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Mesoscale numerical modelling of met-ocean interactions

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Abstract

Offshore wind energy compared to its onshore counterpart appears more attractive due to its lesser visual impact and lesser issues related to land acquisition. Relatively more convenient accessibility to open sea allows for the installation of larger and larger turbines capable of producing much more power resulting in far lesser number of turbines per wind farm to produce the same amount of power. However, the large size of the turbines ($\approx 200m$) implies that they have to operate in conditions affected by phenomena characteristic of marine boundary layer. Complete inversion of wind profiles close to coasts, strong high waves and their interaction with the structures supporting the turbines can have a profound influence on the performance of wind turbines and their life time. A lot of development is taking place in the area of numerical and experimental modeling of wind turbines and its support structures but those studies are generally conducted for idealized cases. In reality the conditions can be markedly different. In order to understanding the behavior of turbines in operational condition, a good understanding of the marine boundary layer and ocean waves is an obvious prerequisite. In the current paper we explain the coupling of an atmospheric code HARMONIE using AROME physics with the ocean wave model WAM. Some preliminary results related to the effects of coupling on wind speed and significant wave height are presented for a few sites close to the Norwegian coast.

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1. Introduction

Over ocean surface, the fluxes between the atmosphere and the 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 fluxes. The ocean-atmosphere interaction can either be modeled deterministically using a multiphase modeling approach or can be modeled stochastically using an action balance equation. While the former approach can give a better insight into the mechanisms of interactions, it is computationally too expensive and not suited for modeling ocean waves which are inherently random in nature. It is for this reason that in a forecasting context, stochastic approach is still the workhorse. In the current work we simulate the ocean atmospheric interaction through unidirectional and

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bidirectional coupling of the atmospheric code HARMONIE (Hirham Aladin Regional Mesoscale Operational NWP In Europe) and a stochastic wave modeling code WAM (Wave Modeling). It is expected that in the bidirectional coupling, the atmospheric and wave models will mutually benefit each other through a frequent update (every 60s time step) of the inter-facial conditions (wind computed by the atmospheric model and Charnock parameter computed by the wave model) and provide information regarding the Marine Boundary Layer that can be utilized for wake simulations as presented in [1]. In the following sections we present a brief description of the coupling approach followed by some results regarding the effect of the coupling on wind speed and significant wave height.

2. Coupling Methodology

The atmospheric model used in the coupled system is a version of the non-hydrostatic HARMONIE model ([2]) using AROME physics at a resolution of $2.5km \times 2.5km$. The configuration is similar to the operational model AROME-MetCoOp developed in a collaboration between The Norwegian Meteorological Institute (MET) and Swedish Hydrological and Meteorological Institute (SMHI). The surface model SURFEX (Surface Externalisée) is used for calculations in the surface layer. 1-hourly boundary data comes from the global model IFS (Integrated Forecast System) developed at ECMWF (The European Centre for Medium-Range Weather Forecasts).

The ocean wave model used is a version of WAM developed at ECMWF. WAM uses a two-dimensional wave spectrum to describe the ocean state. The wave spectrum contains information regarding the 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 the 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 ([4]):

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

where S_{in} describes the physics of the 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.

WAM is originally configured to run on a lat/lon grid while AROME is running using cartesian coordinates. The WAM model has been modified in order to run on the same grid using the same coordinate system as AROME. The tested domain together with significant wave height and 10m winds is shown in figure 2. The boundary spectrum for WAM is received on a lat/lon grid and needs to be rotated corresponding to the rotation of each boundary grid point with respect to the true north.

The wave model is called from a subroutine in AROME every 60s time step. The 10m wind speed and sea ice mask is provided to WAM from AROME. In the case of 2-way (bi-directional) coupling, the Charnock parameter, α , calculated in WAM is returned and used for calculations of the surface fluxes in SURFEX the next time step. Figure 1 shows the exchange of information between WAM and AROME. Section 3 describes this in more detail.

2.1. Model experiments and verification

One 1-way and one 2-way coupled model run for the period 2013.12.18 to 2014.02.20 was conducted. Four forecast cycles are performed each day at 00, 06, 12 and 18 UTC. Observations are assimilated each cycle for AROME. The forecast length is 48 hours for 00 UTC and 6 hours for 06, 12 and 18 UTC. All 48 hours from 00 UTC is used for verification against wind measurements in figure 4 and 5 while the time series in figure 3 is constructed using the first 24 hours of the forecast.

The verification for 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. Measurements from the platform Gullfaks C is chosen for wave verification.

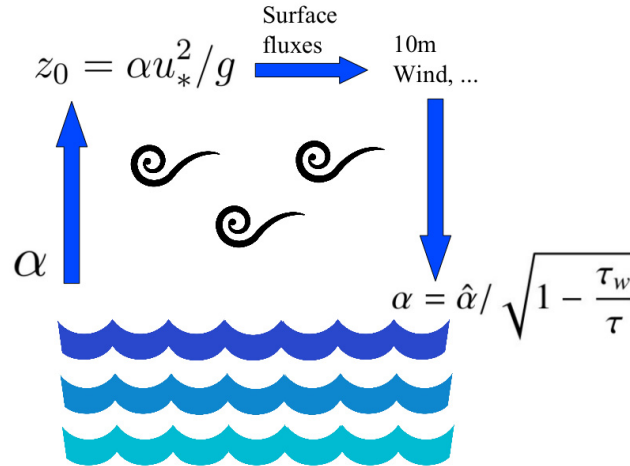


Fig. 1: The exchange of parameters between WAM and AROME for a 2-way coupled system. The Charnock parameter, α , calculated in WAM from equation 6 is used for calculations of the surface fluxes in AROME. The resulting 10m wind speeds from AROME is used as input to WAM.

3. Computation of fluxes and input source term

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

$$\overline{\tau}_{sea} = -\rho_a C_D U^2 \quad (2)$$

where C_D is the exchange coefficient for momentum (relates the surface stress to the wind speed at certain height), U is the mean relative wind speed and ρ_a the air density. When using Louis's parametrisation, C_D is determined by the neutral exchange coefficient at 10m, C_{D10n} , and the so called Louis's function F_D [5]:

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

where

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

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 [5]

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

where α is the Charnock parameter, u_* is the friction velocity and g the acceleration of gravity. For an uncoupled system (or 1-way coupled), 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 [4]

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

where $\hat{\alpha}$ is a constant, τ_w is the wave-induced stress and τ the total stress (see section 3.1). For a young wind sea, the wave-induced stress is close to the total stress and the Charnock parameter becomes large. The constant $\hat{\alpha}$ is chosen so that α has the value 0.0185 for old wind sea. [4]

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 [5].

3.1. 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

$$\tau_w = \epsilon^{-1} g \int d\omega d\theta \frac{\mathbf{k}}{\omega} S_{in}(\omega, \theta) \quad (7)$$

where ϵ is the air–water density ratio, g the acceleration of gravity, S_{in} the source term for wind input, \mathbf{k} the wave number vector and ω the angular frequency. The source term S_{in} describes the physics of the wind input to the energy balance equation (equation 1) and is give by [4]

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

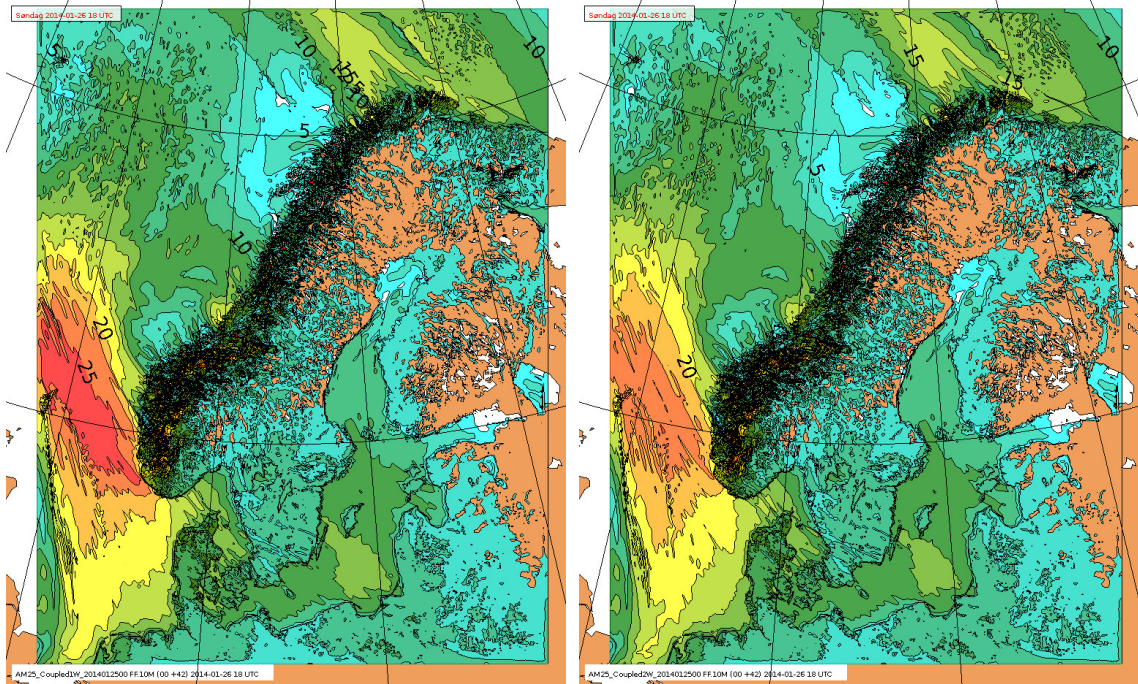
where γ is the growth rate and N is the action density spectrum (energy spectrum divided by intrinsic frequency). For new waves, the growth rate will be large and a large proportion of the energy will be put into generating waves compared to old fully developed waves. The total stress in equation 6 is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

$$\tau = (\kappa U(z_{obs}) / \ln(z_{obs}/z_0))^2 \quad (9)$$

where $U(z_{obs})$ is the wind speed at height z_{obs} 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 a iterative process using Newtons method. The approximation of τ comes from a linear interpolation of this table. [6].

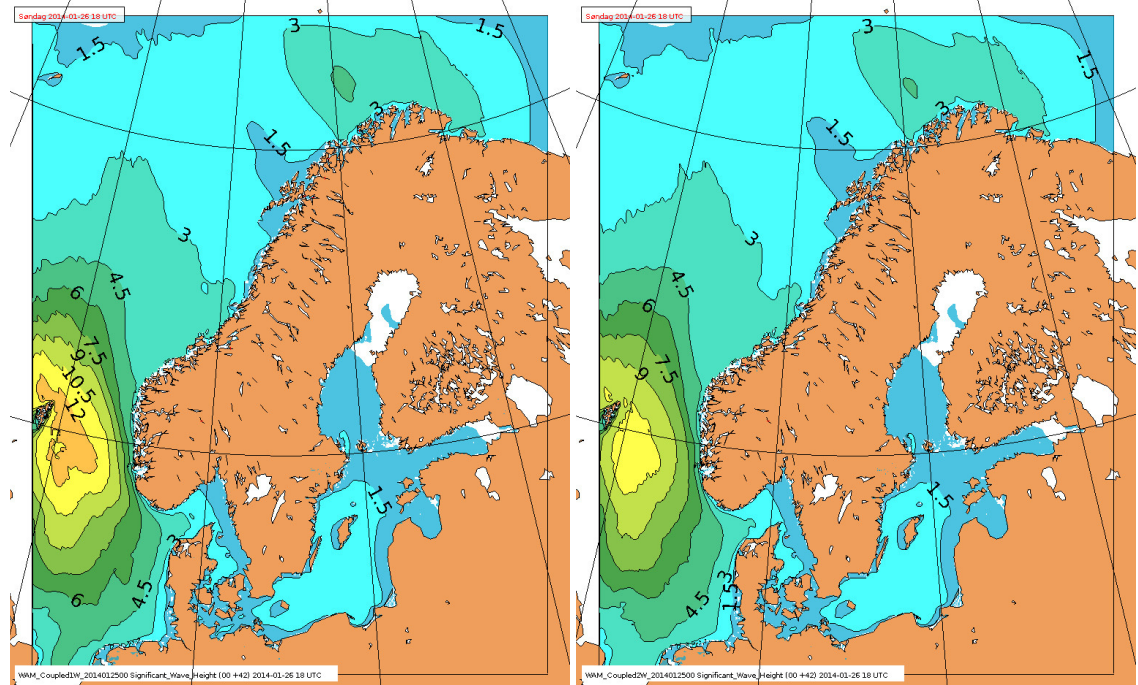
4. Results

In this section we present a comparison of the results generated from the 1-way (unidirectionally) coupled, 2-way (bidirectionally) coupled, standalone 4km resolution and standalone 10km resolution models. In particular we concentrate on the comparison of 10m wind speed and significant wave height. Figure 2 shows snapshots of significant wave height and 10m wind speed of the 1-way and 2-way coupled models. A reduced wave height can be seen in areas with high waves as well as a reduction of wind speed in areas with high wind speeds. The differences are small between the models over areas with low wind speeds and low wave heights.



(a) 1-way coupled 10m wind

(b) 2-way coupled 10m wind



(c) 1-way coupled significant wave height

(d) 2-way couple significant wave height

Fig. 2: Example of the coupling impact on 10m wind and significant wave height.

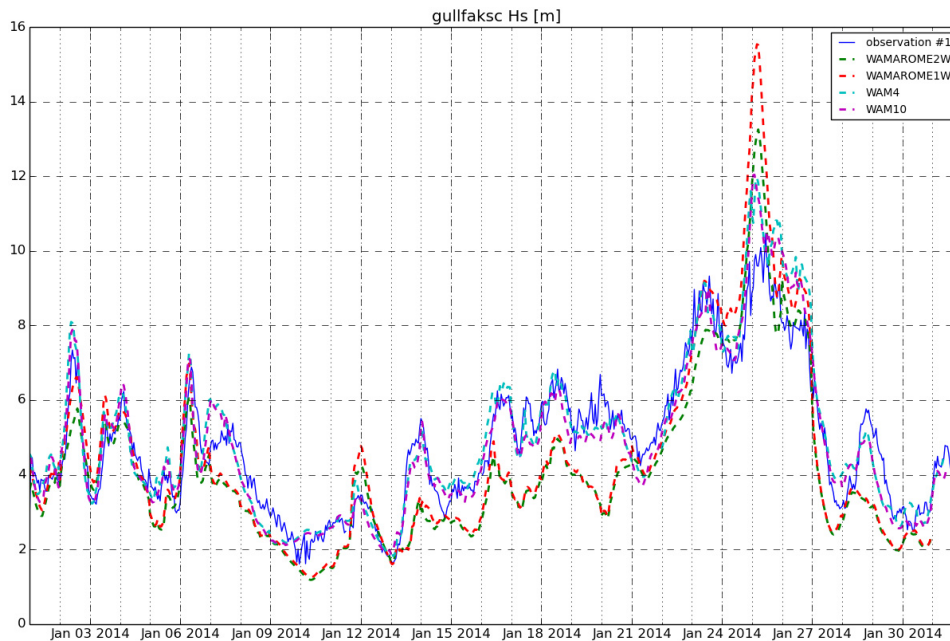


Fig. 3: Time series of significant wave height for the station Gullfaks C.

4.1. Significant wave height

Figure 3 shows a time series of significant wave height at the platform Gullfaks C. The stand alone 4km (WAM4) and 10km (WAM10) models shows good agreement with the observations while the 2-way coupled (WAMAROME2W) and the 1-way coupled (WAMAROME1W) shows errors of around 2m during large parts of the time period. There is a reduction of the wave height at the peak around Jan 25 of approximately 2.5m for the 2-way coupled system compared to the 1-way coupled. All the models overestimates the wave height during this event.

4.2. 10m wind speed

Figure 4 shows mean error (ME), standard deviation error (SDE), root mean square error (RMSE) and mean absolute error (MAE) depending on lead time averaged over 8 ocean stations in the period 2013.12.18 to 2014.02.20. The models are AROME 1-way and 2-way coupled as well as the operational weather prediction model at MET (AROME-MetCoOp without post processing). All the models shows a positive bias. The ME, RMSE and MAE is reduced by around 0.2m/s for 2-way coupled AROME compared to 1-way coupled. Figure 5 shows a quantile-quantile plot for the same stations and period as figure 4. The 1-way coupled model shows an overestimation of the wind speed over the whole range. The 2-way coupled system reduces wind speeds above approximately 15m/s.

5. Discussion

One of the reasons for doing the coupling was to investigate if the performance of the wave model could be improved in situations with high waves where the stand alone models tends to overestimate the wave height. The results of the coupling when looking at the wave verification shows a reduction of wave height in those situations when introducing 2-way coupling compared to 1-way coupling. The large errors of the significant wave height in figure 3 shows that the coupled wave model is not behaving as expected. The problem is related to the wave propagation in north-south direction and needs to be sorted out before drawing any clear conclusions.

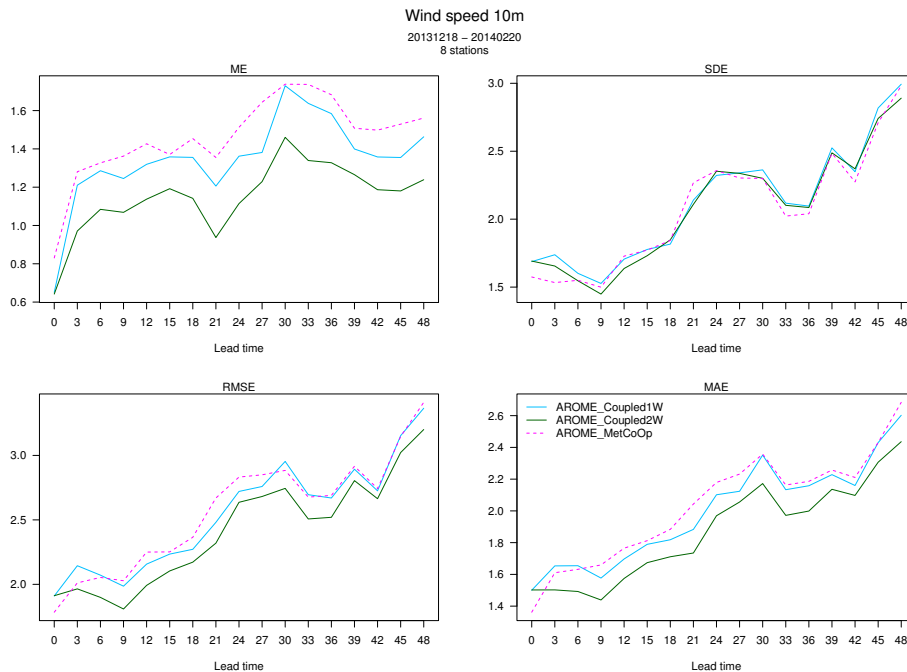


Fig. 4: 10m wind speed statistics ocean

There is an overestimation of the wind speeds over ocean according to the verification against 10m wind speed from observations at platforms. Figure 4 shows that in average the reduced wind speed for the 2-way coupled system leads to improved ME, RMSE and MAE. The quantile-quantile plot in figure 5 shows that the reduction of the 10m winds leads to an underestimation of high wind speeds. A method to reduce this problem could be to include the effect that wind speeds over approximately 25m/s tends to break down the waves, making the surface more smooth. It should be noted that the interpolation related to observations at platforms, which was introduced in section 2.1, does not take into consideration the atmospheric stability. This means that the observations are not reliable for all weather situations. Future work should therefore include verification against scatterometer measurements.

The reduction of the wind speed, and from that the significant wave height, for the 2-way coupled system comes from the sea-state dependent Charnock parameter described by equation 6. The constant Charnock parameter used in 1-way coupling is estimated from a case with old waves. The introduction of the dependency on wave induced stress will give a higher value for newly generated waves. These occurs, for example, in the case of a passing pressure system with large wind speeds. The growth rate parameter in equation 8 gives a high wave induced stress and an increased surface roughness (equation 5). The momentum flux in equation 2 will increase, resulting in lower wind speeds which in turn will lead to lower significant wave heights.

The results at this point is preliminary since there are problems with the coupled wave model. Still, the results shows steps in the right direction when considering reduced wave height and reduced wind speed in situations with high waves and wind speeds.

6. Future Work

Interesting future work includes solving the wave propagations problem, case studies of polar lows and analysis of the surface fluxes. It should also be investigated if the resulting wind profile over ocean for a coupled system could give improvements for power prediction at offshore wind farms compared to an uncoupled system. Extensive work is in progress in the FSI-WT (www.fsi-wt.no) ([7]) project to understand the different aspects of wind engineering ranging from simulation of flow around turbine blades ([8] and [9], simulation around a vertical axis turbine ([10])

Q–Q plot 10m wind speed 20131218–20140220

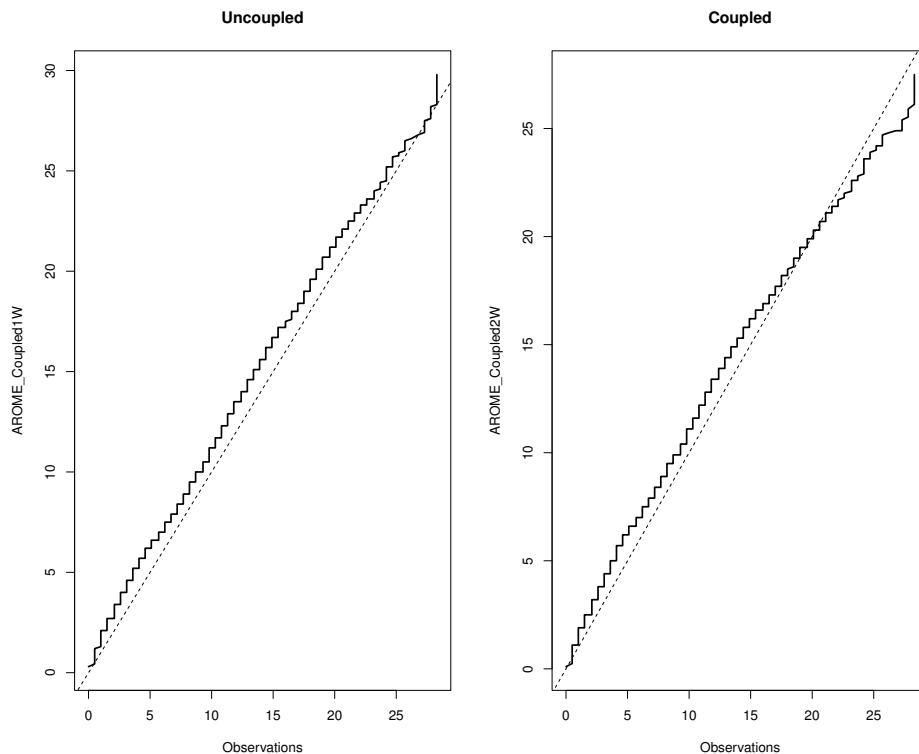


Fig. 5: Quantile quantile plot ocean

with different turbulence intensity to simulation of a full wind farm located in a highly complex terrain ([1]). The focus is now on the offshore wind farms and in that regard the current work gains significance. The plan in near future is to use the coupled model presented in this paper to provide boundary conditions to the wind farm model and study its impact on the loading of wind turbine structures and wakes.

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References

- [1] Tabib, M., Rasheed, A., Kvamsdal, T.. Les and rans simulation of onshore bessaker wind farm: analyzing terrain and wake effects on wind farm performance. *Journal of Physics Conference Series* 2015;625(012032).
- [2] Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F., et al. The arome-france convective-scale operational model. *Monthly Weather Review* 2011;139:976 – 991.
- [3] Ocean wave modelling, accessed on 12th september 2015;URL: <http://www.ecmwf.int/en/research/modelling-and-prediction/marine>.
- [4] IFS DOCUMENTATION – cy40r1, operational implementation, PART VII: ECMWF WAVE MODEL. European Centre for Medium-Range Weather Forecast, Shinfield Park, Reading, RG2 9AX, England 2013;.
- [5] Moigne, P.L.. Surfex scientific documentation 2012;Version 2.

- [6] Doortmont, D., Makin, V.. On the air-sea coupling in the wam wave model. Scientific report (ISSN 0169-1651 ; WR 2000-02) 2000;.
- [7] Rasheed, A., Holdahl, R., Kvamsdal, T., Åkervik, E.. A comprehensive simulation methodology for fluid-structure interaction of offshore wind turbines. Energy Procedia 2014;53(0):135 – 145. URL: <http://www.sciencedirect.com/science/article/pii/S1876610214010996>. doi:<http://dx.doi.org/10.1016/j.egypro.2014.07.222>; {EERA} DeepWind' 2014, 11th Deep Sea Offshore Wind R&D Conference.
- [8] Fonn, E., Rasheed, A., Kvarving, A.M., Kvamsdal, T., Tabib, M., van Opstal, T.. Spline based mesh generator for high fidelity simulation of flow around turbine blades. To be published in Energy Procedia 2015;.
- [9] van Opstal, T., Fonn, E., Holdahl, R., Kvamsdal, T., Kvarving, A.M., Mathisen, K.M., et al. Isogeometric methods for CFD and FSI-simulation of flow around turbine blades. To be published in Energy Procedia 2015;.
- [10] Siddiqui, M.S., Rasheed, A., Kvamsdal, T., Tabib, M.. Effect of turbulent intensity on the performance of an offshore vertical axis wind turbine. To be published in Energy Procedia 2015;.