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Evaluation of Marine Wind Profiles in the North Sea and Norwegian Sea Based on Measurements and Satellite-Derived Wind Products

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ABSTRACT

The wind conditions at oil platforms are typically measured at 40–140-m height, and then reduced to standard 10-m height before being distributed via the Global Telecommunication System. The 10-m values are further used for assimilation and verification of weather forecasts models. An accurate representation of the wind profile is therefore essential.

Here five wind profiles; power law, Norsok, logarithmic, Monin-Obukhov and Gryning are studied to find the best method for reduction of platform wind speeds to 10-m height level. Observations from nine oil platforms are used together with 10-m wind speed from ASCAT for evaluation of the wind profiles. In addition the wind profiles are evaluated using observations from the FINO3 offshore mast outside Denmark.

The present wind profile used for wind reduction at the oil platforms (power law with a constant wind-shear coefficient of 0.13) underestimates the 10-m wind speed by as much as 0.8 m/s on average. For near neutral atmospheric stability the Norsok and the logarithmic wind profiles yield on average a near perfect fit with a wind shear coefficient of 0.085. However, 10-m wind speeds are underestimated for unstable and overestimated for stable conditions.

The Monin-Obukhov and Gryning wind profiles give the most accurate estimates of 10-m wind speed during unstable and near-neutral conditions. For stable situations the Gryning wind profile, which also includes information about height of the boundary layer, gives the best agreement, but still an underestimation of the low level wind speed is encountered. The results strongly underline that atmospheric stability needs to be taken into account.

For future wind reduction from observation level to 10 meter, it is recommended to use a method which takes stability into account, for example the Gryning method. For long-term average assessments however, the logarithmic and Norsok wind profiles are sufficient.

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1. INTRODUCTION

Reliable weather forecasts are important for everyone, especially when you are offshore. The accuracy of weather predictions is strongly dependent on the amount and quality of observational data, and methods to assimilate them in Numerical Weather Prediction (NWP) models *[e.g. Bauer et al., 2015]*. Over the ocean, oil platforms are important sources of observational data. In the Norwegian territorial waters atmospheric pressure, wind speed, wind direction and air temperature are reported regularly from many platforms. While the wind speed at the platforms usually are measured between 40 and 140 m a.s.l, a vertical wind profile is applied to estimate the wind speed at 10 m, which then is distributed via the Global Telecommunication System. NWP models assimilate wind direction and wind speed based on the 10 m a.s.l values, e.g., as in the Norwegian Meteorological Institute NWP-system MEPS *[Müller et al. 2017, Bengtsson et al. 2017, Frogner et al. 2019]*. The same estimates of observed wind speed at 10 m is also used for forecast quality assessment and weather monitoring by operational forecasters. The choice and accuracy of the used vertical wind profile are therefore essential for multiple purposes, and inaccuracies in the choice of wind profiles may ultimately lead to erroneous observation estimates, less accurate forecasts and inaccurate evaluation of forecasts.

There are several wind profile models that can be used to reduce wind speed from sensor level to 10 m. According to *WMO [2018]* a logarithmic wind profile is sufficient over the sea due to small stability correction there. Presently, the measured wind speed at Norwegian platforms is reduced to 10 m by assuming an empirically decided power law wind profile with a wind shear coefficient equal to 0.13 *[Miros 2009]*. However, it is well known that 0.13 is a high value offshore and only valid for very high wind speeds or during periods of high vertical atmospheric stability. For example, assuming a logarithmic wind profile and a surface roughness expressed by Charnock's relation *[Charnock 1955]* yields a wind shear coefficient close to 0.09 for wind speed levels around 10 m/s over the open sea. In a study in the Gulf of Mexico and outside Chesapeake Bay, *Hsu et al. [1994]* found a typical offshore wind shear coefficient of 0.106 for neutral conditions, not far from the value suggested above. However, *Furevik and Haakenstad [2012]* found a wind shear coefficient of 0.06 for all data and wind shear coefficients of 0.04, 0.05 and 0.09 for unstable, neutral and stable conditions respectively, when they studied wind profiles from rawinsondes in the North Sea and Norwegian Sea.

The Norsok wind profile is another empirical wind profile independent of atmospheric stability. This wind profile was developed based on measurements from Frøya, an island at the Norwegian coast [*Standards Norway, 2007]*. *Furevik and Haakenstad [2012]* found an overestimation of 0.9 m/s when they used the Norsok wind profile to estimate the wind at 150 m from 10 m wind speed at the weather ship Polar Front in the Norwegian Sea.

According to the Monin-Obukhov similarity theory (MOST) *[e.g. Obukhov, 1971]* and further discussed in *[Stull 1988]* the wind profile in the surface layer (the lowest 10% of the boundary layer) is mainly controlled by three factors; surface roughness, friction velocity and atmospheric stability. Over open sea the MOST wind profile has been found to be applicable *[Edson and Fairall, 1998]*, but closer than 70–100 km from the coast, the sea-land discontinuity may influence the wind profiles *[Källstrand et al., 2000* and *Barthelmie et al. 2007]*. This is also in good agreement with *Lange et al. [2004]* who found significant deviation from the MOST wind profiles for near-neutral and stable condition at Rødsand 11 km off the coast in the Baltic Sea and *Møller et al. [2019]* who found abnormal wind profiles at the three FINO platforms 30–80 km off the coast in the Baltic Sea and southeastern part of the North Sea.

Gryning et al. [2007] found progressive deviations from the MOST wind profile above the surface layer (above 50–80 m) and proposed a wind profile for the entire boundary layer, by using additional length scales. Even though the Gryning profile initially was proposed for land areas where the roughness length is constant in time, it is also found to be applicable over open sea [*Peña et al. 2008* and *Sathe et al. 2011*].

The prior studies have documented different methods for estimating a wind profile, but usually only one or two different methods are compared and validated by use of measurements. In the present study five different wind profiles are compared and evaluated; the power law, Norsok, logarithmic, Monin-Obukhov and Gryning wind profiles. Satellite based wind products, measurements from the FINO3 offshore wind mast and oil platforms are applied in the evaluation.

The paper is structured as follows: Section 2 presents the five different wind profiles, Section 3 gives a description of the datasets and methods used in this study, Section 4 evaluates the different wind profiles by comparing estimated wind speed with observations, in order to find the best method to reduce wind speed from sensor level to 10 m, and finally Section 5 discusses and summarizes the main findings.

2. THE FIVE WIND PROFILES

In this section a brief presentation of the five different wind profiles is given. The input data applied to the wind profiles are described in Section 3.

2.1. LOGARITHMIC WIND PROFILE

The logarithmic wind profile is theoretically derived based on the wind profile for a neutral, homogenous and stationary flow given as *[Panofsky, 1973]*:

$$\frac{du}{dz} = \frac{u_*}{\kappa l} \quad (1)$$

Here du/dz is the variation of the horizontal wind speed, u, with the height, z, u_* is friction velocity, κ is the von Karman constant and l is the local length scale. The friction velocity is almost constant with height, and the length scale is assumed to be equal to height. Integrating equation 1 gives the logarithmic wind profile:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (2)$$

where z_0 is the roughness length. The logarithmic wind profile is only valid in the surface layer.

2.2. MONIN-OBUKHOV WIND PROFILE

Monin-Obukhov Similarity Theory (MOST) describes the effect of stability on the wind profile in the surface layer *[Stull 1988]*. The variation of the horizontal wind speed with height is in MOST expressed by:

$$u(z) = \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right] \quad (3)$$

Here $\psi_m(z/L)$ is an empirical function accounting for the effects of stability through the stability index $\frac{z}{L}$ where L is the Obukhov length given as:

$$L = \frac{-u_*^3\overline{\theta_v}}{\kappa g\left(\overline{w'\theta_v'}\right)_s} \quad (4)$$

where $\overline{\theta_v}$ is the mean virtual potential temperature, g is the acceleration of gravity and $\left(\overline{w'\theta_v'}\right)_s$ is the surface virtual potential temperature flux. The Monin-Obukhov wind profile is valid in the surface layer only.

2.3. GRYNING WIND PROFILE

Gryning et al. [2007] derived a wind profile valid in the entire boundary layer based on the homogeneous and stationary atmospheric boundary layer expressed by equation 1. They assumed that the length scale (l) in equation 1 can be composed of the three terms:

$$\frac{1}{l} = \frac{1}{L_{SL}} + \frac{1}{L_{MBL}} + \frac{1}{L_{UBL}} \quad (5)$$

where $L_{SL} = z$ is the length scale in the surface layer, $L_{MBL} = u_*/f\left[\left(\left(-2\ln(u_*/fz_0)\right)+55\right)\exp\left(-(u_*/fL)^2/400\right)\right]^{-1}$ is the length scale in the middle part of the boundary layer and $L_{UBL} = (z_i - z)$ is the length scale of the upper part of the boundary layer. Here f is the Coriolis parameter and z_i is the boundary layer depth. In the surface layer a constant friction velocity is assumed, while a linear decrease with height is assumed in the boundary layer above the surface layer.

The wind profiles for stable, neutral and unstable conditions are then given as:

$$\text{Stable:} \quad u(z) = \frac{u_{*0}}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\left(1-\frac{z}{2z_i}\right) + \frac{z}{L_{MBL}} - \frac{z}{z_i}\left(\frac{z}{2L_{MBL}}\right)\right] \quad (6)$$

$$\text{Neutral:} \quad u(z) = \frac{u_{*0}}{\kappa}\left[ln\left(\frac{z}{z_0}\right) + \frac{z}{L_{MBL}} - \frac{z}{z_i}\left(\frac{z}{2L_{MBL}}\right)\right] \quad (7)$$

$$\text{Unstable:} \quad u(z) = \frac{u_{*0}}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right) + \frac{z}{L_{MBL}} - \frac{z}{z_i}\left(\frac{z}{2L_{MBL}}\right)\right] \quad (8)$$

For more details see *Gryning et al. [2007].*

2.4. POWER LAW WIND PROFILE

The power law wind profile is an empirical wind profile given as:

$$u(z) = u_{zr}\left(\frac{z}{z_r}\right)^P \quad (9)$$

where u_{zr} is the wind speed at a reference height z_r and P is the empirically determined wind shear coefficient. The wind shear coefficient will vary with the atmospheric conditions, the roughness length and the height above the surface, but often a constant value is used for simplicity, e.g. as in the present treatment of platform measurements in the North Sea and Norwegian Sea where a wind shear coefficient of 0.13 is used *[Miros, 2009]*.

2.5. NORSOK WIND PROFILE

The Norsok wind profile is another empirical wind profile developed from measurements at the island Frøya in Norway [*Standards Norway, 2007*]. This wind profile is only dependent on wind speed and height given as:

$$u(z) = u_{zr}\left[1 + C\,ln\left(\frac{z}{z_r}\right)\right] \quad (10)$$

where $C = 5.73 \times 10^{-2}\left[1 + 0.15 \times u_{zr}\right]^{1/2}$ and u_{zr} is the wind speed at a reference height z_r.

3. DATASETS

In this study the following datasets have been applied: Hourly wind observations from the Norwegian oil platforms and the FINO3 research platform west of Southern Denmark, satellite-based Advanced SCATterometer (ASCAT) wind products and hourly re-analysis model data from ECMWF (ERA5). The observations cover a three-year period from 1 January 2017 to 31 December 2019. Several of the wind profiles investigated require information of surface roughness, atmospheric stability, and friction velocity. At FINO3 these parameters might be estimated from observations, but this is not possible at the oil platforms. However, these parameters are available from the ERA5 archive and this is the reason why ERA5 is used in this study. The four data sources are described in the following sections.

3.1. PLATFORM OBSERVATIONS

For the time period studied here, quality controlled wind observations were available at 22 oil platforms in the Norwegian territorial waters from The Norwegian Meteorological Institute (*https://frost.met.no/*).

The quality control consists of both automatic and human quality control routines to flag or remove suspicious and erroneous observations [Kielland 2005]. Unfortunately the quality control system does not capture effects from the platform itself on the wind flow. To study this effect, wind roses from the quality controlled wind sensor are compared subjectively with wind roses from all additional wind sensors at the same or a closeby platform in addition to wind roses from ASCAT. From these comparisons it is clear that many of the wind sensors are affected by flow distortion from one or more wind directions (not shown).

From the 22 available oil platforms, wind observations from nine platforms located at different oil fields were selected for further analyses. The wind sensors of these nine platforms are not found to be significantly affected by flow distortion from any wind direction. In addition at least one other wind sensor of the same oil field confirmed the quality of the selected sensor.

The selected platforms are Heidrun and Draugen in the Norwegian Sea and Snorre, Gullfaks, Kvitebjørn, Troll, Oseberg, Gudrun and Ula in the North Sea (***Figure 1***).

Table 1 shows location, sensor height and data availability of the quality controlled wind sensor at the nine oil platforms. The height of the wind sensors varies between 78 and 141 m above sea level, e.g. often well above the surface layer. Only hourly observations of 10 min average wind speed with the highest quality flag are used in this study. The data availability of the platform observations is between 94 and 99% of the time.

3.2. ASCAT WINDS

ASCAT is an active microwave radar carried on-board the polar-orbiting MetOp satellites operated by the European

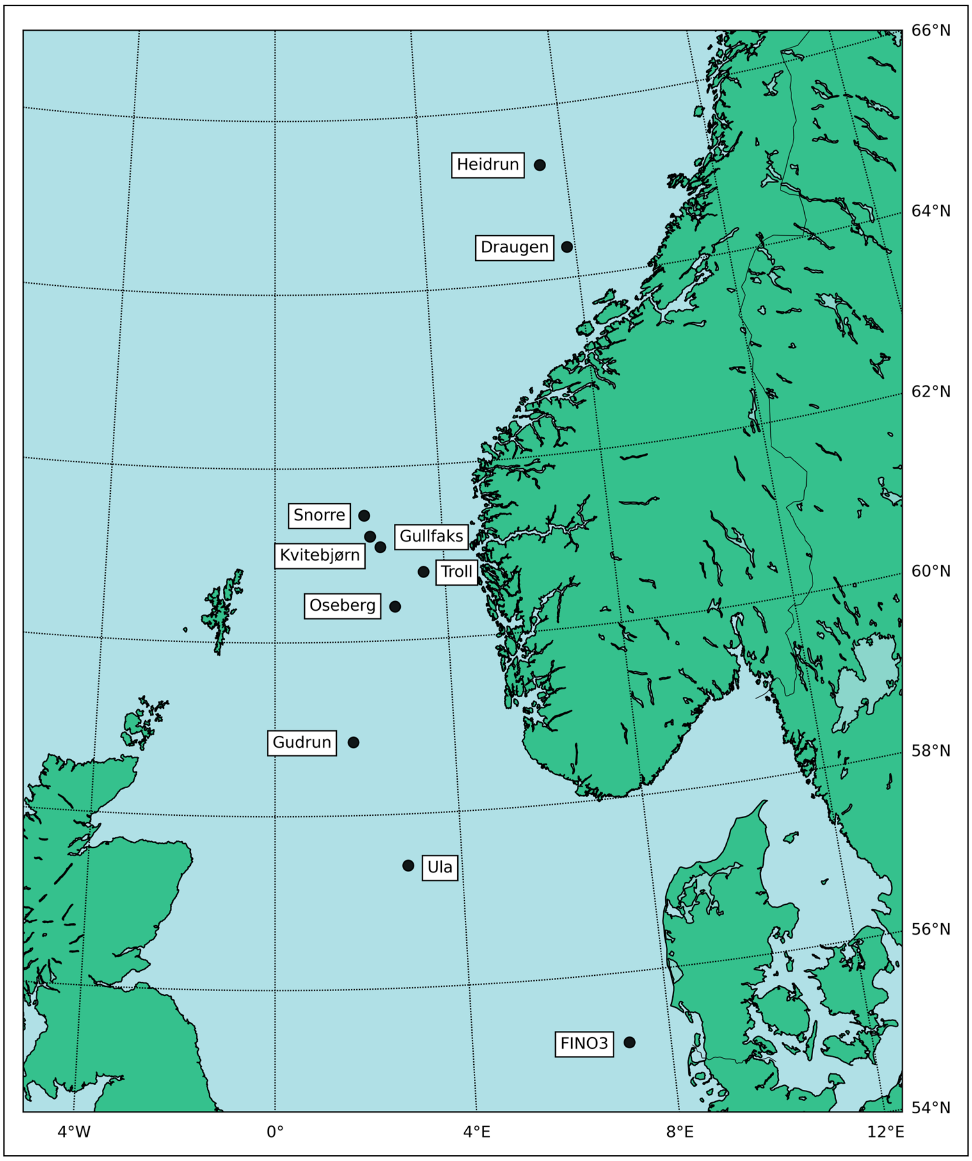

Figure 1 A map showing the location of the nine oil platforms used in this study in addition to the FINO3 wind mast outside Southern Denmark.

PLATFORM	LOCATION	SENSOR HEIGHT [M]	AVAILABILITY [%]
Heidrun	N 65.32 E 7.32	131	99
Draugen	N 64.35 E 7.78	78	95
Snorre	N 61.45 E 2.14	115	98
Gullfaks	N 61.20 E 2.27	141	98
Kvitebjørn	N 61.08 E 2.51	115	95
Troll	N 60.77 E 3.50	84	99
Oseberg	N 60.39 E 2.80	126	98
Gudrun	N 58.85 E 1.74	84	94
Ula	N 57.41 E 2.85	111	97

Table 1 Location, sensor height and data availability for the nine oil platforms used in this study.

Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The dataset can be downloaded from *https://eoportal.eumetsat.int/*.

ASCAT measures the ocean's surface backscatter at multiple azimuth angles and provides estimates of 10 m wind speed and wind direction based on an assumption of neutral atmospheric stability conditions and standard atmospheric density. In this study, the ASCAT coastal wind product on a 12.5 km grid from the MetOp-A and MetOp-B satellites, is utilised. Only data with the highest quality flag are used. For more information about ASCAT data see *Verhoef et al. [2012]*.

Hourly data for each platform is constructed by using the wind vector cell where the combined mismatch in space (less than 30 km) and time (less than 30 minutes) are as small as possible. The data availability of the ASCAT winds is around 16% at Heidrun and decreases southwards to around 11% of the time at Ula. Notice that the ASCAT data represent wind over an area (i.e. the instrument footprint) while the observations from the oil platform represent a point.

3.3. FINO3 OBSERVATIONS

FINO3 is a research platform located in the North Sea 80 km west of Southern Denmark (***Figure 1***). The FINO3 data has kindly been made available for research purposes by *http://www.bsh.de*. Details about the data are found at *https://www.fino3.de/en/*.

The FINO3 platform is equipped with cup anemometers at 31, 41, 51, 61, 71, 81, 91, 101 and 107 m, wind vanes at 29, 81 and 101 m and ultrasonic anemometers at 61 and 101 m a.s.l. To avoid mast distortion there are wind sensors pointing in three different directions: 105, 225 and 345 degrees *[Obhrai et al., 2012]*. In addition to wind measurement the following observations, relevant for calculating the atmospheric stability, are available: pressure at 23 and 95 m, relative humidity and air temperature at 29, 55 and 95 m in addition to sea surface temperature.

The FINO3 mast is located close to two wind farms; the DanTysk wind farm on the east side of FINO3 and the Sandbank wind farm about 25 km to the west. To examine the influence of the wind turbines on the wind measurement at the FINO3 platform, the turbulence intensity (TI) for different wind directions has been investigated in the present paper. TI indicates disturbances from the DanTysk wind farm and therefore only observations where the wind direction is between 190 and 360 degrees are included in this study.

To avoid mast effects, wind speed from the cups directed towards 345 degrees and the wind directions from the ultrasonic anemometer directed towards 225 degrees are chosen. In this study hourly observations of 10 min average wind speed between 31 and 107 m and wind direction at 61 m with the highest quality flag are used. In addition, pressure at 23 m, relative humidity at 29 m, air temperature at 29 m and sea surface temperature (SST) are used for calculation of atmospheric stability. SST is missing for an extended period, from late November 2018 to mid-May 2019. When observations of SST are missing, the SST are instead taken from the ERA5 archive. By comparing SST from observations with SST from the ERA5 archive, only minor differences were found. The correlation between the SST data from the two dataset is as high as 0.995.

The data availability for all parameters combined is around 90%. After removing observations when the wind direction is between 0 and 190 degrees, the availability is reduced to 55%.

3.4. ERA5

Calculating wind profiles, information about several atmospheric parameters are needed. Since many of these parameters are not observed routinely, data from the ERA5 archive is applied. The ERA5 data are downloaded from the Copernicus Climate Data Store (*https://doi.org/10.24381/cds.adbb2d47*).

ERA5 is the most recent version of global reanalysis from ECMWF *[Hersbach et al. 2020]* and is based on the Integrated Forecasting System (IFS) Cy41r2, operational at ECMWF in 2016. ERA5 benefits from a decade of developments in model physics, core dynamics and data assimilation compared to its predecessors. ERA5 uses an approximately 31 km horizontal grid spacing and provides hourly output and shows a substantial increase in quality in comparison with earlier ECMWF re-analysis.

ERA5 is preferred compared to higher-horizontal resolution operational datasets because of consistency through the studied period and the availability of all necessary parameters. In addition, the vertical resolution is reasonably good, while the horizontal resolution is of less importance over the flat ocean for our purposes.

For the studied period, SST in ERA5 is taken from the satellite based Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA). All parameters used from the ERA5 archive are described in Section 3.5.

3.5. DATA PROCESSING

Only wind speeds exceeding 3 m/s at 31 m at FINO3 or 10 m from ASCAT at the oil platforms are included. The data is divided into seven stability classes based on the Obukhov length, *L* (***Table 2***). The seven classes are the same as in *Gryning et al. [2007]*, but the classes 'very unstable' and 'very stable' are extended to |L| = 0 m to include all data.

3.5.1. Atmospheric stability

The atmospheric stability is characterized by the Obukhov length (equation 4). According to *Stull [1988]* the virtual potential temperature is approximated as:

$$\theta_v \approx \theta(1+0.61r) \tag{11}$$

where θ is the potential temperature and r is the mixing ratio of water vapor, while the virtual potential temperature flux, $\overline{w'\theta'_v}$, is approximated as:

$$\overline{w'\theta'_v} \approx \overline{w'\theta'}(1+0.61\overline{r})+0.61\overline{\theta}\,\overline{w'r'} \tag{12}$$

where $\overline{w'\theta'}$, is the mean heat flux and $\overline{w'r'}$ is the mean humidity flux. The Obukhov length can then be calculated from the ERA5 data. The mixing ratio, r, is calculated from surface pressure, 2-m temperature and 2-m dew point temperature, while for the heat and moisture fluxes instantaneous surface heat flux and instantaneous moisture flux are used from ERA5.

STABILITY	OBUKHOV LENGTH
Very unstable (VU)	$-100\ m \le L < 0\ m$
Unstable (U)	$-200\ m \le L < -100\ m$
Near neutral – unstable (NU)	$-500\ m \le L < -200\ m$
Neutral (N)	$\lvert L\rvert > 500\ m$
Near neutral – stable (NS)	$200\ m < L \le 500\ m$
Stable (S)	$50\ m < L \le 200\ m$
Very stable (VS)	$0\ m < L \le 50\ m$

Table 2 Classification of the stability according to the Obukhov length intervals.

At FINO3 the Obukhov length is also estimated by the bulk Richardson number calculated from observations. The relations between the dimensionless stability parameter z/L and the bulk Richardson number R_{ib} following Grachev and Fairall [1997] are:

$$\frac{z}{L} = C_1 R_{ib} \text{ for unstable conditions} \tag{13}$$

$$\frac{z}{L} = \frac{C_2 R_{ib}}{1-C_3 R_{ib}} \text{ for stable conditions} \tag{14}$$

where $C_1 = 10$, $C_2 = 10$ and $C_3 = 5$.

The bulk Richardson number is then given as [*Grachev and Fairall 1997* and *Peña et al. 2008*]:

$$R_{ib} = -\frac{gz\Delta\theta_v}{T_z u_z^2} \tag{15}$$

where T_z is the mean temperature and u_z the mean wind speed measured at the reference height *z*. At FINO3 the reference height for the measured mean temperature in this study is 29 m, while the mean wind speed is measured at 31 m. $\Delta\theta_v$ is the difference between mean virtual potential temperature at the reference height and the sea surface. In estimating $\Delta\theta_v$, the relative humidity observed at 29 meters is used together with an assumed relative humidity of 100% at the sea surface.

3.5.2. Friction velocity

The friction velocity is available from the ERA5 archive. From the observations at FINO3 the friction velocity u_* is estimated from the wind speed at 31 m, *U*, and the bulk Richardson number, R_{ib} as described by *Vickers et al. [2015]*:

$$u_* = f(U)h(R_{ib}) \tag{16}$$

where

$$f(U) = 0.17 - 0.019U + 0.0042U^2 - 8.4\times10^{-5}U^3 \tag{17}$$

and

$$h(R_{ib}) = (1-60R_{ib})^{0.1}, R_{ib} < 0 \tag{18}$$

$$h(R_{ib}) = (1+60R_{ib})^{-0.2}, R_{ib} > 0 \tag{19}$$

In this study the friction velocity is set to be a minimum value of 0.02 m/s.

3.5.3. Roughness length

The roughness length is also available from ERA5. At FINO3 the roughness length is estimated from the observations by using the Charnock's relation [*Peña et al. 2008*]:

$$z_0 = a_c \frac{u_*^2}{g} \quad (20)$$

where a_c is the Charnock's parameter. The value used for the Charnock's parameter is 0.0185. The roughness length is set to be a minimum of 0.0002 m.

3.5.4. Height of the boundary layer

The height of the boundary layer is available in the ERA5 dataset and is retrieved for both the FINO3 mast and the oil platform. For estimation of the boundary layer height at FINO3 from observation, the Rossby-Montgomery formula *[Rossby & Montgomery, 1935]* has been used. Here z_i is assumed to be climatologically proportional to u_{*0} for neutral conditions given as:

$$z_i = c \frac{u_{*0}}{|f_c|} \quad (21)$$

where u_{*0} is the friction velocity near the ground, f_c is the Coriolis parameter and c is a proportionality constant. Over a homogeneous terrain *Peña et al. [2010]* estimated c to be 0.15. Since climatologically z_i is assumed to decrease with increasing stability *Sathe et al. [2011]* used the value 0.14 for stable conditions and 0.13 for very stable conditions. By using equation 21 together with the constants suggested above, the mean height of the boundary layer is calculated for the four stability categories from neutral to very stable conditions. This mean value is used for all data within each stability category. Like *Sathe et al. [2011]* the mean value of z_i for neutral conditions is also used for all unstable categories in absence of a suitable expression for the height of the boundary layer for unstable conditions. The height of the boundary layer is set to a minimum of 100 m and a maximum of 2000 m.

3.5.5. Stress-equivalent wind speed

ASCAT winds represent horizontal stress-equivalent wind vectors at 10 m height. In order to compare ASCAT winds with standard 10 m wind observations, it is recommended to convert the standard wind observations into stress-equivalent wind speed *[Kloe et al. 2017]*. The stress-equivalent 10 m wind speed is given as:

$$u_{10s} = u_{10n} \sqrt{\frac{\rho_{air}}{< \rho_{air} >}} \quad (22)$$

where ρ_{air} is the actual air density, $<\rho_{air}> = 1.225\ kg/m^3$ is the global average air density over ocean and u_{10n} is the equivalent neutral 10 m wind speed.

The equivalent neutral 10 m wind speed is found by using a surface layer wind profile to reduce the wind speed from 10 m to near surface height, and then using a neutral wind profile back to 10 m. By using the Monin-Obukhov wind profile the equivalent neutral wind speed can be given as:

$$u_{10n} = u_{10} \frac{ln\left(\frac{10}{z_0}\right)}{\left[ln\left(\frac{10}{z_0}\right) - \psi_m\left(\frac{10}{L}\right)\right]} \quad (23)$$

In this study, ASCAT data are also used together with wind observations at sensor level to calculate mean wind reductions and mean wind shear coefficient at the oil platforms. That is why the ASCAT data are instead converted from stress-equivalent wind speed u_{10s} into "normal" 10 m wind speed u_{10} by using the inverse formulations above. The ASCAT data shown in the following sections are always stability and air density corrected 10 m wind.

3.6. COMPARISON OF WIND PROFILE PARAMETERS ESTIMATED FROM OBSERVATIONS AND ERA5

Table 3 shows mean values of the following wind profile parameters: Obukhov length (L), friction velocity (u_*), roughness length (z_0) and height of the boundary layer (z_i) for the seven different stability categories. At FINO3 parameters estimated from observations (EOBS) and from ERA5 are shown, while only parameters from ERA5 are available at the oil platforms.

Applying the Obukhov length estimated from observations at FINO3, gives a few percent more cases for each of the unstable categories and a few percent fewer cases for each of the stable categories compared to the Obukhov length from ERA5.

At the oil platform it is very unstable conditions that are most frequent and occur 34% of the time. By looking at the different platforms (not shown), very unstable conditions occur 22% of the time at Ula and increase northwards to around 45% of the time at Draugen and Heidrun. At FINO3 however, it is neutral stability conditions that are most frequent and occur ~25% of the time. Very stable conditions are rare and occur only 2–3% of the time at both FINO3 and the oil platforms.

By comparing the mean values of the Obukhov length, friction velocity, roughness length and height of the boundary layer, the values are rather similar in the three different datasets, except for the height of the boundary layer. The mean boundary layer height from ERA5 is much higher than the estimated height from observations. The height of the boundary layer is only included in the Gryning wind profile. To investigate how much these differences in boundary layer height affects this wind profile, mean wind profiles using boundary layer height from ERA5 vs boundary layer heights based on equation (21) are compared for each stability category. Only for stable and very stable conditions some differences are encountered in the mean 10 m wind speed, with a mean difference of 2–3%.

FINO3 EOBS (L, u_*, z_0 AND z_i IS ESTIMATED FROM OBSERVATIONS)					
STABILITY	***N***	***L***	u_*	z_0	z_i
Very unstable	3345 [24%]	−38	0.25	0.00013	*
Unstable	2518 [18%]	−140	0.35	0.00026	*
Near neutral unstable	2536 [18%]	−290	0.41	0.00037	*
Neutral	3366 [24%]	–	0.42	0.00039	522
Near neutral stable	1037 [7%]	308	0.28	0.00017	328
Stable	830 [6%]	109	0.19	0.00008	220
Very stable	213 [2%]	9	0.12	0.00003	130
FINO3 ERA5 (L, u_*, z_0 AND z_i FROM ERA5)					
STABILITY	***N***	***L***	u_*	z_0	z_i
Very unstable	2939 [21%]	−29	0.22	0.00008	755
Unstable	2055 [15%]	−140	0.34	0.00019	925
Near neutral unstable	2279 [16%]	−295	0.42	0.00034	998
Neutral	3422 [25%]	–	0.46	0.00051	964
Near neutral stable	1216 [9%]	303	0.34	0.00025	677
Stable	1487 [11%]	101	0.23	0.00010	384
Very stable	447 [3%]	23	0.13	0.00004	180
OIL PLATFORMS (L, u_*, z_0 AND z_i FROM ERA5)					
STABILITY	***N***	***L***	u_*	z_0	z_i
Very unstable	10699 [34%]	−14	0.21	0.00008	780
Unstable	4230 [14%]	−139	0.35	0.00020	886
Near neutral unstable	4611 [15%]	−294	0.43	0.00035	947
Neutral	7154 [23%]	–	0.51	0.00059	950
Near neutral stable	1978 [6%]	311	0.33	0.00023	584
Stable	1877 [6%]	101	0.22	0.00010	369
Very stable	503 [2%]	23	0.14	0.00005	182

Table 3 Number of observations (N) in addition to mean values of the Obukhov length (L), friction velocity (u_*), roughness length (z_0) and height of the boundary layer (z_i) for the seven stability classes at FINO3 and oil platforms.

* The mean value of z_i found for neutral conditions (522 m) are also used for all unstable conditions in calculation of the Gryning wind profile (see Section 3.5.4).

While the Gryning wind profile is valid in the entire boundary layer, the logarithmic and Monin-Obukhov wind profiles are valid in the surface layer only. According to *[Stull, 1988]* the surface layer is approximately the lowest 10% of the boundary layer. From the mean values of the boundary layer height found here, the surface layer is 50–100 m thick for unstable and neutral conditions and only 10–40 m thick during stable conditions. Since the wind profiles investigated here are used to reduce wind speeds from a height often well above the surface layer, the logarithmic and Monin-Obukhov wind profiles are often used outside their area of validity. However, Peña et al. [2008] found a good agreement with observations also above the surface layer during unstable and neutral conditions, when they compared Monin-Obukhov profile data with observations from lidar up to 161 meter in the Danish North Sea. Thus, good agreements can also be expected in our cases during unstable and neutral conditions, while larger errors should be expected under stable conditions.

4. RESULTS

In this section, mean observed wind reduction at both FINO3 and oil platforms are first investigated. Then the optimal wind shear coefficients for the power law wind profiles are found for both FINO3 and the oil platforms. Finally, the five wind profiles; logarithmic, Monin-Obukhov, Gryning, Norsok and power law are evaluated by comparing reduced wind speed by the different wind profiles with near surface observations.

4.1. MEAN OBSERVED WIND REDUCTION

Figure 2 shows mean observed wind profiles at FINO3 for each of the seven stability classes defined in ***Table 2***. In addition, the mean wind profile for all data is given (red curve). The mean profiles are shown when using the Obukhov length from ERA5 (L_{era5}) and from observations (L_{eobs}) for the stability classification.

The mean wind profiles when using the two different estimates of the Obukhov length for the stability classification, are rather similar. The largest difference is for neutral to stable conditions, for which L_{eobs} gives 1–3% larger wind reduction and for very stable conditions where L_{eobs} gives around 3% smaller wind reduction, than L_{era5}. For unstable conditions the differences are less than 1%.

At FINO3 the smallest wind reduction is for very unstable conditions, with a mean reduction around 4% from 107 m to 31 m height. The largest wind reduction on the other hand, is for stable conditions with a mean reduction of approximately 22%. Very stable conditions also have a large wind reduction below 71 m, but a much smaller wind reduction above 71 m. The mean reduction from 107 m to 31 m is therefore only 14% when using L_{eobs} and 17% when using L_{era5} for the stability classification. The small wind reduction between 71 and 107 m is most likely because of the low boundary layer height during very stable conditions. The top of the stable layer is then often located below the top of the FINO3 mast, leaving the highest wind sensors in the free atmosphere where the wind is little influenced by the sea surface and the wind speed changes slowly with height.

Figure 3 shows a box plot of the mean wind reduction from the nine oil platforms for each stability category classified by the Obukhov length estimated from ERA5. The mean wind reduction is calculated from the mean wind speed at sensor level and the mean 10 m wind speed from ASCAT. Since no wind speed is available at intermediate levels, only the total reduction is shown. The spread in mean wind reduction between the different oil platforms is at least partly due to the different sensor height ranging from 78 m to 141 m (***Table 1***), as also seen if the reduction in mean wind speed is calculated from different heights in ***Figure 2***.

Also, at the oil platforms, very unstable conditions give the least wind reduction (~10% on average). The largest wind reduction is for stable and very stable conditions with a mean reduction of 33–35%. Since the lowest wind speed level is 10 m at the oil platforms and 31 m at FINO3, a larger reduction in wind speed is found for the oil platforms. However, qualitatively the reduction in wind speed with height shows similar patterns at both FINO3 and at the oil platforms.

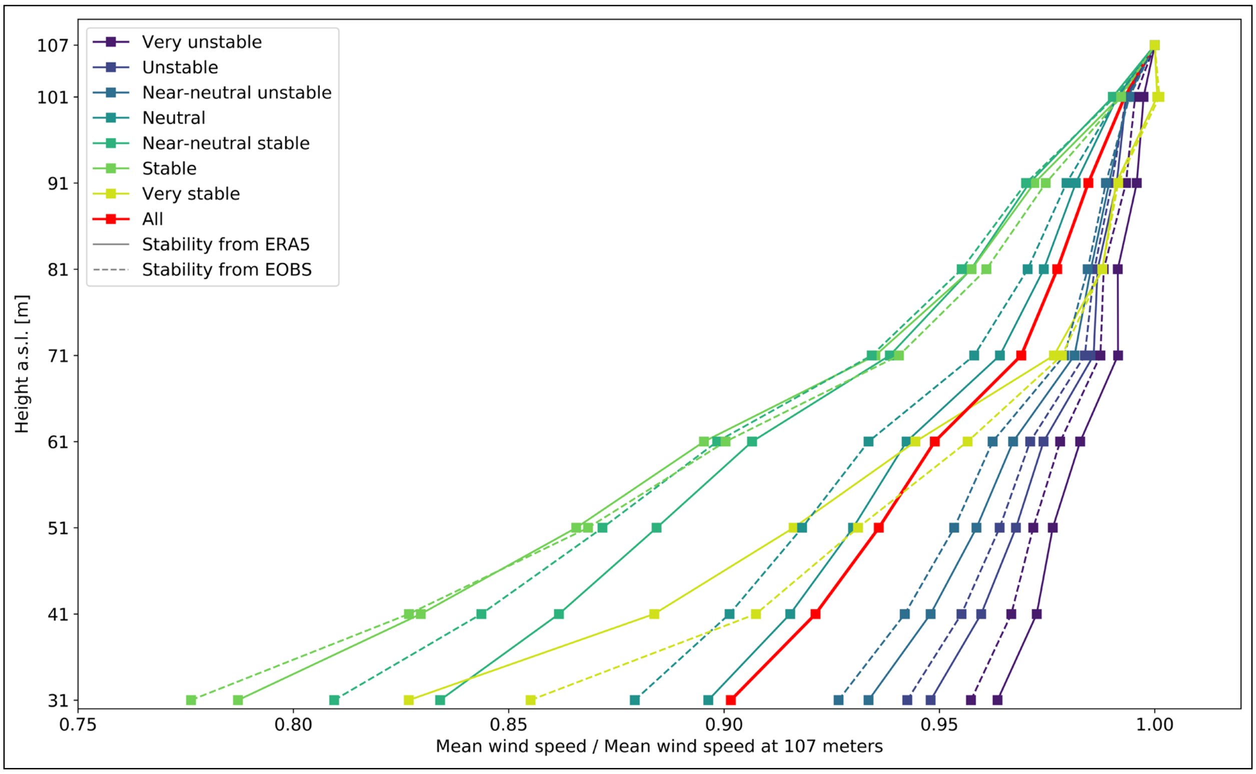

Figure 2 Mean observed wind profiles at FINO3 for the seven stability categories given in Table 2. The stability is classified by the Obukhov length from ERA5 (solid lines) and observations (dashed lines). The mean wind profile for all data is the solid red line.

4.2. OPTIMIZING THE POWER LAW WIND PROFILES

An evaluation of the power law wind profiles (equation 9) using both a constant value of the wind shear coefficient and a wind shear coefficient that varies with stability, is carried out. To find the optimal wind shear coefficients, the mean wind shear coefficient for each stability category and for all data together, are calculated from wind speeds at 31 and 107 m at FINO3 and 10 m and sensor level at oil platforms. Only the Obukhov length estimated from ERA5 are used.

Figure 4 shows a scatter plot of hourly wind shear coefficients against stability (1/*L*) at both FINO3 and oil platforms. Also, the mean wind shear coefficients for

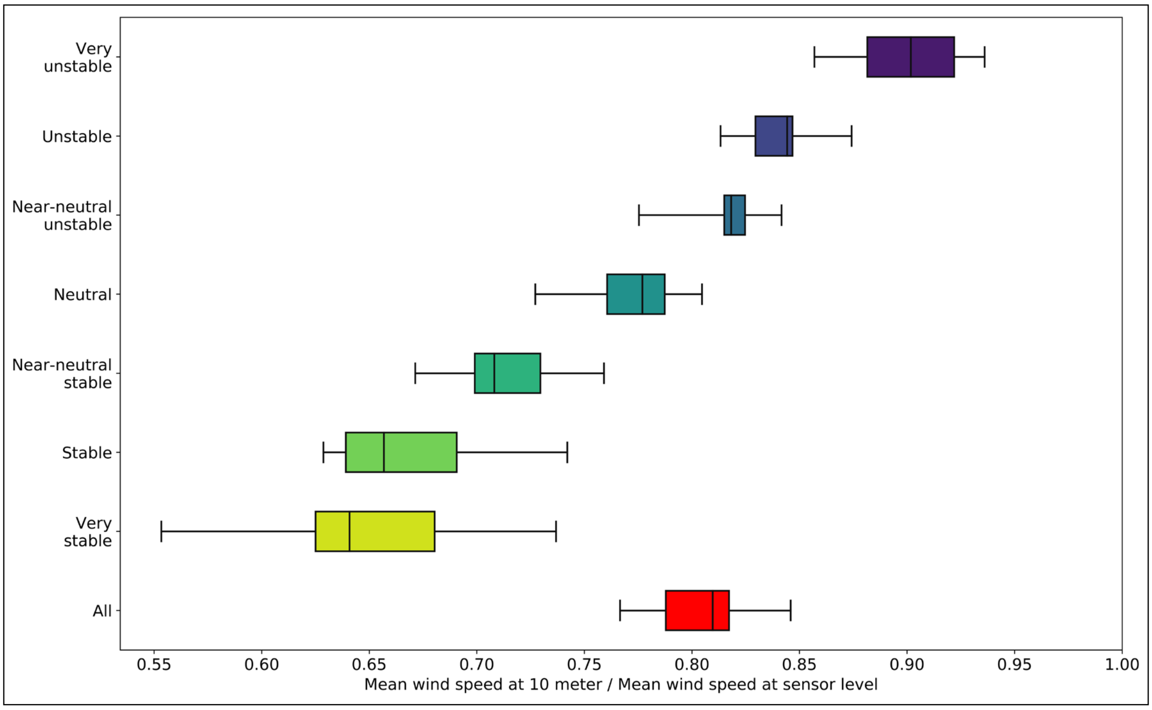

Figure 3 Mean wind reduction at the nine oil platforms for the seven different stability categories (Table 2) and for all data. The box represents the 25, 50 and 75 percentile of the mean wind reduction and whiskers represent min and max.

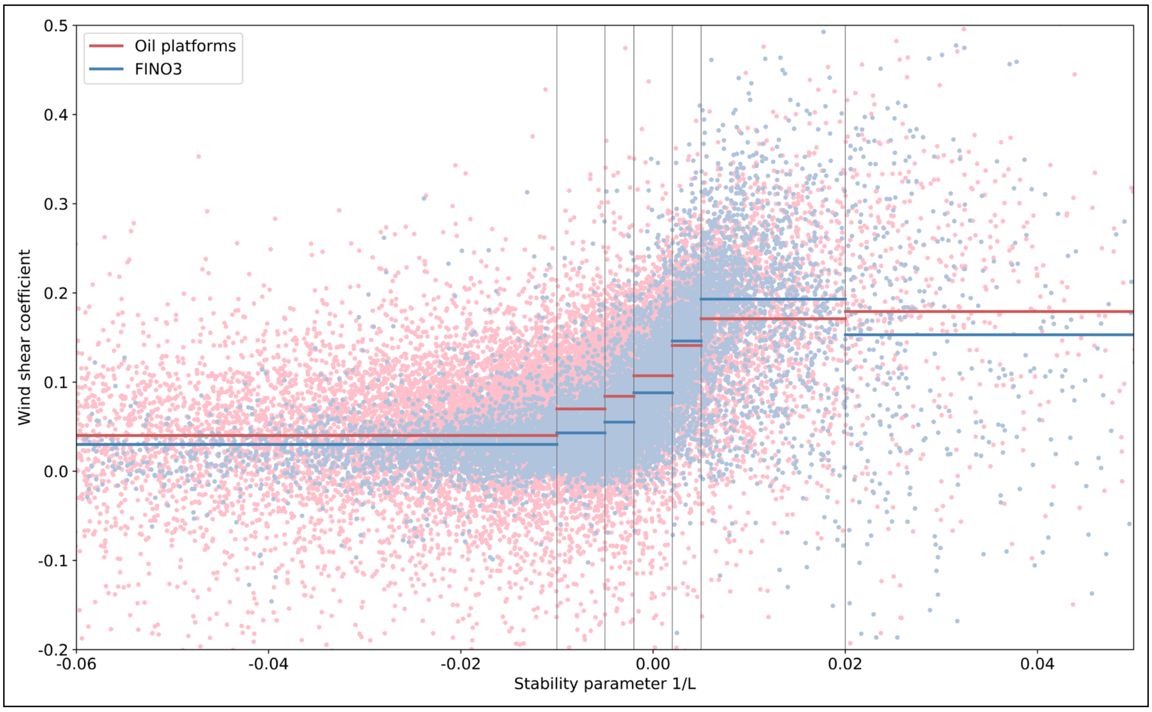

Figure 4 Scatter plot of wind shear coefficient vs the Obukhov length from ERA5 for oil platforms (light red dots) and FINO3 (light blue dots). The solid red and blue lines are the mean wind shear coefficient for each stability category calculated from mean wind speed at sensor level and 10 m for oil platforms and at 107 and 31 m for FINO3 respectively. The dark grey vertical lines mark the border between the different stability categories.

each stability category are shown in the same plot. For the oil platforms there is a much larger spread compared to FINO3. This is at least partly because of variable sensor height between the different platforms. When plotting one station at a time, the spread is more equal to what is found at FINO3 (not shown).

Both for FINO3 and the oil platforms the scatter plot shows a clear connection between the wind shear coefficient and the atmospheric stability except for very high values of 1/L (stable conditions). The mean wind shear coefficient increases with increasing atmospheric stability from around 0.04 for very unstable conditions to around 0.09 for neutral conditions and 0.18 for stable conditions. Then for very stable conditions the mean wind shear coefficient decreases to 0.15 at FINO3, while it is still 0.18 at the oil platforms. This difference is most likely because of the different height of the lowest wind level (31 m at FINO3 and 10 m at oil platforms). As seen from the wind profile for very stable conditions at FINO3 (***Figure 2***), there is almost no decrease in wind speed near the top of the wind mast and a rapid decrease in wind speed closer to the surface. If this rapid decrease in wind speed continues down to 10 m as expected, this will lead to a higher wind shear coefficient when using 10 m as the lowest wind level compared to 31 m in calculation of the wind shear.

The wind shear coefficient that gives the best overall fit is 0.084 at FINO3 and 0.088 at the oil platforms. For the evaluation of wind profiles in the next section, Power Law with Constant wind shear coefficient of 0.085 (PLC) is therefore used. In addition, the power law wind profile with a constant wind shear coefficient of 0.13 (Power Law Present, PLP) is used, since this is the present wind profile applied at Norwegian oil platforms for reducing platform winds to 10 m wind speed.

Also two power law wind profiles with a wind shear coefficient that varies with stability are evaluated. Power Law Stability – FINO3 (PLS-F) uses the mean wind shear coefficients found at FINO3: 0.030, 0.043, 0.055, 0.088, 0.146, 0.193 and 0.153 ranging from very unstable to very stable conditions, while Power Law Stability – oil Platforms (PLS-P) uses the mean coefficients found at the oil platforms: 0.040, 0.070, 0.084, 0.107, 0.141, 0.171 and 0.179 for the same stability categories.

4.3. EVALUATION OF THE WIND PROFILES

At FINO3 the wind speed at 107 m is reduced to 31 m by the four power law wind profiles described in the previous section (PLP, PLC, PLS-F and PLS-P) in addition to Norsok (NOR), logarithmic (LOG), Monin-Obukhov (MOS) and Gryning (GRY) wind profiles. At the oil platforms the wind speed at varying sensor levels is reduced to 10 m by the same wind profiles. At FINO3 the wind profiles are calculated by using the wind profile data (L, u_*, z_0 and z_i) from both ERA5 and observations, while only values from ERA5 are available at the oil platforms. The results are presented in ***Figure 5***. The mean error (ME) is used as a measure of the systematic error, while the standard deviation of the error (STDE) normalized by the mean wind speed is a measure of the random error of each wind profile.

PLP, the present wind profile used at the oil platforms *[Miros, 2009]*, underestimates the 31 m wind speed at FINO3 by 0.5 m/s and the 10 m wind speed at the oil platforms by 0.8 m/s on average. These systematic errors are removed by PLC. The coefficient used in PLC is not estimated from totally independent data, but the estimated coefficient is very similar based on both FINO3 and oil platform data which indicate that it has a more general validity.

One should keep in mind that the same data are used for both finding the optimal wind shear coefficient for the different stability categories and for evaluation of the power law profiles afterwards. Hence PLS-F gives a small mean error at FINO3 and PLS-P a small mean error at the oil platforms. However, PLS-F overestimates the 10 m wind speed at the oil platforms by 0.4 m/s, while PLS-P underestimates the 31 m wind speed at FINO3 by 0.1–0.2 m/s on average. GRY, MOS, NOR and LOG wind profiles give all small or moderate biases (mostly below ± 0.25 m/s) at both FINO3 and the oil platforms.

The STDE is approximately double at the oil platforms compared to FINO3, independent of applied wind profiles. The latter indicates that an important part of this is related to the data at the oil platforms (e.g. variation in sensor level, possible wind distortion, use of ASCAT for estimation of 10 m wind). However, a clear pattern is that the wind profiles with the smallest STDE are the wind profiles which vary with stability; PLS-F, PLS-P, MOS and GRY. This is particularly seen at FINO3.

To further assess the wind profiles, the ratio of the mean estimated and observed wind speed as a function of stability, is shown in ***Figure 6***. The ratio is very similar for profiles based on ERA5 and observations. This indicates that ERA5 is a reasonable choice when observations are not available, at least for the study of mean wind profiles.

All wind profiles are in rather good agreement with observations for neutral conditions, but for unstable and stable conditions some of the wind profiles give large systematic errors compared to observations. For MOS and GRY wind profiles the results at FINO3 and the oil platforms are rather similar. For the other wind profiles the errors within each stability class are qualitatively similar, but more pronounced at the oil platforms. This is most likely because the comparison is for wind speed at 31 m at FINO3 and 10 m at the oil platforms.

Both MOS and GRY are in a good agreement with the observed low-level wind speed for all unstable and neutral conditions, but underestimate the low-level wind speed for stable and especially very stable conditions. For very stable conditions MOS underestimates the low-level wind speed with as much as 30–35% on average, while the underestimation for GRY is much smaller, around 15%.

Figure 5 Mean error (ME) (upper panel) and standard deviation of the error (STDE) normalized by the mean wind speed (lower panel) for the five wind profile methods (with four different versions of the power law profile: PLP, PLC, PLS-F and PLS-P). At FINO3 wind profiles are calculated by using Wind Profile Parameters (WPP) based on both ERA5 and observations.

The three wind profiles PLC, NOR and LOG have corresponding characteristics. They all underestimate wind speed for unstable conditions with around 5% at FINO3 and 5–10% at the oil platforms, and overestimate the wind speed for stable conditions with 5–15% at FINO3 and as much as 15–30% at the oil platforms on average. PLP underestimates the wind speed even more for unstable conditions (around 10% at FINO3 and 15–20% at the oil platforms), but gives a much smaller overestimation of the wind speed for stable conditions.

PLS-P (with wind shear coefficients calculated from oil platforms) are in rather good agreement with observations also at FINO3. The largest deviation is for very stable conditions where this wind profile underestimates the 31 m wind speed with around 5% on average. PLS-F (with wind shear coefficients calculated from FINO3) overestimates the 10 m wind speed at the oil platforms for several of the stability classes, especially very stable conditions where the overestimation is around 10% on average.

5. DISCUSSION AND CONCLUSION

High quality observations are important for data assimilation into NWP systems, weather forecasting and

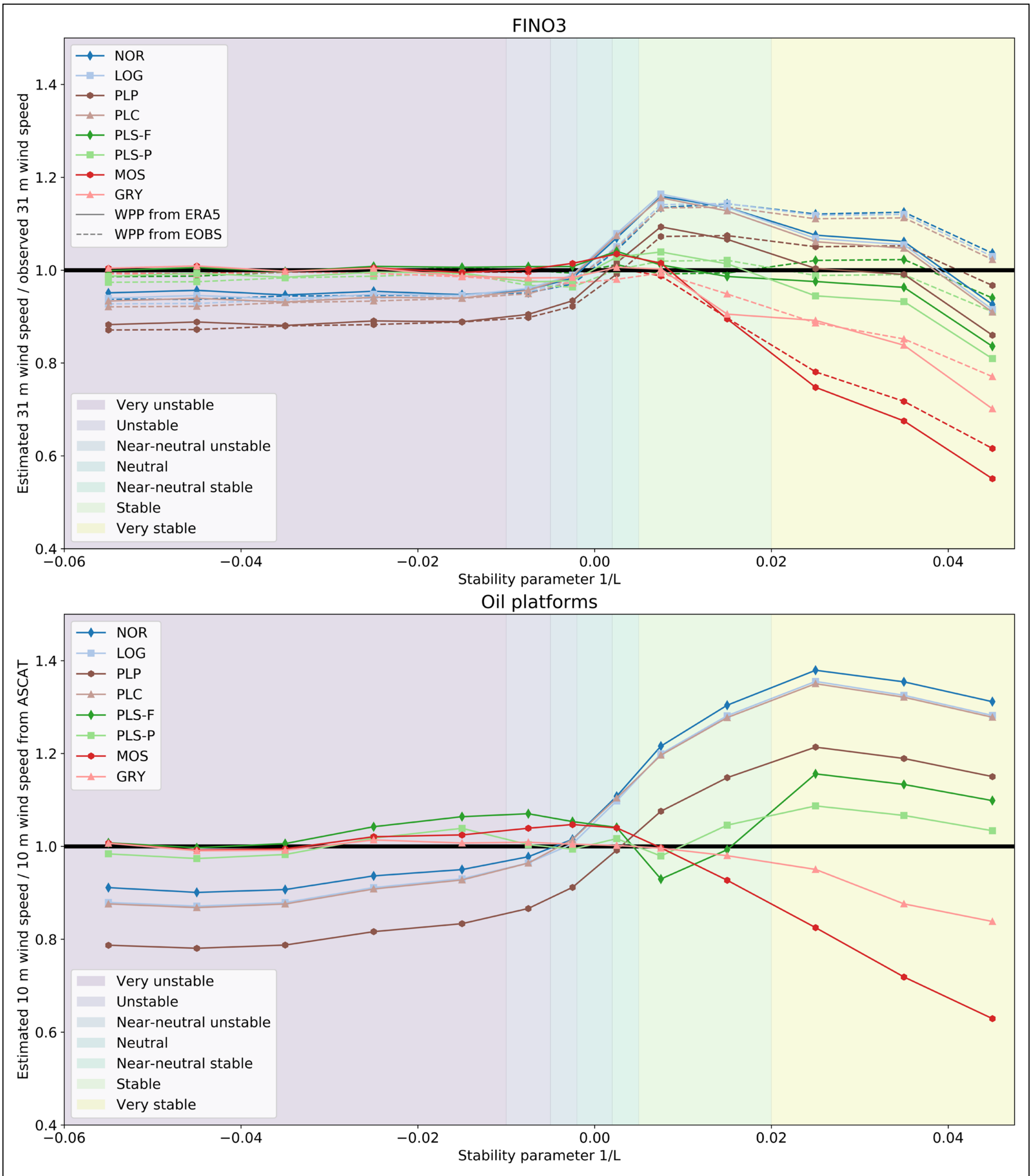

Figure 6 Mean estimated wind speed divided by observed wind speed, as a function of stability at: FINO3 (top) and oil platforms (bottom). FINO3 data are shown when using both Wind Profile Parameters from ERA5 (solid lines) and estimated from observations (dashed lines).

model validation. In weather forecasting, the standard height for wind speed is 10 meter. It is also the 10 m wind speed that is distributed via the Global Teleconnection System and later used for weather monitoring, model validation and data assimilation into the forecasting models. At oil platforms in the North Sea and Norwegian Sea the wind speed is measured at heights varying between 40 and 140 m a.s.l., the 10 m wind speed is estimated by employing a vertical wind profile.

In this article five different wind profile models are evaluated over the ocean to find the best method for reduction of platform wind at sensor level to 10 m wind speed. The five studied wind profile models are the power law, Norsok, logarithmic, Monin-Obukhov and Gryning. Observations are from nine oil platforms in the North Sea and Norwegian Sea, where wind speed at sensor level is used together with 10 m wind speed from ASCAT for the evaluation of the wind profiles. For comparison the wind profiles are also evaluated using observations from the tall wind mast, FINO3, outside Southern Denmark.

The results show a large spread in the near-surface wind speed from the various wind profiles, especially for stable, but also for unstable conditions.

Presently at Norwegian oil platforms, a power law wind profile with a wind shear coefficient equal to 0.13 is used for reduction of observed platform wind to 10 m wind speed [Miros 2009]. This is well known to be a high value for the coefficient valid only during stable atmospheric conditions, which occurs only around 10% of the time according to the data in this study. An underestimation of 0.8 m/s on average was found using this wind profile for estimation of 10 m wind speed at the oil platforms.

The optimal average wind shear coefficient for the power law wind profile was found to be in the range 0.08–0.09 based on all data at both FINO3 and the oil platforms. By classifying the data after atmospheric stability, a wind shear coefficient increasing from around 0.04 for very unstable conditions to around 0.09 for neutral conditions and around 0.17 for stable and very stable conditions were found. For near-neutral cases this is not far from the value 0.106 Hsu et al. [1994] found in the Gulf of Mexico. Furevik and Haakenstad [2012] on the other hand, found wind shear coefficients of 0.04, 0.05 and 0.09 for unstable, neutral and stable conditions respectively, when they studied rawinsonde observations at two stations in the North Sea and Norwegian Sea. These values are lower than the corresponding values found here.

The evaluation of the wind profiles shows similar results at both FINO3 and the oil platforms. Using a wind shear coefficient of 0.085 for the power law wind profile instead of the present value of 0.13, almost removes the systematic error. However, this wind profile and the Norsok and logarithmic wind profiles do not vary with stability and therefore underestimate the near surface wind speed with around 5–10% for unstable conditions and overestimate the wind speed with 5–15% at FINO3 and 15–30% at the oil platforms for stable conditions on average.

Using a power law wind profile with wind shear coefficients that vary with stability gives a much better agreement with observations. The wind shear coefficients must, however, be found empirically since they also vary with other factors. For instance, the power law wind profile with wind shear coefficient found at FINO3 overestimates the wind speed at the oil platforms by as much as 0.4 m/s on average.

Monin-Obukhov and Gryning wind profiles give a very good agreement with observations for unstable and near-neutral conditions. Although the Monin-Obukhov wind profile is used outside the surface layer, there is almost no bias compared to observations during these stability conditions, as were found by Peña et al. [2008].

For stable conditions an underestimation that seems to increase with increasing stability is found at both FINO3 and the oil platforms. For very stable conditions the Monin-Obukhov wind profile underestimates the near surface wind speed by as much as 30–35% on average, while the underestimation using Gryning is 15–20%. Similar results for the Monin-Obukhov profile were found by Peña et al. [2008] and Sathe et al. [2011]. By using the Monin-Obukhov wind profile to estimate the wind speed at different heights over the ocean from near surface wind speeds, they both found a significant overprediction above the surface layer for stable and very stable conditions. When they studied the Gryning wind profile, they did not find any significant deviations from observations during stable and very stable conditions inside the boundary layer. However, Peña et al. found an overestimation near the top of and above the boundary layer (above ~100 m) when they compared the Gryning wind profile with lidar observations up to 161 meter. This corresponds well with the underestimation near the surface found here.

Despite the recommendations from *WMO [2018]* to apply the logarithmic wind profile over sea, the data in the present study show that the atmospheric stability must be taken into account to give better estimates of the near surface (10 m) wind speed. Instead of applying the logarithmic wind profile, it is recommended to use the Gryning wind profile.

The Gryning wind profile is the most complicated wind profile investigated here and needs information about several parameters, such as Obukhov length, friction velocity, roughness length and height of the boundary layer. When sufficient observation data are not available, these data might be estimated from observations of sea surface temperature, near surface air temperature and wind observations (see Section 3) or be taken from an NWP model or reanalysis data. For long-term average assessments on the other hand, the logarithmic and NORSOK wind profiles are sufficient.

In the future, it should be considered to distribute wind observations at the original measurement level together with the observation height, instead of wind speed reduced to 10 meter. By doing this, no degradation or additional uncertainty is introduced to the observation. Also for data assimilation and model validation it is recommended to use observations at the original height to reduce the uncertainty in the observation. If model validation is needed at specific user required heights (e.g. 10 m), this should be done carefully to minimize the errors introduced in estimation of the wind profile.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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REFERENCES

Barthelmie, RJ, Badger, J, Pryor, SC, Hasager, CB, Christiansen, MB and **co-authors.** 2007. Offshore Coastal Wind Speed Gradients: Issues for the Design and Development of Large Offshore Windfarms. *Wind Engineering*, 31(6): 369–382. DOI: *https://doi.org/10.1260/030952407784079762*

Bauer, P, Thorpe, A and **Brunet, G.** 2015. The quiet revolution of numerical weather prediction. *Nature*, 525: 47–55. DOI: *https://doi.org/10.1038/nature14956*

Bengtsson, L, Andrae, U, Aspelien, T, Batrak, Y, Calvo, J and co-authors. 2017. The HARMONIE–AROME Model Configuration in the ALADIN–HIRLAM NWP System. *Monthly Weather Review*, 145(5): 1919–1935. DOI: *https://doi.org/10.1175/MWR-D-16-0417.1*

Charnock, H. 1955. Wind stress on a water surface. *Quarterly Journal of the Royal Meteorological Society*, 81(350): 639–640. DOI: *https://doi.org/10.1002/qj.49708135027*

de Kloe, J, Stoffelen, A and **Verhoef, A.** 2017. Improved Use of Scatterometer Measurements by Using Stress-Equivalent Reference Winds. *IEEE, Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 10(5): 2340–2347. DOI: *https://doi.org/10.1109/JSTARS.2017.2685242*

Edson, JB and **Fairall, CW.** 1998. Similarity Relationships in the Marine Atmospheric Surface Layer from Terms in the TKE and Scalar Variance Budget. *Journal of the Atmospheric Science*, 55(13): 2311–2328. DOI: *https://doi.org/10.1175/1520-0469(1998)055<2311:SRITMA>2.0.CO;2*

Frogner, I-L, Singleton, AT, Køltzow, MØ and **Andrae, U.** 2019. Convection-permitting ensembles: Challenges related to their design and use. *Quarterly Journal of the Royal Meteorological Society*, 145(51): 90–106. DOI: *https://doi.org/10.1002/qj.3525*

Furevik, BR and **Haakenstad, H.** 2012. Near-surface marine wind profiles from rawinsonde and NORA10 hindcast. *Journal of Geophysical Research*, 117(D23). DOI: *https://doi.org/10.1029/2012JD018523*

Grachev, AA and **Fairall, CW.** 1997. Dependence of the Monin–Obukhov Stability Parameter on the Bulk Richardson Number over the Ocean. *Journal of Applied Meteorology and Climatology*, 36(4): 406–414. DOI: *https://doi.org/10.1175/1520-0450(1997)036<0406:DOTMOS>2.0.CO;2*

Gryning, S-E, Batchvarova, E, Brümmer, B, Jørgensen, H and **Larsen, S.** 2007. On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer. *Boundary-Layer Meteorology*, 124: 251–268. DOI: *https://doi.org/10.1007/s10546-007-9166-9*

Hersbach, H, Bell, B, Berrisford, P, Hirahara, S, Horányi, A and co-authors. 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730): 1999–2049. DOI: *https://doi.org/10.1002/qj.3803*

Hsu, SA, Meindl, EA and **Gilhousen, DB.** 1994. Determining the Power-Law Wind-Profile Exponent under Near-Neutral Stability Conditions at Sea. *Journal of Applied Meteorology and Climatology*, 33(6): 757–765. DOI: *https://doi.org/10.1175/1520-0450(1994)033<0757:DTPLWP>2.0.CO;2*

Källstrand, B, Bergström, H, Højstrup, J and **Smedman, A-S.** 2000. Mesoscale Wind Field Modifications over the Baltic Sea. *Boundary-Layer Meteorology*, 95: 161–188. DOI: *https://doi.org/10.1023/A:1002619611328*

Kielland, G. 2005. KVALOBS – The quality assurance system of Norwegian Meteorological Institute observations. *Instruments and Observing Methods Rep*. 82, WMO/TD-1265, 5 pp. Online at: *https://library.wmo.int/index.php?lvl=notice_display&id=11280#.YOQoK3Uzbds*.

Lange, B, Larsen, S, Højstrup, J and **Barthelmie, R.** 2004. Importance of thermal effects and sea surface roughness for offshore wind resource assessment. *Journal of Wind Engineering and Industrial Aerodynamics*, 92(11): 959–988. DOI: *https://doi.org/10.1016/j.jweia.2004.05.005*

Miros. 2009. Data block WI: Wind speed and direction, Parameter Definition Miros Data Blocks Doc. Asker, Norway: DF/WI/UK. Available at *http://miros.no/doc/df_wi.pdf*.

Møller, M, Domagalski, P and **Sætran, LR.** 2019. Comparing Abnormalities in Onshore and Offshore Vertical Wind Profiles. *Wind Energy Science Discussions*. DOI: *https://doi.org/10.5194/wes-2019-40*

Müller, M, Homleid, M, Ivarsson, K-I, Køltzow, MAØ, Lindskog, M and co-authors. 2017. AROME-MetCoOp: A Nordic Convective-Scale Operational Weather Prediction Model. *Weather and Forecasting*, 32: 609–627. DOI: *https://doi.org/10.1175/WAF-D-16-0099.1*

Obhrai, C, Kalvig, SM and **Gudmestad, OT.** 2012. A Review of current guidelines and research on wind modelling for the design of offshore wind turbines. *International Society of Offshore and Polar Engineers*. Online at: *https://www.researchgate.net/publication/285714195_A_review_of_current_guidelines_and_research_on_wind_modeling_for_the_design_of_offshore_wind_turbines*.

Obukhov, AM. 1971. Turbulence in an atmosphere with a non-uniform temperature. *Boundary-Layer Meteorology*, 2: 7–29. DOI: *https://doi.org/10.1007/BF00718085*

Panofsky, H. 1973. Tower micrometeorology. In: Haugen, DA (ed.), *Workshop on Micrometeorology, American Meteorological Society*, 151–176.

Peña, A, Gryning, S-E and **Hasager, CB.** 2008. Measurements and Modelling of the Wind Speed Profile in the Marine Atmospheric Boundary Layer. *Boundary-Layer Meteorology*, 129: 479–495. DOI: *https://doi.org/10.1007/s10546-008-9323-9*

Peña, A, Gryning, S-E, Mann, J and **Hasager, CB.** 2010. Length Scales of the Neutral Wind Profiles over Homogeneous Terrain. *Journal of Applied Meteorology and Climatology*, 49(4): 792–806. DOI: *https://doi.org/10.1175/2009JAMC2148.1*

Rossby, C-G and **Montgomery, RB.** 1935. The layer of frictional influence in wind and ocean currents. *Papers in Physical Oceanography and Meteorology*, 3(3). DOI: *https://doi.org/10.1575/1912/1157*

Sathe, A, Gryning, S-E and **Peña, A.** 2011. Comparison of the atmospheric stability and wind profiles at two wind farm sites over a long marine fetch in the North Sea. *Wind Energy*, 14: 767–780. DOI: *https://doi.org/10.1002/we.456*

Standards Norway. 2007. NORSOK standard: Action and action effects, N003 edition 2. Online at: *http://www.standard.no/PageFiles/1149/N-003e2.pdf*.

Stull, RB. 1988. An Introduction to Boundary Layer Meteorology. Dordrecht, the Netherlands: Kluwer Academic Publishers. DOI: *https://doi.org/10.1007/978-94-009-3027-8*

Verhoef, A, Portabella, M and **Stoffelen, A.** 2012. High-resolution ASCAT Scatterometer Winds Near the Coast. *IEEE Transactions on Geoscience and Remote Sensing*, 50(7): 2481–2487. DOI: *https://doi.org/10.1109/TGRS.2011.2175001*

Vickers, D, Mahrt, L and **Andreas, EL.** 2015. Formulation of the Sea Surface Friction Velocity in Terms of Mean Wind and Bulk Stability. *Journal of Applied Meteorology and Climatology*, 54(3): 691–703. DOI: *https://doi.org/10.1175/JAMC-D-14-0099.1*

WMO. 2018. Guide to Instruments and Methods of Observations. Volume I – Measurements of meteorological variables. Online at: *https://library.wmo.int/index.php?lvl=notice_display&id=19673#.YL8TepozY5m*.

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