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Demonstrating the impact of bidirectional coupling on the performance of an ocean-met model

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Abstract

The mass, momentum and energy fluxes between the atmosphere and ocean surface depend on the state of the ocean surface. The fluxes in turn can significantly alter the nature of the marine boundary layer and the state of the ocean surface. These interactions can be modelled deterministically using a multiphase modelling approach or using a semi-stochastic approach. While the multiphase approach can give better insights (e.g. wave generation), it is computationally too expensive and not suited for modelling ocean waves which are inherently random in nature. It is for this reason that in a forecasting context, semi-stochastic approach is still the workhorse. Furthermore, even in a semi-stochastic approach ocean and atmospheric models can be coupled in either unidirectional way (ocean affecting the atmosphere) or bidirectional way (both ocean and atmosphere affecting each other). Current work compares the performance of these two coupling approaches and validates them using significant wave heights and 10m wind magnitude.

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1. Introduction

The exchange of mass, momentum and energy between atmosphere and ocean surface depend on the state of the surface. For example, young ocean waves typically have a larger roughness compared to older waves and hence bigger mass, momentum and energy flux. The flux in turn can significantly alter the nature of the marine boundary layer (MBL) and the state of ocean surface. Many offshore engineering applications rely on a detailed ocean and atmospheric state at specific locations. Within the marine industry attention to joint met-ocean description was given already three decades ago due to expected economic advantages of using it. It was shown that typically, the environmental forces on marine structures may be reduced from 5% to 40% by accounting for the lack of full correlation

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of met-ocean parameters; see e.g. [1]. Gregersen et al [2] suggested that the met-ocean model developed originally for design purpose can also be applied for specification of operational criteria for marine structures in general. Since direct measurements of waves are often constrained by budget that allows only short or intermittent datasets, numerical modeling is becoming more of a norm. Wave models like WAM [3] and SWAN [4], and atmospheric models like HARMONIE [5] are now increasingly used for getting a real time state of ocean and atmosphere. However, most often than not the ocean and atmospheric models are run in isolation. For a better prediction of the ocean-atmospheric state interaction between the two needs to be modeled accurately. The interactions can either be modeled deterministically using a multiphase modeling approach (where a liquid phase represent ocean and gas phase represents atmosphere) or can be modeled using a semi-stochastic approach where stochastic action balance equation is used to model the state of ocean surface and a deterministic approach based on the Navier Stokes equations is used for atmospheric modeling. While a multiphase approach can give better insights into mechanisms of wave generation, white capping, dissipation and diffraction, it is computationally expensive and not suited for modeling ocean waves which are inherently random in nature under realistic meteorological conditions. It is for this reason that in a forecasting context, semi-stochastic approach is still the workhorse. Barbariol in 2013 [6] used coupled wave-ocean model for improving wave energy assessment. To better identify the significant processes affecting coastlines and how those processes create coastal changes COAWST Modeling System, which is comprised of the Model Coupling Toolkit to exchange data fields between the ocean model ROMS, the atmosphere model WRF, the wave model SWAN, and the sediment capabilities of the Community Sediment Transport Model was developed [7]. The coupled modeling system was used to investigate atmosphereoceanwave interactions in November 2009 during Hurricane Ida and its subsequent evolution to NorIda, [8]. There has also been efforts to couple wave models having different resolutions and focus like WAVEWATCH III (WWIII) for wave generation and deep water propagation and SWAN model for wave propagation in intermediate and shallow water [9]. Waves at the surface of the deep ocean can be well predicted with third-generation wave models that are driven by predicted wind fields [10] [3]. Although these recent models are coupled they were mostly unidirectional in nature (only atmosphere affecting the ocean state). In the current work we simulate the ocean atmospheric interactions through both unidirectional and bidirectional coupling of the atmospheric code HARMONIE [5] and the wave modeling code WAM ([3]). It is expected that in bidirectional coupling, atmospheric and wave models will mutually benefit each other through a frequent update of the inter-facial conditions (wind computed by atmospheric model and Charnock parameter computed by wave model) and provide a better prediction of significant wave height and local wind. The atmospheric code HARMONIE solves for the standard governing equations of mass, momentum, energy and humidity using appropriate physical models to simulate the effects of clouds, pollutants, rotation of earth etc. For the state of ocean surface, action balance equation is solved giving wave energy spectrum as a function of location, frequency and direction of the waves. Ocean surface characteristics (like surface roughness, Charnock number) are evaluated using the spectrum. Surface fluxes for momentum, energy and humidity is then computed and passed on to the HARMONIE model as boundary condition at the ocean surface. The HARMONIE model in turn computes wind magnitude and direction at 10 meter height above the average ocean surface and hence provide the source term corresponding to wind generated waves. In the current work uni- and bi-directional coupling effectiveness is evaluated by comparing the predicted results with data from sea-buoy and observation platforms located in offshore locations.

2. Computational Models

In this section we give a brief description of the computational models used. Readers are directed to relevant articles giving more details about the models wherever required.

2.1. Atmospheric Model

The atmospheric component in the coupled system is a mesoscale model named HARMONIE based on the equations governing mass, momentum, energy and species conservation. The model is a non-hydrostatic model, of which the dynamical core is based on a two-time level semi-implicit semi-Lagrangian discretisation of the fully elastic equations, using a hybrid coordinate system in the vertical direction [5]. The simulation domain is shown in Figure 1(b). A horizontal resolution of $2.5\text{km} \times 2.5\text{km}$ is used. This is the same resolution that is used for weather forecast on a

daily basis. The surface model Surface Externalisée (SURFEX) is used for calculations in the surface layer. Hourly boundary data comes from the global model IFS developed at the ECMWF.

2.2. Wave Model

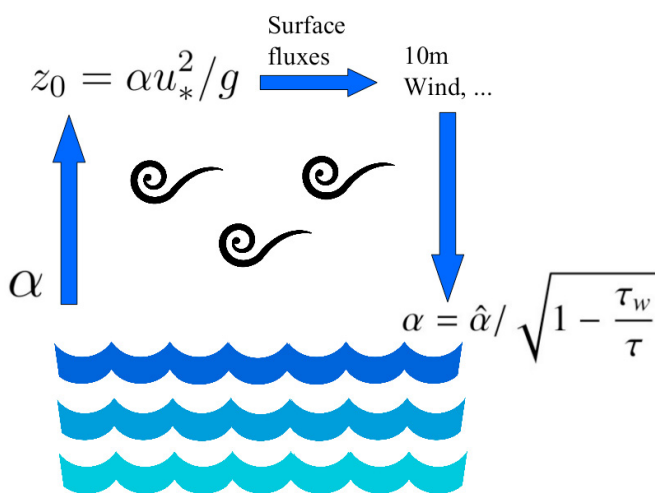
The wave model used is a version of WAM developed at ECMWF. WAM uses a two-dimensional wave spectrum to describe ocean state. The wave spectrum contains information regarding wave propagation direction and wave variance. An energy balance equation is constructed using the conservation of energy. The equation is explicitly solved to get an evolution of wave spectrum [3] in space and time. The rate of change of the energy is expressed as a sum of various source and sink terms [11]:

$$\frac{d}{dt}E(\omega, \theta, \mathbf{x}) + \frac{d}{d\mathbf{x}}(\mathbf{v}_g E) = S_{in} + S_{nl} + S_{ds} + S_{bot} \quad (1)$$

where S_{in} describes the physics of wind input, S_{nl} the wave-wave interactions, S_{ds} the whitecapping dissipation, S_{bot} the bottom friction. \mathbf{v}_g is the group velocity and $E(\omega, \theta, \mathbf{x})$ is the 2-dimensional wave spectrum which gives the energy distribution depending on the angular frequency, ω and the direction θ at any location \mathbf{x} . In WAM, the wave spectrum is divided into 36 discrete frequencies and directions.

2.3. Coupling

WAM is originally configured to run on a latitude / longitude grid while HARMONIE is running using UTM coordinate system. The WAM model was therefore modified to run on the same grid using the same coordinate system as HARMONIE. The wave model is called from a subroutine in HARMONIE every 60s time step. The 10m wind speed is provided to WAM from HARMONIE. In the case of bidirectional coupling, the Charnock parameter, α , calculated in WAM is returned and used for the calculation of the surface flux in SURFEX in the next time step. Figure 1(a) shows the exchange of information between WAM and HARMONIE. The following section describes this in more detail.



(a) Parameter exchange between WAM and HARMONIE



(b) Locations of measuring stations

Fig. 1. Information exchange and simulation domain

2.4. Computation of fluxes and input source term

The sea surface momentum flux, or stress, τ_{sea} using transfer coefficients is given by

$$|\vec{\tau}|_{sea} = -\rho_a C_D U_{10}^2 \quad (2)$$

where C_D is the exchange coefficient for momentum (relates the surface stress to the wind speed at certain height), U_{10} is the mean relative wind speed at 10m above the average sea surface and ρ_a the air density. When using Louis's parametrization, C_D is determined by the neutral exchange coefficient at 10m, C_{D10n} , and the so called Louis's function F_D [12]:

$$C_D = C_{D10n} F_D(R_i, z, z_0) \quad (3)$$

where

$$C_{D10n} = \frac{\kappa^2}{\ln(\frac{z}{z_0})^2} \quad (4)$$

where κ is the Von Karman's constant, z is the height and z_0 the surface roughness. The Louis's function F_D depends on z , z_0 and the Richardson number R_i (fraction of a layers potential and kinetic energy). The surface roughness length, z_0 , over open water is given by the Charnock's relation [12]

$$z_0 = \alpha u_*^2 / g \quad (5)$$

where α is the Charnock parameter, u_* is the friction velocity and g the acceleration of gravity. For a unidirectionally coupled system, the Charnock parameter is a constant equal to 0.015. For the 2-way coupled system, α is calculated in WAM and varies depending on the sea state according to [11]

$$\alpha = \hat{\alpha} / \sqrt{1 - \frac{\tau_w}{\tau}} \quad (6)$$

where $\hat{\alpha}$ is a constant, τ_w is the wave-induced stress and τ the total stress (see section 2.4.1). For a young wind sea, the wave-induced stress is close to the total stress and the the Charnock parameter becomes large. The constant $\hat{\alpha}$ is chosen so that α has the value 0.0185 for old wind sea. [11]

The influence of the Charnock parameter is similar for sensible and latent heat fluxes but are not included in the content of this paper. However, interested readers are referred to the paper [12].

2.4.1. Wind input wave evolution

The wave induced stress in equation 6 is in WAM given by an integral which, theoretically, cover all frequencies and directions

$$\tau_w = \rho_w \int_0^\infty \omega(\mathbf{k}/k) S_{in}(\mathbf{k}) d\mathbf{k} \quad (7)$$

where ρ_w is the water density and \mathbf{k} the wave number vector. The source term S_{in} describes the physics of the wind input to the energy balance equation (Equation 1) and is give by [11]

$$S_{in} = \gamma N \quad (8)$$

where γ is the growth rate and N is the action density spectrum (energy spectrum E divided by intrinsic frequency). For new waves, the growth rate will be large and a large proportion of the energy will be put into generating waves compared to old fully developed waves. The total stress in Equation 6 is given by

$$\tau = (\kappa U(z/\ln(z/z_0)))^2 \quad (9)$$

where $U(z)$ is the wind speed at height z and z_0 the surface roughness given by Equation 5. This means that the surface roughness is determined by the total stress, which in turn depends on the surface roughness. In WAM this is solved by at the start of the model run calculating a 2-dimensional table where τ depends on a range of discrete values for U_{10} and τ_w . This table is constructed from an iterative process using Newton's method. The approximation of τ comes from a linear interpolation of this table [13].

3. Numerical Experiments

3.1. Model experiments and verification

Both the uni- and bi-directionally coupled models were run for a period of one month between 01.01.2015-01.02-2015. The validation of 10m wind is done against 8 stations over ocean which are located on platforms (Ekofisk, Sleipner A, Heimdal, Troll A, Gullfaks C, Draugen, Heidrun and Norne). The measurement height at platforms differs from the typical (for wind) 10m height and an interpolation is therefore needed when comparing with the model 10m winds.

4. Results and Discussions

To quantify the added benefits of bidirectional coupling over a uni-directional coupling, we compare the predicted significant wave heights and 10m wind magnitude against data obtained from different sources. The measuring stations are shown in Figure 1(b). Throughout the result section we have used scatter plots and Quantile-Quantile (Q-Q) plot. The scatter plot is a plot with the observation data on the X-axis and the corresponding predicted data on the Y-axis. Each point on the graph corresponds to a particular instance of time. In the case of a perfect match between the observed and predicted time series all the points will lie on a line with slope equal to one. The Q-Q plot on the other hand is a graphical technique for determining if the two data-set exhibit similar distributional shape.

Table 1. Mean Absolute Error and Root Mean Square Error associated with wind and wave predictions using Uni- and Bi- directionally coupled models

	Wind (U) (m/s)	Wind (Bi) (m/s)	Wave (U) (m)	Wave (Bi) (m)
MAE	2.41	2.31	0.60	0.42
RMSE	5.31	5.07	1.18	0.80

Table 1 summarizes the mean absolute error (MAE) and root mean square errors (RMSE) for wind and wave predictions corresponding to uni- and bi-directional coupling. The table highlights the reduction in MAE and RMSE when opting the bidirectional coupling over the unidirectional coupling.

Figure 2 and 3 show snapshots of significant wave height and 10m wind speed computed by the uni- and bi-directionally coupled models. As expected, the regions dominated by high wind in Figure 2 are associated with ocean surfaces with high significant wave heights (Figure 3) and vice versa. A more detailed description while comparing to observation data is presented in the following section. From this point onwards we concentrate only on one of the stations: Draugen.

4.1. Validation of wave data

Figure 4(a) gives the predicted timeseries of the significant wave height compared against the observed ones. It is clear that the bi-directionally coupled model's prediction is better (look at the errors in the Table 1) than its counterpart. Generally, the unidirectionally coupled model tends to overestimate the magnitude of significant wave height. This is also evident from the scatter and Q-Q plot shown in Figure 5(a). For significant wave height less than 4m both the models seem to be working fine however, as wave heights increase beyond 4m the models show deterioration in predictions. The deterioration is more pronounced in the unidirectionally coupled model. The differences in predictions between the two approaches can be attributed to the bidirectional feedback which here, seems to act in a restraining fashion. The exact instances of noticeable maxima of significant wave height (see Figure 4(a)) coincide with the instances of noticeable peaks in the timeseries of the 10m wind speed shown in Figure 4(b). In a bidirectional coupling, wave model provides a dynamic surface roughness (which in turn is related to the wave heights) to the atmospheric codes. The surface roughness is used to compute the sink term of the momentum equation. An increased surface roughness implies smaller magnitudes of wind close to the ocean surface. The wind at 10m height is then

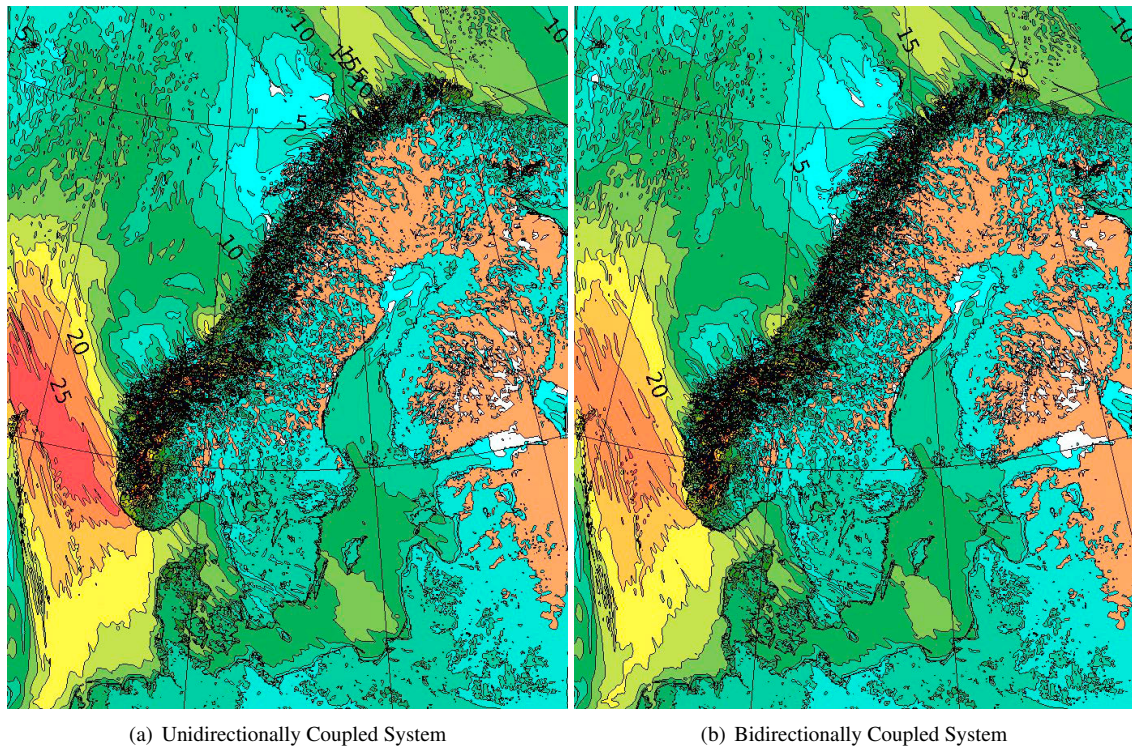


Fig. 2. Contour plots of wind at 10m above the average sea surface (m/s) (25-01-2015, 18UTC)

used to compute the source term of the action balance equation. In a unidirectional coupling only the atmospheric model feeds the wave model and there is no feedback from the wave model to the atmospheric code. Thus, when the wind speed increases it results in higher waves but this information is not fed back to the atmospheric code so the sea roughness and so the surface flux is underreported. Thus the wave height keeps on increasing. In a bidirectional coupling the higher wave height produces bigger sink term in the momentum equation and tends to bring down the magnitude of predicted wind.

Figure 6 gives a one dimensional energy spectra. It is clear that the observation, unidirectionally and bidirectionally coupled simulation results are in good agreement. Both uni and bidirectionally coupled models do a great job in predicting the dominant frequencies associated with the waves although the former overestimates the peaks in the spectrum. As expected during the night only one peak is observed but during the day multiple peaks are observed. The peak corresponding to lower frequency represents the swell while wind-generated young waves are represented by peaks corresponding to the higher frequencies

4.2. Validation of wind data

10m wind modeled using both the coupling approaches was also compared against the observation data. Better accuracy of the bidirectionally coupled approach is clear from Figure 5(b) and Table 1 just like the significant wave height, the added advantage of using a bidirectionally coupled approach is more evident at higher wind speeds. From Figure 4(b), for reasons explained earlier the unidirectionally coupled model overestimates the wind speed. The overestimation is more pronounced when the wind magnitudes are very high.

5. Conclusion and future work

In the current work atmospheric code HARMONIE was uni- and bi-directionally coupled to the stochastic wave model WAM. The coupled models were run over a period of 50 days and the resulting time series was compared

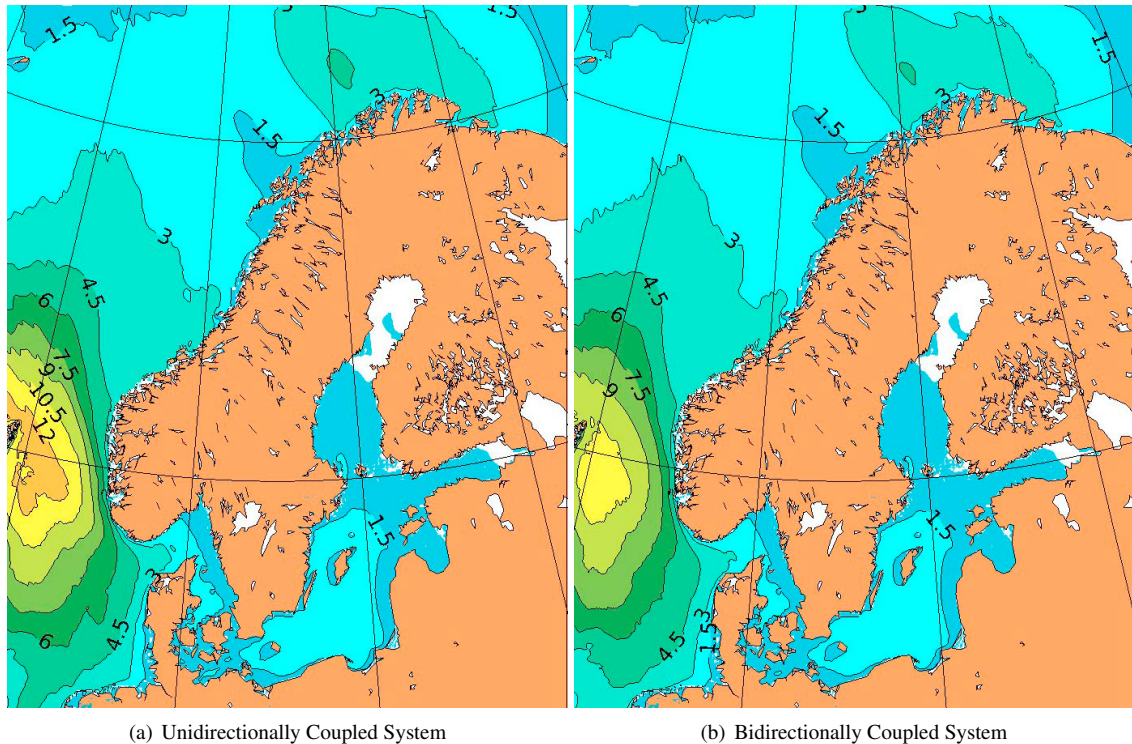


Fig. 3. Contours of Significant Wave Height (m) (25-01-2015, 18UTC)

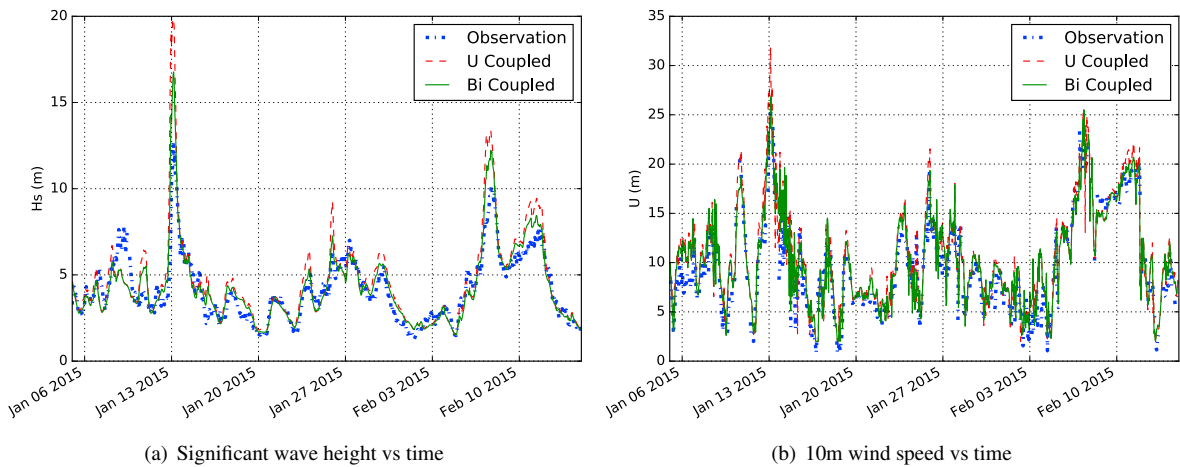


Fig. 4. Draugen offshore platform: Timeseries of significant wave height and wind speed.

against observational data from offshore platforms. Significant wave heights and 10m wind magnitude were used for a quantitative validation. Based on the validation results presented in figures and summarized in Table 1 it can be concluded that compared to the available offshore observations of wind and wave height, bidirectional coupling is more accurate than the unidirectionally coupled approach specially when the wind and significant heights have bigger values. Unidirectionally coupled model tends to overestimate both wind as well as wave height. A continuation of this work will be to validate the vertical profiles of wind and temperature profiles using radiosonde data. These profiles can then be used for MBL characterization. The characterized profiles of wind, temperature and turbulence can then be used to simulate flow in an offshore wind farm.

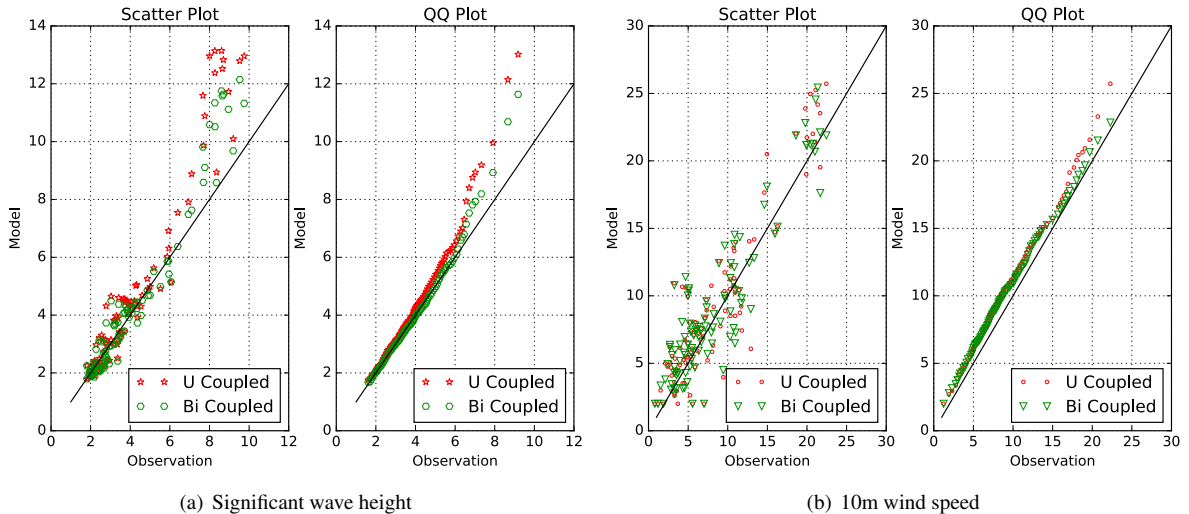


Fig. 5. Draugen offshore platform: Scatter and Q-Q plot for significant wave height and wind speed (model vs observation)

The wind and waves are overestimated with the standard (unidirectional) setup and the overestimation is reduced with the 2-way coupling. The offshore platforms generate speedup of the wind which may impact the wind measurements. The MIROS wave radars used at most of the platforms (including Draugen) are underestimating the high waves. This means that the 2-way coupled model may be overestimating even less than shown in figure 5, but it can also mean that the 2-way coupled model is actually underestimating for some wind and wave levels.

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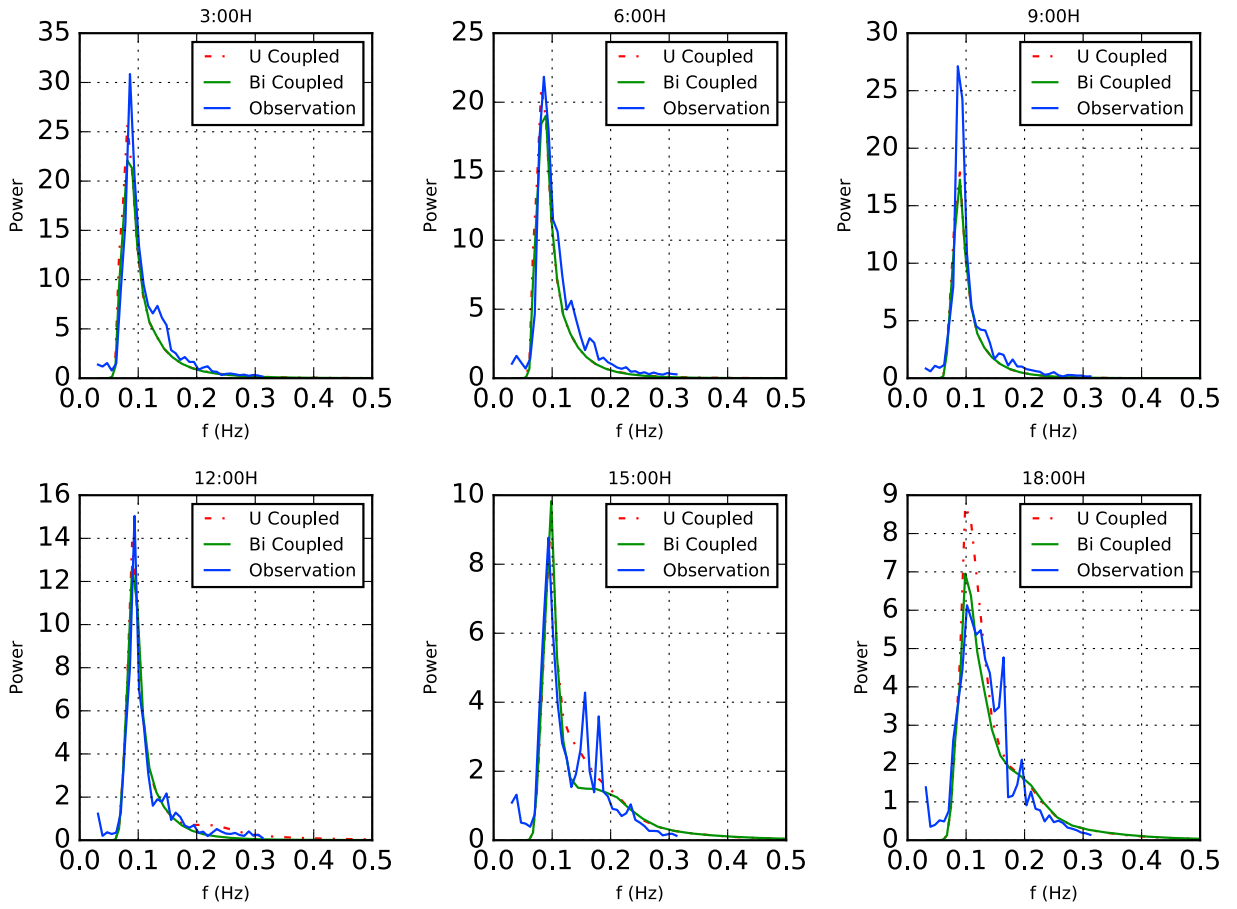


Fig. 6. Draugen platform: 1-D power spectrum of waves (25-01-2015)