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Sensitivity analysis of observational nudging methodology to reduce error in wind resource assessment (WRA) in the North Sea

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ABSTRACT

Towards the improvement of the mesoscale modeling for offshore wind application, the real time observational nudging capability of the Weather Research and Forecasting (WRF) model has been implemented aiming for enhanced model performance. Utilizing three different horizontal levels of the offshore meteorological mast, FINO3, in the North Sea, wind speed observations were integrated into the model core. The performance of this modified model was then assessed for three different atmospheric stability conditions. Results from this study, illustrate that for all three stratification cases, there is a significant improvement in model performance when using observational nudging showing a reduction in Root Mean Square Error of up to 27% when compared to the observations from FINO1 platform. This study suggests that observational nudging takes a step towards more accurate simulations in wind resource assessment (WRA).

1. Introduction

Offshore wind energy has recently become a rapidly growing renewable energy resource worldwide triggering many projects in Europe either in developmental or in grid-connected operational stages [1]. Mesoscale modeling is one broadly used technique to evaluate a prospective wind project and lead wind resource assessment (WRA) which has made it an undoubtedly indispensable part of wind energy research [2]. The main aim of mesoscale modeling is to explicitly resolve the atmospheric equations and produce precise simulations applying the prognostic factors at the model grid points. Mesoscale models implement dynamical downscale in order to obtain a better spatial resolution for specific purposes. Various studies in this field have been conducted using the Weather Research and Forecasting (WRF) mesoscale model, taking advantage of the physical characteristics of the atmosphere, focusing either on offshore WRF performance [3–6] or solely on atmospheric stability [7] and investigating physics sensitivity [8,9].

WRF itself and specifically the Advanced Research WRF (ARW) solver has been widely used in different applications simulating the Marine Atmospheric Boundary Layer (MABL) and there has been an ongoing research on improving its configuration and performance. The MABL is the most significant part of the troposphere for offshore wind applications as that is the region that directly regulates the energy and moisture fluxes controlling the convective energy and moisture transfer to the free atmosphere. Hence, the MABL includes the wind resource itself and the accurate modeling of it could transitionally affect the prospective of a project. Muñoz-Esparza et al. [3,4] have carried out a study validating different planetary boundary layers (PBL) schemes under different stability conditions in order to assess the influence of the vertical mixing due to turbulence in the PBL. Similarly, Sood, et al. [5] compared analysis data with WRF under different atmospheric stratification cases showing an improvement during stable conditions. Subsequently, Giannakopoulou and Nhili [6] conducted a comprehensive study evaluating the sensitivity of WRF to different configuration modules and parameters such as horizontal resolution, PBL schemes, input data and nesting options. All of the aforementioned studies verified WRF against the FINO1 meteorological (met) mast observations in the North Sea [10].

Aiming to advance the model's performance, a data assimilation

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scheme has been implemented in WRF through the capability of a general form of analysis nudging [11]. Observational nudging has been broadly studied since Stauffer and Seaman [12,13] and Stauffer [14] used observations to drive the model solution to a relaxation mode by adding a nudging term to the model prognostic equations [12–14]. That term is called innovation term and is essentially the difference between the observations and the first guess of the initial conditions introduced to the model, expressed in spatial and temporal weighting terms [15]. Since it was originally proposed in the early 1990s, data assimilation has been further developed to four dimensional data assimilation (FDDA), where the data assimilation is applied in consecutive time-steps during the simulation [16]. Data incorporation can be applied directly towards gridded analyses that have been calculated based on observations (analysis nudging) or towards the observations themselves (observational nudging) [15]. Pattantyus et al. [17] applied observational nudging to validate precipitation levels and intensity for different radius of influence regimes of nudging. These results indicate that large radii of influence are necessary for both surface and upper air observational nudging in WRF-ARW. Hughes [18] employed observational nudging using an onshore met mast in Shell Flats in the UK. In two cases, his results showed an overall improvement in performance for wind speed modeling. Finally in an onshore wind power study, Cheng et al. [19] have implemented observational nudging using onshore wind turbines wind speed data resulting in a 30–40% improvement of the mean absolute error of 0–3 h wind power forecasts.

Observational nudging has, however, never been implemented offshore. Nowadays, more and more observational equipment has been installed offshore (met mast platforms, LiDARs and nacelle anemometers) providing us the opportunity to incorporate observations into models and correct the simulations. The current study focuses on the impact of observational nudging on the performance of offshore WRF simulations and is based on the physics schemes setup, nesting options and spatial spacing determined by Giannakopoulou and Nhili [6]. Light will be thrown on the data assimilation concept and on how the uncertainty of the wind flow model can be reduced, through the objective analysis of the observations. The observational nudging technique described in the present piece of work is based on continuous four-dimensional data assimilation (FDDA) scheme and it was implemented to WRF mesoscale model version 3.8 [20]. To conclude, it incorporates into the model quality observations from one neighboring met mast platforms in the North Sea, to the West of Denmark (FINO3) and the results are compared with the non-nudged simulations under different stability conditions against another high quality met mast platform (FINO1).

2. Observational and model data

2.1. Assimilated observational data: FINO3 measurements

FINO3 met mast began monitoring in 2009 and is located approximately 80 km to the west of Sylt in northern Germany (latitude 55.19° N and longitude 7.16° E) (see Fig. 2). It mainly focuses on the effect of offshore wind energy plants (OffWEA) on the ecological environment. There are two ultrasonic anemometers located at 30 m, 60 m and 100 m above lowest astronomical tide (LAT) on booms mounted oriented 225° from North and eight cup anemometers with 1 Hz sampling frequency at heights starting at 30 m to approximately 100 m (every 10 m) on booms mounted oriented 345° from North [21] (Table 1). For the purposes of the particular study and in order to maintain consistency of the temporal resolution of input data, 6-hourly instantaneous values from FINO3 met mast were post-processed and assimilated into the model.

2.2. Validation data: FINO1 measurements

FINO1 is an offshore platform in southern North Sea, west of Denmark and is located 45 km north of the Borkum island (latitude 54.00° N and longitude 6.58° E) (see Fig. 2) and has been recording multilevel measurements of wind speed, wind direction, air temperature, relative humidity and air pressure since 2003. The height of this measurement mast is approximately 100 m above lowest astronomical tide (LAT). Three ultrasonic instruments (10 Hz sampling frequency) are located at 41.5 m, 61.5 m and 81.5 m heights on north-westerly oriented booms. In addition, eight cup anemometers with a lower sampling frequency of 1 Hz are installed at different heights starting from 34 m up to about 100 m (every 10 m) on south-easterly oriented booms of the meteorological mast [10,22] (Table 2).

2.3. Initial and boundary conditions

The WRF model was used to refine the state of the atmosphere, especially the PBL, by dynamically down-scaling the global National Centers for Environmental Prediction (NCEP) Final Analysis

Table 1
Meteorological parameters with their associated heights and the sensor types including their accuracy at the FINO3 offshore met mast.

Variable	Heights (m) LAT	Sensor type	Accuracy	Sampling Rate
Wind speed (m/s) (ultrasonic)	30, 60, 100	2-d Laser Cantilever	(±0.01 m/s)	10 Hz
Wind speed (m/s) (cup anemometer)	30, 40, 50, 60, 70, 80, 90 100	Vector A100LK-WR-PC3	(±0.01 m/s)	1 Hz
Wind direction (degree)	40, 90	Thies wind vane classic	(±1°)	
Air temperature (°C)	30, 60, 100	Pt-100	(±0.1 K at 0 °C)	
Relative Humidity (%)	30, 60, 100	Hydrometer, Thies	(±3% RH)	
Air pressure (hPa)	30, 100	Barometer, Vaisala	(±0.03 hPa)	

Table 2
Meteorological parameters with their associated heights and the sensor types including their accuracy at the FINO1 offshore met mast.

Variable	Heights (m) LAT	Sensor type	Accuracy	Sampling Rate
Wind speed (m/s) (ultrasonic)	41.5, 61.5, 81.5	Gill Instruments R3-50	(±0.01 m/s)	10 Hz
Wind speed (m/s) (cup anemometer)	34, 41.5, 51.5, 61.5, 71.5, 81.5, 91.5, 104.5	Vector A100LK-WR-PC3	(±0.01 m/s)	1 Hz
Wind direction (degree)	41.5, 51.5, 61.5, 71.5, 81.5, 91.5	Thies wind vane classic	(±1°)	
Air temperature (°C)	30, 41.5, 52, 72, 101	Pt-100	(±0.1 K at 0 °C)	
Relative Humidity (%)	34.5, 90	Hydrometer, Thies	(±3% RH)	
Air pressure (hPa)	22.5	Barometer, Vaisala	(±0.03 hPa)	