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Published in:
Proceedings of EWEA Offshore 2015 Conference

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Du, J., Larsén, X. G., & Bolanos, R. (2015). A Coupled Atmospheric and Wave Modeling System for Storm Simulations. In *Proceedings of EWEA Offshore 2015 Conference* European Wind Energy Association (EWEA).

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A Coupled Atmospheric and Wave Modeling System for Storm Simulations

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Abstract. This study aims at improving the simulation of wind and waves during storms in connection with wind turbine design and operations in coastal areas. For this particular purpose, we investigated the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System which couples the Weather Research and Forecasting (WRF) Model with the third-generation ocean wave model–SWAN. This study investigates mainly two issues: spatial resolution and the wind-wave interface parameter – roughness length(z_0). To study the impact of resolution, the nesting function for both WRF and SWAN is used, with spatial resolution ranging from $25km$ to $2km$. Meanwhile, the atmospheric forcing data of different spatial resolution, with one about $100km$ (FNL) and the other about $38km$ (CFSR) are both used. In addition, bathymetry data of different resolutions ($1arc-minute$ and $30arc-seconds$) are used. We used three approaches to parametrize z_0 . The results are validated through QuikScat data and point measurements from an open ocean site Ekofisk and a coastal, relatively shallow water site Horns Rev. It is found that the modeling system captures in general better strong wind and strong wave characteristics for open ocean condition than for the coastal condition. With the current model setup, using high spatial resolution gives better results for strong winds both for the open ocean and coastal sites. The significant wave height (H_{m0}) is very sensitive to the model resolution and bathymetry data for the coastal zone. In addition, using Janssen (1991) z_0 expression gives better results of the significant wave height under high sea state conditions.

Keywords: Atmosphere and wave coupling, Storm, Coastal zone, High resolution

1 Introduction

Wind and wave forecast at coastal zones during storms are important for the offshore wind turbine design and wind power operations. Zamboni et al. (2014) pointed out that the inaccuracy of uncoupled wave models are due to the coarse-grid spacing of the wind fields and the treatment of surface roughness as a function of local wind vector. The objective of the present study is to understand the sensitivity of the spatical resolution and to evaluate the role of wind-wave interation in coastal areas. The outline of this paper is as follows: The coupling system, the methodology of momentum flux calculation, and the experimental design are described in section 2; the results are discussed in section 3; and a conclusion is presented in section 4.

2 Model and Experiments Description

The Coupled Ocean-Atmosphere-Wave-Sediment-Transport (COAWST) Modeling System (Warner et al., 2010) was used in this study. The modeling system consists of four model components: the Regional Ocean Modeling System (ROMS) (Shchepetkin & McWilliams, 2005), the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005), the Simulating Waves Nearshore (SWAN), and the Community Sediment Transport Model (CSTM) (Warner et al. 2008). Data exchange between models are handled by the Model Coupling Toolkit (MCT) (Larson et al., 2005) and the remapping

weights between different grid structures are calculated by SCRIP—A Spherical Coordinate Remapping and Interpolation Package. The detailed descriptions of the coupling methodology is presented in Warner et al. (2008, 2010). In this study, we focus on the influence of the ocean surface waves on the atmospheric modeling. So the ROMS model was turned off.

2.1 Roughness length expressions

Fields exchanged in the two-way coupled system are shown in Fig.1. WRF transfers wind speeds at 10m above the sea surface (u_{10} , v_{10}) to SWAN, and SWAN passes back significant wave height (H_{m0}), wave length (L_p) and wave period (T_p) at the peak frequency of the wave spectrum. In COAWST version 3.1, there are three methods for the parameterization of z_0 (Olabarrieta et al., 2012), including Taylor & Yelland(2001), Oost et al.(2002), and Drennan et al.(2005). In the present study, two more methods are implemented (Bolaños et al., 2014). One is from Fan et al. (2012) in which the Charnock parameter is fitted by wave age, where the fitting constants are functions of 10m wind speed. The other is from Janssen (1991) in which the z_0 is directly transferred from the wave model.

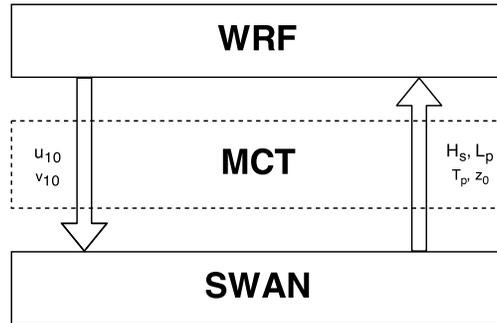


Fig. 1. Diagram of fields exchanged in the WRF-SWAN two way online coupling system

2.2 Experimental design

The model domains as well as the measurements locations are shown in Fig.2. Both of WRF and SWAN are two-domain nested. The resolution of WRF outer and inner domains are 25km and 5km respectively, with 41 vertical levels. The initial and boundary conditions are from NCEP FNL (Final) Operational Global Analysis data on 1-degree grids. The planetary boundary layer was modeled with the Mellor-Yamada Nakanishi Niino (MYNN) (Nakanishi & Niino, 2009) closure scheme. The horizontal resolution of SWAN outer and inner domain is $\sim 12km$ and $\sim 6km$ respectively. The bathymetry data is from ETOPO 1arc - minute Global relief model (Amante et al. 2009). SWAN initials from zero spectra and its open boundaries are set to Jonswap spectrum with $H_{m0} = 2m$, $T_p = 8s$. Directional space was utilized with 36 directional bins. And the frequency resolution is equal to $\Delta f = 0.1435f$ between 0.04Hz and 1Hz. The wind input and the white-capping dissipation source function are based on Janssen (1991,1992). Data exchange frequency between WRF and SWAN is once every 5 minutes. Three storms were studied representing different wind directions and onshore/offshore conditions. Fig.4 gives a glance of the respective structure of the storms. The first one is from 22nd Dec.2002 to 25th Dec.2002, which is an offshore case at Horns Rev. The wind direction is mainly from southeast

(SE02). The second one is from 14th Dec.2003 to 16th Dec.2003, which is an onshore case at Horns Rev. The wind direction is mainly from northwest (NW03). The third one is from 19th Mar.2004 to 23rd Mar.2004, which is another onshore case at Horns Rev. The wind direction is mainly from southwest (SW04). Table 1, EXP1-EXP6 is a summary of the model settings for the experiments.

To examine the impact of spatial resolution, in addition to the model setup of the spatial resolution ranging from 25km to 2km (Table 1, EXP7-EXP9), we also used a relatively high resolution large scale forcing for WRF. High resolution bathymetry data are also used. Accordingly, a refined three-domain nested experiment was designed for storm NW03(Fig.3). The horizontal resolution of WRF are from 18km to 6km to 2km, and the horizontal resolution for SWAN are from ~ 12km to ~ 4km to ~ 1.3km. Initial and boundary conditions for WRF are from NCEP Climate Forecast System Reanalysis (CFSR) data on about 38km grids. Bathymetry for SWAN is from GEBCO (Ioc, I. ,2008) 30arc-second global gridded data.

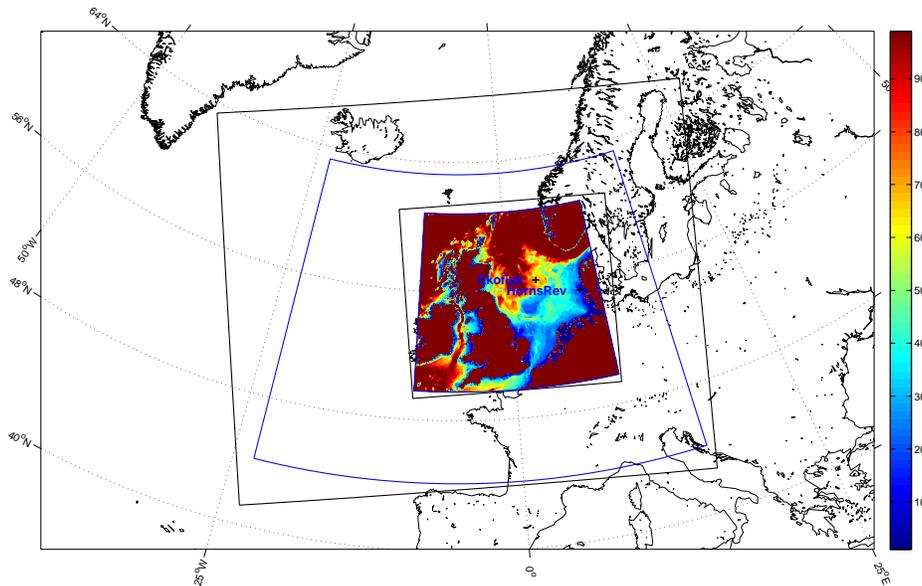


Fig. 2. Model domains for the experiments (EXP1-EXP6) as well as the locations of the measurements at Ekofisk and Horns Rev. The black boxes are WRF domains, and the blue boxes are SWAN domains. The colored area is the depth at SWAN innermost domain.

3 Results

3.1 Spatial distribution

Fig. 4 shows a snapshot of 10m wind speeds and directions in comparison with NASA’s Quick Scatterometer (QuikScat) data at time 18 : 40, UTC, 29th Dec., 2002, 19 : 00, UTC, 14th Dec., 2003, and 19 : 20, UTC, 19th Mar., 2004. The QuikScat data are of 25km resolution, which is too coarse to capture the cell structure as present in storm NW03 (Middle column in Fig.4), as shown by the cloud type

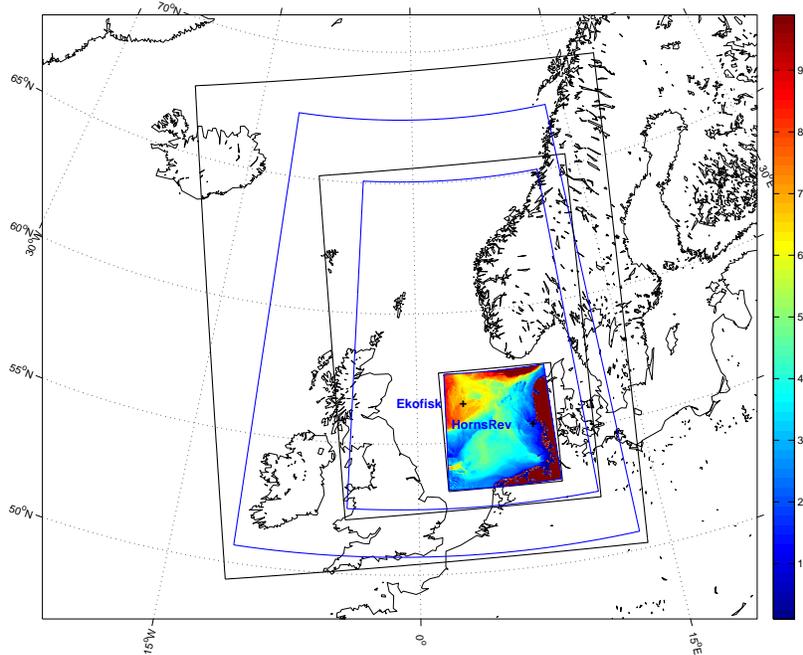


Fig. 3. Model domains for the experiments (EXP7-EXP9) as well as the locations of the measurements at Ekofisk and Horns Rev. The black boxes are WRF domains, and the blue boxes are SWAN domains. The colored area is the depth at SWAN innermost domain.

of horizontal wind pattern at this time. It could be seen that the model in general captures the storm structure well. Wind structures close to the domain boundaries are not always in good agreement where the uncertainty in the modeled data is high. The response of the spatial wind distribution to the different z_0 methods is not immediately obvious.

3.2 Time Series

The wind speed at measurement height and the significant wave heights are presented for one open ocean site Ekofisk (Fig.5) and one coastal relatively shallow water site Horns Rev(Fig.6). The water depth at the two sites are 66m and 10m respectively. The high resolution runs improve the model results in both wind speed (10m at Ekofisk and 15m at Horns Rev) and significant wave height, especially for the coastal site at Horns Rev (Fig.6(d)). The influence of different z_0 expressions are not obvious at the coastal site where the sea state are not very high (Significant wave height under 3m). But when it comes to the open ocean site, where the sea state are higher (Significant wave height higher than 4m), the influence of z_0 expressions become more significant. The Janssen (1991) expression tended to intensify the significant wave height and wind speed during the peak of storm SE02 and NW03 at Ekofisk(Fig.5(a-d)). Since the modeled H_{m0} are lower than measurements in these two cases, using the coupled Janssen (1991) z_0 expression give more accurate H_{m0} than the others. During storm SE02, the modeled 10m wind speed are on average higher than measurements at Ekofisk(Fig.5(a)). On the contrary, the modeled H_{m0} are on average lower than measurements(Fig.5(b)). Such phenomenon is also found in NW03 (Fig.5(c,d)). It becomes much better after the resolution increased to 2km. As shown in Fig.5(e, f) and Fig.6(e, f), storm SW04 has two peaks. The 10m wind speed changes fast

Table 1. Design of the experiments relating to the spatial resolution and z_0 expressions

Name	WRF resolution	SWAN resolution	z_0	Coupling	WRF input	Stroms
EXP1	25km	~ 12km	Fairall et al. (2003)	Off	FNL	SE02,NW03,SW04
EXP2	5km	~ 6km	Fairall et al. (2003)	Off	FNL	SE02,NW03,SW04
EXP3	25km	~ 12km	Fan et al. (2012)	On	FNL	SE02,NW03,SW04
EXP4	5km	~ 6km	Fan et al. (2012)	On	FNL	SE02,NW03,SW04
EXP5	25km	~ 12km	Janssen (1991)	On	FNL	SE02,NW03,SW04
EXP6	5km	~ 6km	Janssen (1991)	On	FNL	SE02,NW03,SW04
EXP7	2km	~ 1.3km	Fairall et al. (2003)	Off	CFSR	NW03
EXP8	2km	~ 1.3km	Fan et al. (2012)	On	CFSR	NW03
EXP9	2km	~ 1.3km	Janssen (1991)	On	CFSR	NW03

between the two peaks. The coupling system doesn't perform well during those fast changing winds. Such phenomenon is also found in storm SE02 around 00 : 00, *UTC*, 23rd Dec. 2002 (Fig.5(a)) and storm NW03 around 12 : 00, *UTC*, 14th Dec. 2003 (Fig.5(c) and Fig.6(c)).

4 Conclusions and discussion

Validation of modeled wind and wave fields using the nested COAWST system with point measurements as well as QuikScat data suggest the following: 1) The modelling system as implemented here performs better for storms of certain structure than the other (it performs better for storms from the west than for storms from the north). 2) The storm wind field favors from the nested, high resolution modeling as well as input of high resolution data. 3) The system is more challenged by fast changing wind conditions. 4) Using Janssen (1991) z_0 expression gives better results of the significant wave height. Further investigation will focus on the following issues: 1) use higher resolution tests for the coastal zone. 2) include more severe storms. 3) examine heat exchange 6) include ocean model.

5 Acknowledgment

This study is funded mainly by the Danish Forskel project X-WiWa (PSO-12020). The second and third authors acknowledge the EU INNWIND project for the support. QuickScat data for the three storms are provided by Ioanna Karagali.

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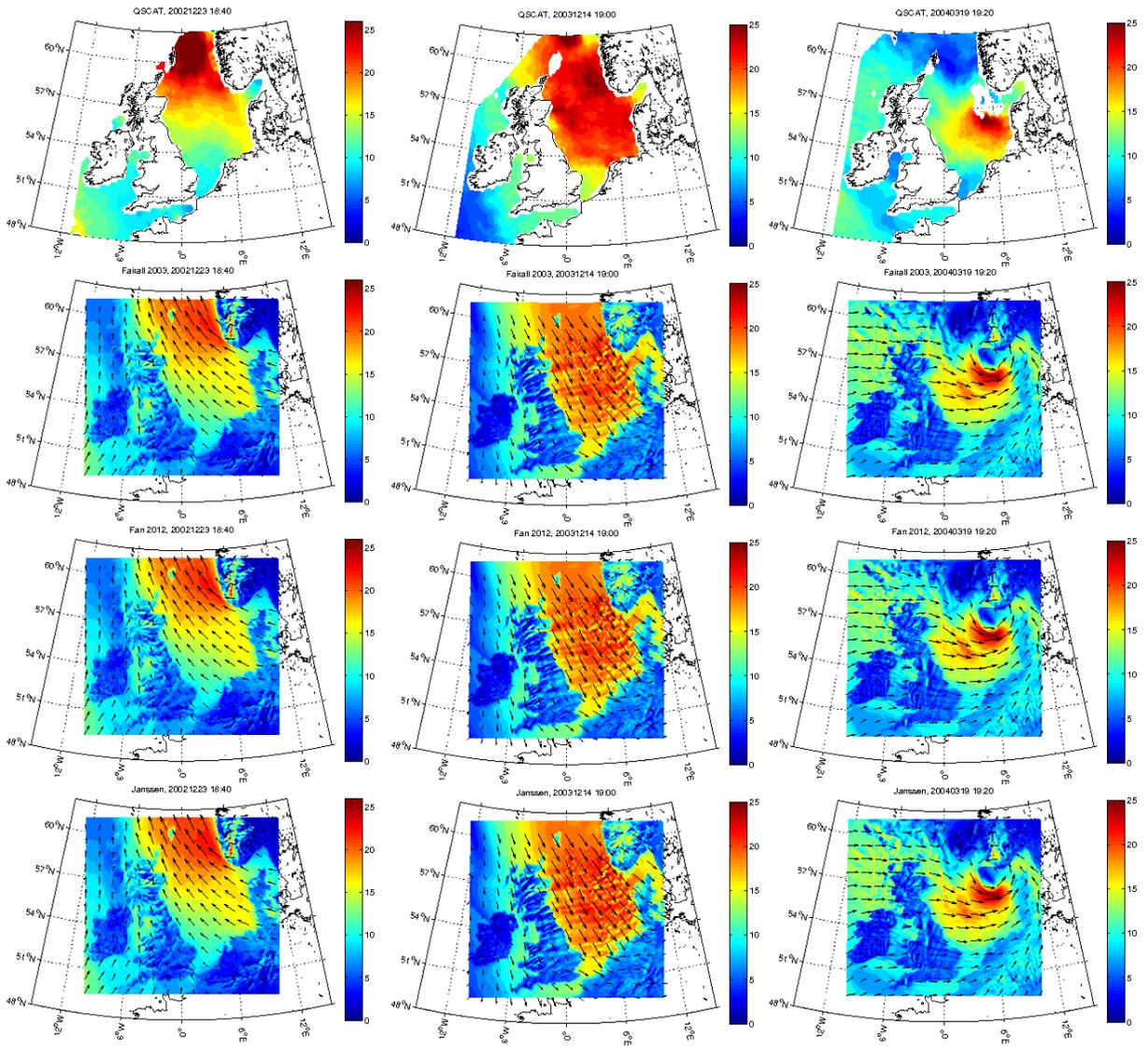


Fig. 4. Snapshot of wind intensities and directions in comparison with QuikScat data. The rows from top to bottom are from QuikScat data, modeled data by EXP2, EXP4, and EXP6. The columns from left to right are from SW02, NW03, SW04 respectively.

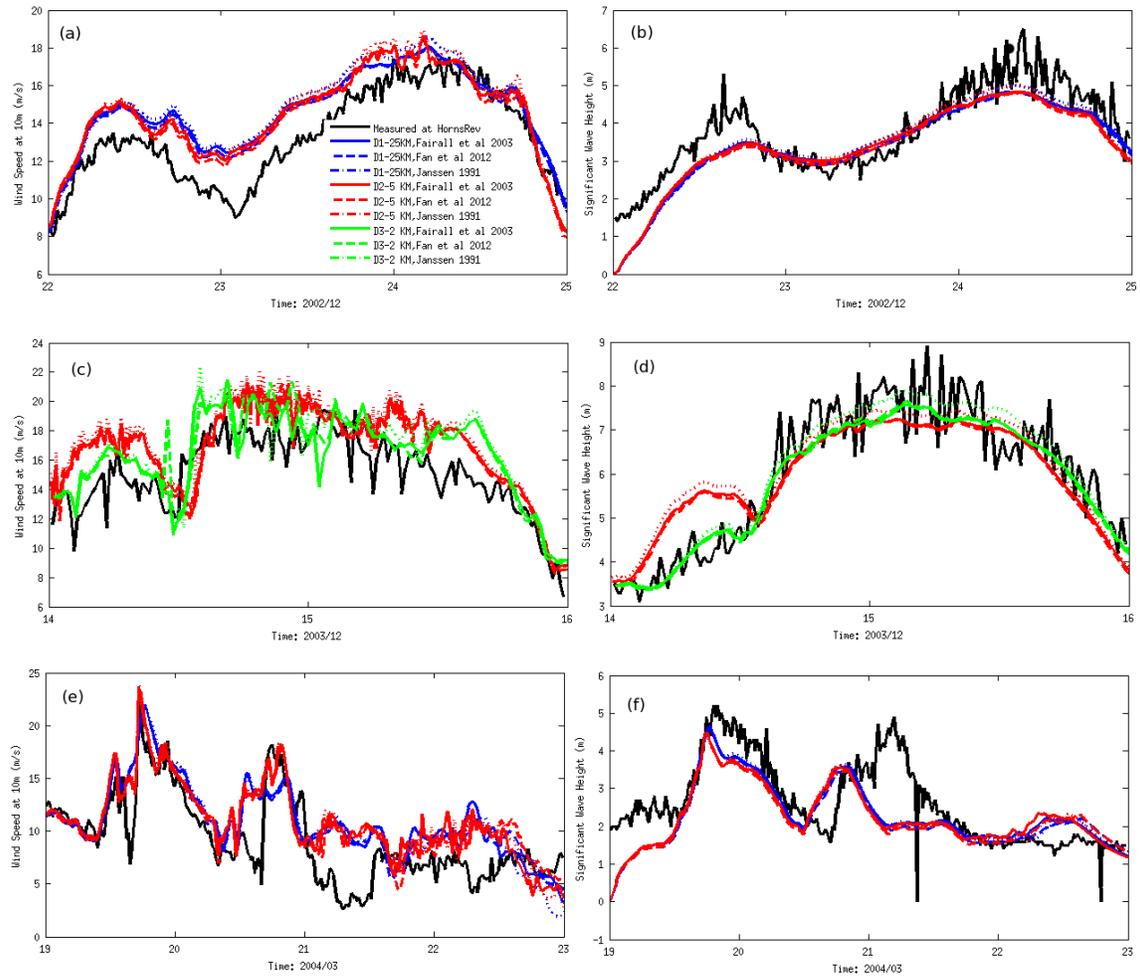


Fig. 5. Time series of the three storms at Ekofisk. The left column are the 10m wind speed. The right column are the significant wave height. The rows from top to bottom are storm SW02, NW03, SW04 respectively. For storm SW02 and SW04, EXP1-EXP6 are compared. For storm SW03, EXP2, EXP4, and EXP6-EXP9 are compared.

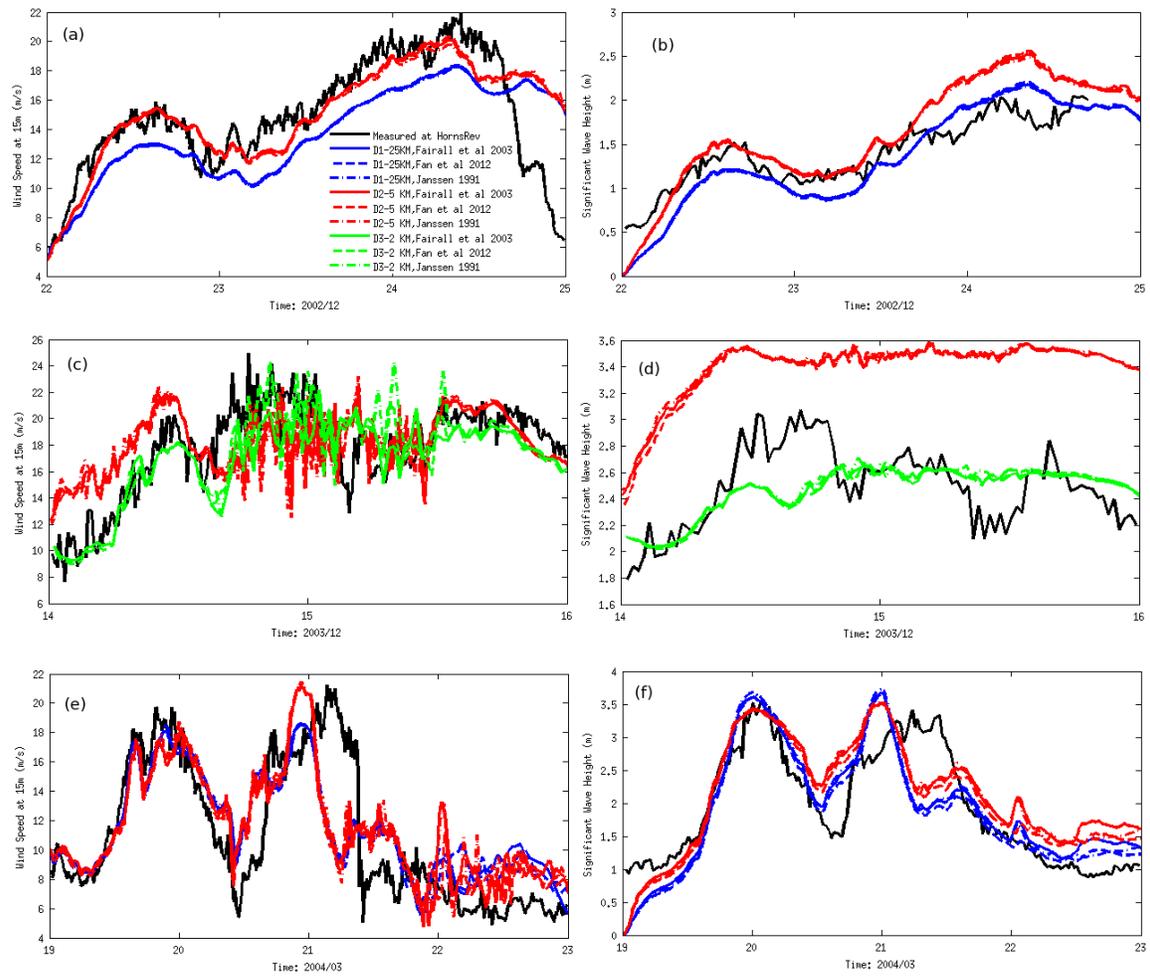


Fig. 6. Time series of the three storms at Horns Rev. The left column are the 15m wind speed. The right column are the significant wave height. The rows from top to bottom are storm SW02, NW03, SW04 respectively. For storm SW02 and SW04, EXP1-EXP6 are compared. For storm SW03, EXP2, EXP4, and EXP6-EXP9 are compared.