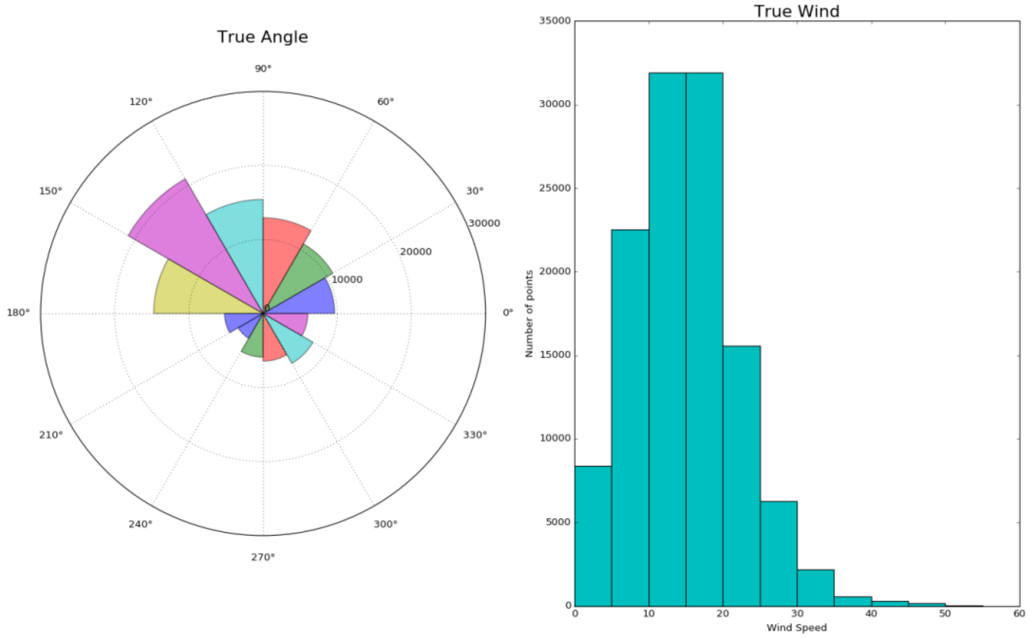

Fig.5: True wind speed and direction obtained by accounting for vessel speed and heading

2.3 Calm-water filtering

The in-service data are used to estimate the calm water power by appropriately filtering for weather effects. *ITTC (2014)*, 'Recommended Procedures and Guidelines' provide procedures and sea states for speed/power trials that defines a suitable calm water condition to conduct the trials. These may be used as an initial means to define a calm water condition, although it should be noted that when conducting trials in these conditions, corrections for wind and wave effects would be applied to measured power/speed data.

According to the ITTC, wind and wave limits for conduct of sea trials are as follows:

- Wind speeds shall not be greater than Beaufort number 6 (L_{pp}> 100 m) or Beaufort number 5 (L_{pp} < 100 m)
- Significant wave height shall not be higher than $2.25\sqrt{L_{pp}/100}$ (where L_{pp} is the length between perpendiculars [m]).

The wind and wave limits to define calm water based on the above conditions are 10 m/s and 3.74 m, respectively. When establishing calm water conditions, it is also necessary to examine how much the sea state influences the ship speed and shaft power. Fig.6 shows the power vs speed curves with different filtering criteria for true wind speeds. The trends look similar, but the regression curves for true wind speeds greater than 6 and 7 m/s require higher shaft power than at 5 m/s or less, albeit, the difference is not very substantial. In the case of significant wave height, the effect of waves can be discerned more clearly. The gradient of the fitted curve begins to be considerably higher for a significant wave height greater than 2 m. Thus, it is considered reasonable for these vessels to limit the true wind speed and significant wave height to 10 m/s and 1.5 m, respectively.

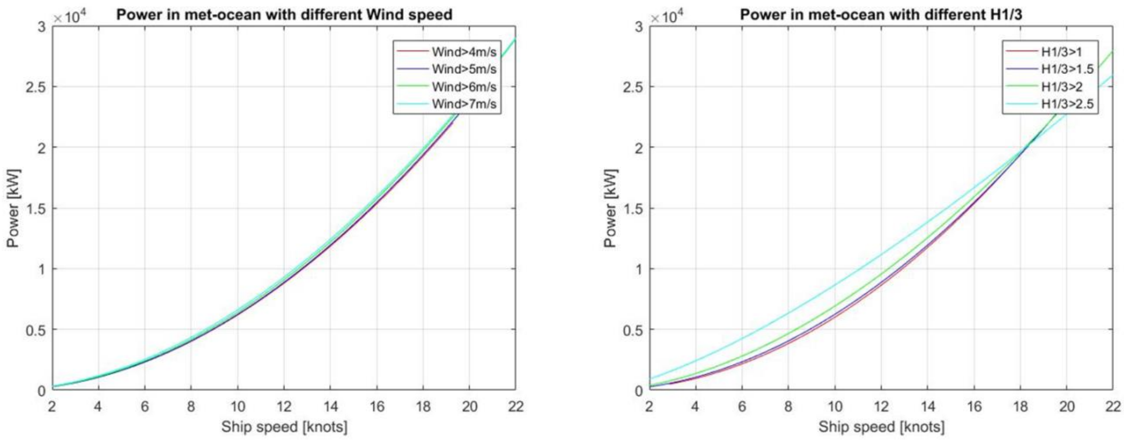

Fig.6: Power vs Speed curves for different wind speeds and wave heights.

To calculate the calm water powering characteristics for these vessels the raw data were filtered by applying the following constraints:

- True wind speed less than 10 m/s
- Significant wave height less than 1.5 m
- The difference between the speed over ground and the speed through water less than 1 knot. This constraint is to ensure that the effect of ‘current’ is small in the calm water model.
- Engine RPM is greater than zero, hence astern running is not included.
- Change in speed over ground between successive samples does not exceed 0.5 knots. In this case, only data points that represent the ship moving at a reasonably steady speed will be considered.

3. Results and Discussion

3.1. Wind and Wave correlation

According to the National Oceanic and Atmospheric Administration (NOAA), swell travels outside of the generated area and does not necessarily correlate well with the wind, whereas the wind wave is formed due to local winds, *Ainsworth (2006)*. Before trying to derive a correlation between the true wind recorded using the anemometer and the significant wave height, some insights are provided on the realtionship between the directions of the combined and the component sea-states.

Fig.7 illustrates the relationships between the true wind angle with the wind wave angle and the combined wave angle obtained from the hindcast data. It is to be noted that the angles are converted to 0-180° for convenience. As expected, the wind wave angle exhibits good correlation with the true wind angle, while a large degree of scatter apparently exists in the comparison with the combined wave. However, a density map of the data points, shown in Fig.8, unveils a possible trend between the combined wave angle and the true wind angle. High-probability points are depicted with bright yellow and red colours and a linear behaviour can be infered between the variables. Hence, it would not be erroneous to speculate that typically the combined wave direction is dominated by the wind wave, unless otherwise affected by a strong swell.

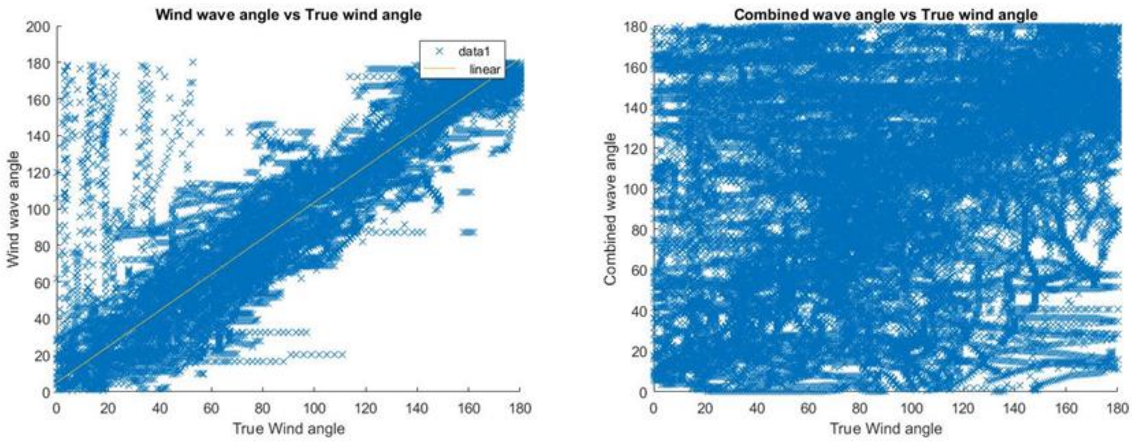

Fig.7: True wind angle (MetOcean) compared with wind wave and combined wave angle

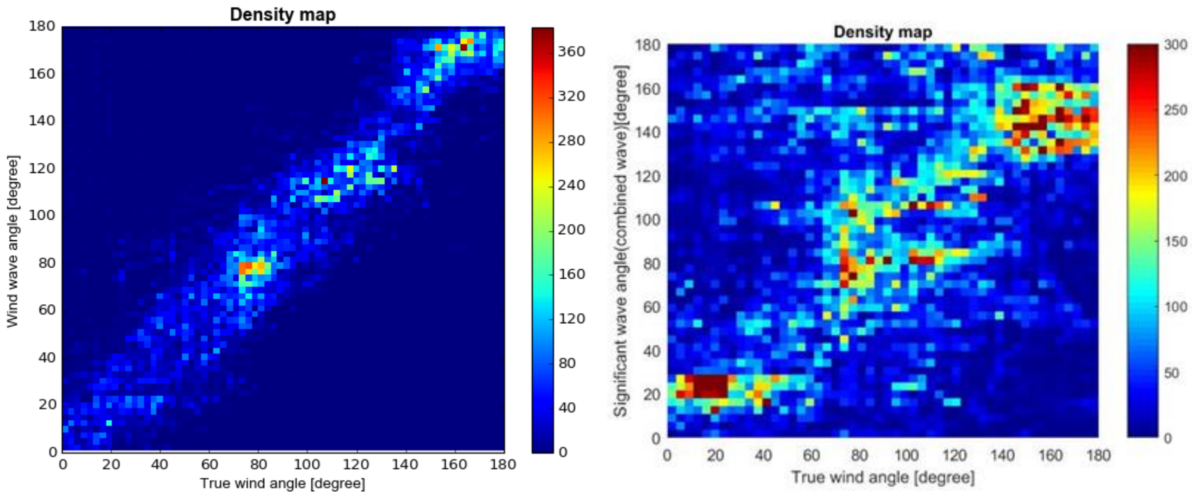

Fig.8: Density map for true wind angle (MetOcean) compared with wind wave and combined wave angle

Fig.9 is a scatter plot between the true wind speeds measured onboard and those from the hindcast MetOcean data. The scale of the true wind speed taken directly from these onboard measurements is approximately 50 % higher than the corresponding speed in the hindcast data. In the majority of cases, wind speed should be measured or corrected to a reference height of 10m above the surface. Since virtually all merchant ship anemometers are higher than 10m, the wind speeds measured onboard should be corrected before making such comparisons *Moat et al. (2005*). In the present study, without precise details of the anemometer mounting position, an assumption is made that the ship anemometer is mounted at a height of 20 m above the sea level. When considering light winds, under stable atmospheric conditions, the surface air layer exhibits strong shear effects and the wind at 10m can be as low as 40% of the wind speed at 20 m, *Isemer and Hasse (1991)*. Fig.10 shows the comparison between the measured true wind speed corrected using a factor of 0.4 and the true wind from the hindcast data. The scales of both the axes are now identical and the density plot understandably reveals a linear correlation between them, if the data points with lower probability are omitted.

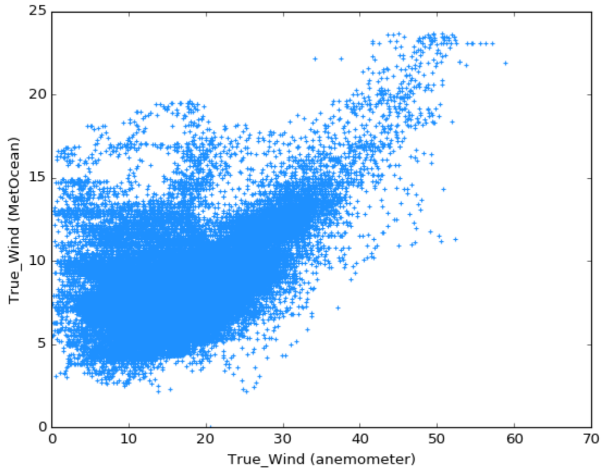

Fig.9: True wind speed (MetOcean) vs True wind speed (anemometer)

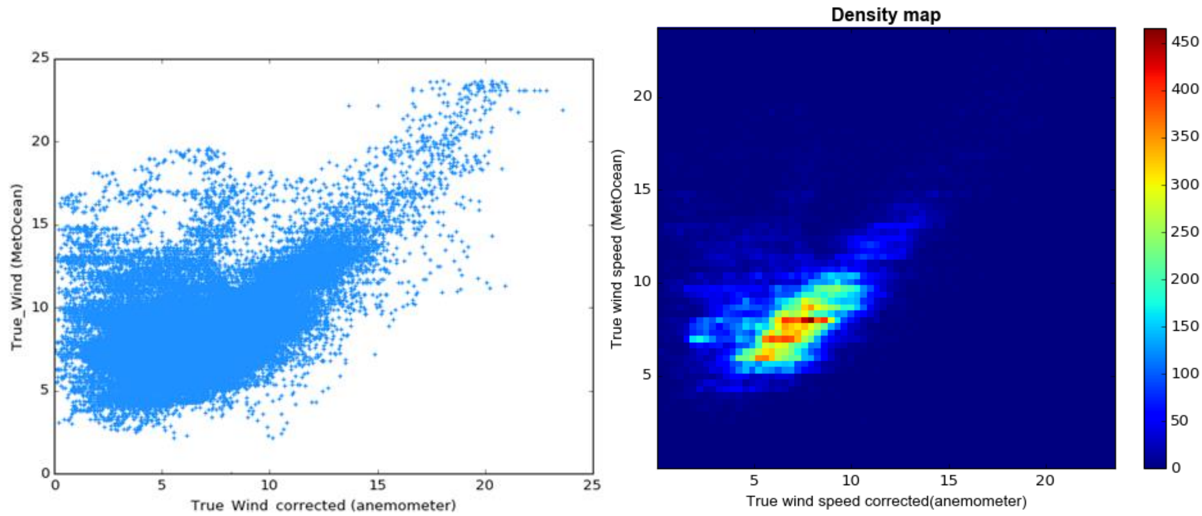

Fig.10: Scatter plot and density map for true wind speed (MetOcean) vs true wind speed (anemometer corrected using a factor of 0.4)

The relationship between the true wind speed and the significant wave height is approximated in the form of $H_{1/3} = kV^{n}_{truewind}$ to obtain a best fit relationship for these data, where the coefficients *k* and *n* are obtained through curve-fitting. Fig.11 presents the scatter plot and the best fit lines for the true wind speeds from both the hindcast MetOcean data and the ship's anemometer with the significant wave height. There is a considerable difference in the correlations obtained from the best fit when using the two different true wind speeds, which is also confimed from the coefficients shown in Table I. The true wind speed obtained from the hindcast data exhibits a linear trend with the significant wave height, which is not surprising since the combined wave parameters are dominated by the wave generated by the local winds rather than the swell, as seen in Fig.7. Although the coefficients in Table I are appreciably different from each other it is encouraging to note that using either true wind speed results in a the significant wave height of less than 2 m for wind speeds less than 5 m/s and 10 m/s. This is particulary important in trying to understand whether the ship's anemometer readings may be used to filter data and predict vessel performance with minimum uncertainty due to the influence of waves. Almost all standards found in the literature (e.g. (ISO19030)) use a filtering criteria of significant wave height less than 1.5 m or 2.0 m to define the calm water performance of a vessel. Comparing the plots and the coefficients obtained in Fig.11 and Table I it can be presumed that using a criteria of true wind (anemometer) less than 5.0 m/s or 10.0 m/s would not be inaccurate in this regard, since it would filter out most of the wave influence in establishing a calm water model. Additionally, the density maps shown in Fig.12 also suggests this possibility, displaying a good comparison in the probability distribution between the wind speed from the hindcast model or the anemometer measurements with the significant wave height. However, difficulty may arise in calculating ship added power due to a larger uncertainty in the predicted significant wave heights using the two alternative means of obtaining the true wind speed.

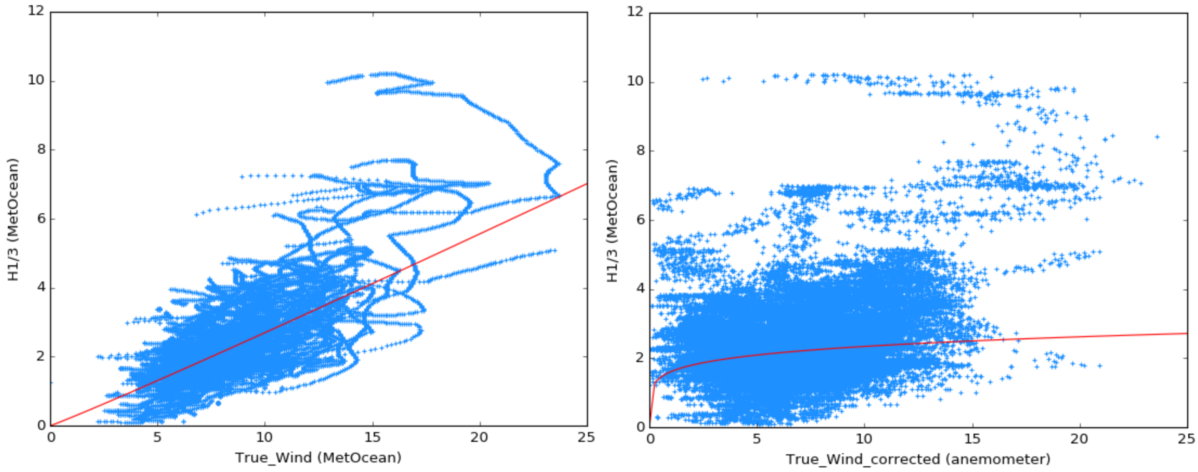

Fig.11: True Wind speed (Met Ocean and anemometer) data compared with the significant wave height. The redline shows the fit obtained using a regression analysis

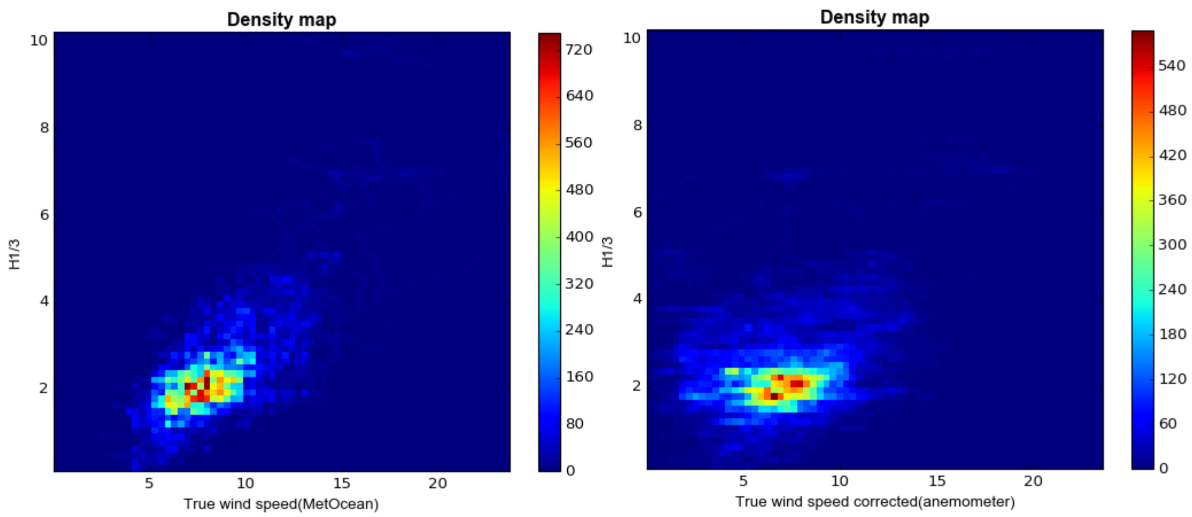

Fig.12: Density plot for true wind speeds (Met Ocean and anemometer) data compared with the significant wave height showing close similarity in the high probability data points

There are a number of data points in Fig.11 for the onboard true wind measurements vs wave height plot that lie in the wave height region greater than 2.0 m for a wind speed less than 10 m/s. Even though the concentration of points in the density plot for this wind speed range is shown to be less (Fig.12) than 2.0 m, it is advised to investigate the effect of wind and wind-wave filtering separately on the power vs speed curves to quantify the difference for a given data set.

Table I: Coefficients k and n for relationship between true wind speed and significant wave height

	k	N
True wind (Met) vs $H_{1/3}$	0.25	1.04
True wind (onboard) vs $H_{1/3}$	1.45	0.21

3.2. Power vs speed analysis

This section presents the results of the power vs speed in calm water, using different wind and wave filtering criteria and the findings from the wind-wave correlation presented in section 3.1.

Firstly, the comparison between the calm water performance in laden condition (>10.0 m draft) of the vessel with the filtering criteria listed in section 2.3 and that obtained by omitting the wave height filtering criteria is shown in Fig.13. In the laden condition, the vessel primarily operates with a speed over ground above 16.0 knots, which aggregates to 76% of the total number of data points. The shaft power predicted with wind and wave filtering is lower for the higher operating speeds and the difference in predicted power varies from 2% to 8% for a speed range of 16-19 knots. When a stricter wind speed filtering criteria is used – true wind speed less than 5.0 m/s – the percentage differences in predicted power improves to about 1-4% for the operating speed ranges, as shown in Fig.14. Nevertheless, the Figs.13 and 14 do demonstrate an apparent improvement in the calm water predictions when using the significant wave height as an additional filtering criteria, as opposed to using only the true wind speed from the anemometer measurements. Figs.13 and 14 show that it is most likely that the calm water power predicted, especially for operating speed ranges, may exhibit an average difference of 2-3% when hindcast weather data are unavailable, provided a strict filtering of true wind speed is used.

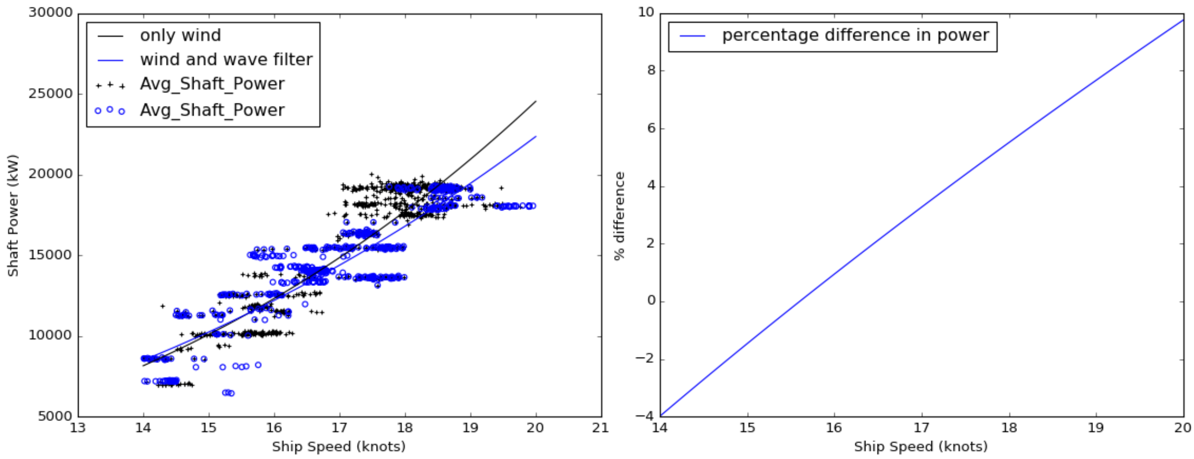

Fig.13: Power vs speed curves comparison between ‘wind-wave’ filtering and only wind filtering

To further explore the sensitivity of power vs speed curve fitting to the inclusion of wind and waves, data analysis is performed by ‘binning’ the wind speed and wave heights into regular intervals. The true wind speed is divided into 2.5 m/s intervals. Additionally, the direction of the wind is also considered in this analysis in the sense that only head winds, categorized as a true wind direction of 0 to 30° are considered. The air resistance caused due to the vessel sailing into head winds causes an increase in shaft power when compared to winds from other directions, *Molland et al. (2017)*.

Fig.15 represents shaft power against ship speed in the laden condition for various wind intervals. In this case the calm water power is calculated using a wind and wave filtering of 5 m/s and 1.5 m, respectively. The increase in shaft power is obvious in the curves with respect to the increase of wind strength. The results obtained by calculating shaft power by binning the wave heights shows a trend similar to that with the strength of head winds. The fewer number of data points for significant wave heights greater than 3.5 m skews the regression curves, making these unreliable for comparison.

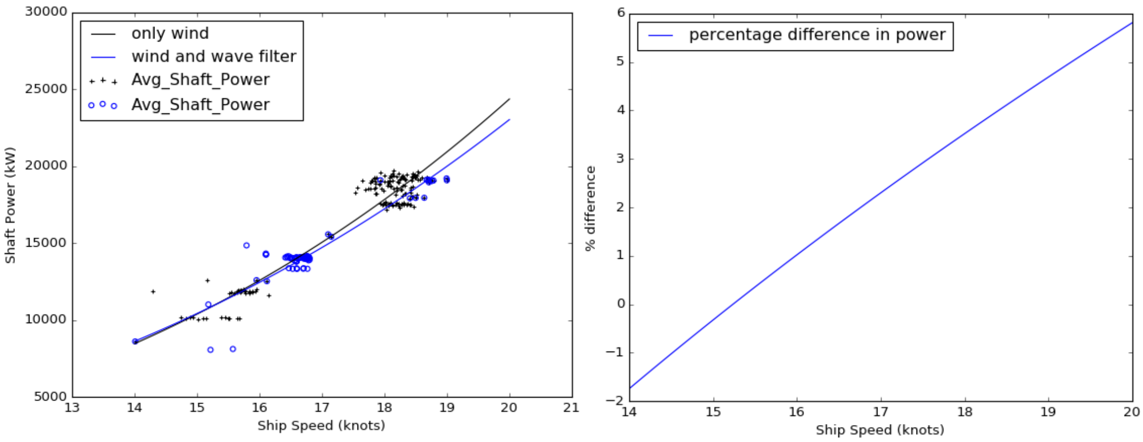

Fig.14: Power vs speed curves comparison between 'wind-wave' filtering and only wind filtering. The wind speed filtering criteria is decreased from 10 m/s to 5 m/s.

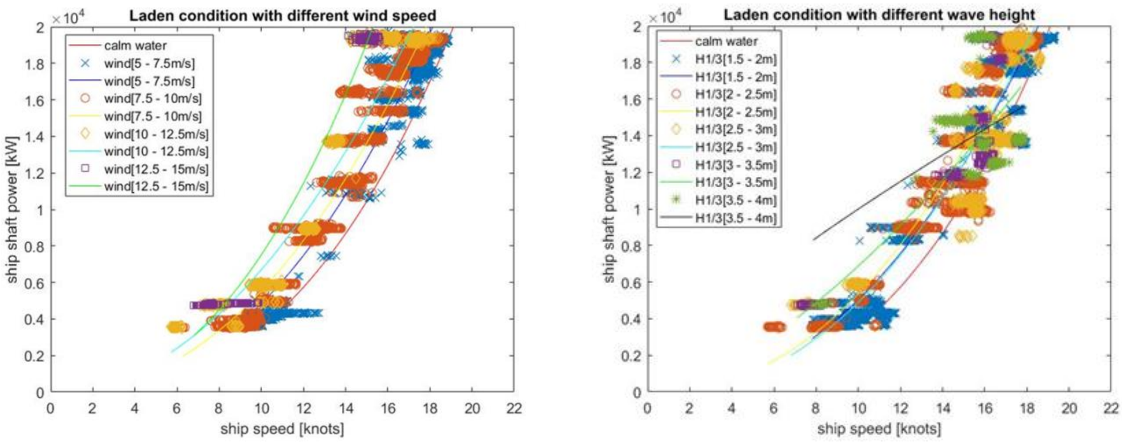

Fig.15: Power vs Speed curves with various wind speed bins (head wind) and wave height bins in laden condition

4. Conclusions

The correlation between the true wind speeds measured using the ship's anemometer and the significant wave height from MetOcean hindcast data are presented in this paper. By comparing the combined significant wave height direction with the true wind direction from hindcast models, it is shown that, whilst there is considerable scatter in the total ranges of data, the majority of points demonstrate a good correlation. This indicates that true wind angle may be used as a reasonable indicator of combined wave angle. The study also uses the true wind speeds obtained from the hindcast MetOcean data and the two are compared. It is shown that the true wind speed from the anemometer should be corrected to a reference level of 10m to correspond with the true wind speed obtained from the hindcast (or other) MetOcean models. Although the true wind speeds obtained from the two sources does not show an exact correlation with the significant wave height, it is demonstrated that for true wind speeds less than 10 m/s (anemometer and MetOcean) the predicted significant wave height is under 2 m. The calm water power is overestimated by a maximum of 8% for the vessel used in this study when using a true wind under 10 m/s as the only filtering criteria for weather, when compared to using both wind and wave filtering. This overestimate in power reduces to 4% when a stricter criterion of 5 m/s true wind speed is used. When MetOcean datasets are not available it is imperative to investigate the sensitivity of true wind speed (anemometer) filtering on the calm water performance for both laden and ballast condition to deduce an appropriate filtering criterion. The above investigations illustrate that by using only true wind speed as a filtering criterion for the weather will, on average, produce a difference of about 2-3% in calm water predictions for the operating speed range as compared to when MetOcean data sets are available to complement the analysis.

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