Strong wind characteristics over the open ocean

John Holmes[1]
[1] *JDH Consulting, Mentone, Victoria, 3194, Australia; john.holmes@jdhconsult.com*

ABSTRACT

This paper reviews the available measurements of profiles and turbulence intensities in strong winds over the open ocean, including some from a ship by Deacon *et al*. in the 1950s, the comprehensive Norwegian Frøya data, and measurements in hurricanes in the Atlantic Ocean and the Gulf of Mexico. The mathematical models for these profiles in the design approaches of the offshore petroleum industry are discussed. Picking the best aspects from these, practical models for mean wind and turbulence intensity profiles and spectra, for structural design of structures such as offshore platforms and wind turbine towers, are recommended.

1. Introduction

Information on strong-wind characteristics over the open ocean, such as vertical profiles of mean wind speed and the intensities of turbulence components, is critical for the design and operation of offshore energy-related structures, such as gas extraction and production platforms, and offshore wind farms. However, the majority of measurements of wind characteristics in the atmospheric boundary layer of the synoptic-scale strong-wind events have been made for over-land fetches, such as those used for the detailed mathematical model of Deaves and Harris, (1978). It is quite difficult to make similar measurements over a large height range in open water, and particularly in the open ocean, at wind speeds relevant to the design of structures.

The profiles of mean wind speed and turbulence intensity in strong winds, with neutral thermal stability, over any surface are largely determined by the surface roughness, as measured by the surface drag coefficient (C_d) and the aerodynamic roughness length (z_o). In over-land winds the surface roughness is essentially invariant with the mean wind speed. This is not the case for over-water winds, for which the surface roughness is a function of mean wind speed which governs wave heights; fetch lengths for wave generation, and water depths, which affect wave 'breaking', may also be important.

The surface drag coefficient and roughness length are related through Eq. (1), derived from the logarithmic wind profile:

$$C_d = \frac{{u_*}^2}{{\bar{U}_{10}}^2} = \left[\frac{k}{log_e\left(\frac{10}{z_0}\right)}\right]^2 \tag{1}$$

u_* is the friction velocity, $\bar{U}_{10}$ is the mean wind speed at 10m above the surface, and k is von Karman's constant ($\cong$ 0.4).

2. Measurement databases and drag coefficient-wind speed relationships

In a pioneering study, Deacon *et al.* (1956) made measurements of surface drag coefficients and wind profiles from a research ship in Port Phillip Bay and the Bass Strait. For these measurements, complex corrections were required for rolling of the vessel, as well as the aerodynamic interference of the hull. However, the study showed a general increase in surface drag coefficient with wind speed, up to about 0.0021 for mean wind speeds of about 15 m/s. The authors also noted that the drag coefficient was largely independent of fetch length, if this exceeded 3 km in deep water.

Charnock (1955), using dimensional analysis, derived a well-known relation for wind over water (Eq. (2)).

$$z_0 = \frac{a{u_*}^2}{g} \tag{2}$$

Here, a is the Charnock 'constant' and g is the acceleration due to gravity.

For a constant value of a, Equation (2) gives the roughness length, z_0, increasing monotonically with u_*, and hence with the reference wind speed, $\overline{U}_{10}$. While Equation (2) has been applied widely, a variety of different values of a between 0.01 and 0.04 have been obtained, when fitting it to different data sets.

Amorocho and DeVries (1980), using a large amount of experimental data, derived a complex non-linear relationship between a and $\overline{U}_{10}$. Notably, this paper was probably the first to identify 'saturation' of the surface drag coefficient, at a value of 0.00254, for mean wind speeds greater than 20 m/s.

There were many studies, before 1980, of wind over shallow and calm water, at low wind speeds ($\overline{U}_{10}$ less than 20m/s), none of these were taken in the open ocean, or at wind speeds approaching design values for offshore structures. In an attempt to rectify this, the Norwegian state oil company (Statoil) sponsored extensive tower measurements from the island of Frøya, between 1988 and 1989, with a fetch for prevailing wind directions over the North Sea. Measurements of mean wind speeds and turbulence were made from three different towers, for heights up to 100m. These results were summarized by Andersen and Lovseth (2006).

The Frøya data are of good quality but are also limited in wind speed – the maximum mean wind speed at 10m height was about 26 m/s. Andersen and Lovseth (2006) found a linear relationship between surface drag coefficient, C_d, and the reference mean wind speed, $\overline{U}_{10}$. However, they also noted a 'saturation' of the surface drag coefficient above about 22 m/s – i.e. a tendency for the surface drag coefficient to become constant above that wind speed.

Up to 26m/s, the surface drag coefficient from the Frøya data was fitted with Equation (3):

$$C_d = 0.000526[1 + 0.148\,\overline{U}_{10}] \quad (\text{for } \overline{U}_{10} < 26 \text{ m/s}) \tag{3}$$

Andersen and Lovseth stated that Equation (3) matched the relationship derived from Equations (1) and (2), with the Charnock parameter, a, equal to 0.0172.

The Frøya data was used in the ISO Metocean Standard (2015) for offshore structures, using Equation (3) for the surface drag coefficient, but, significantly, it was not capped at the saturation wind speed.

Saturation or 'capping' of the roughness length, was confirmed by the analysis of the *dropwindsonde* profiles in Atlantic hurricanes by Powell *et al*. (2003). Although there was considerable scatter in the values obtained, the data indicated capping of the roughness length at about 2mm for mean wind speeds greater than about 30 m/s (see Figure 1).

Based on the Powell *et al*. work, the recommended 'tropical cyclone' wind profile adopted recently by the American Petroleum Institute (API, 2021) has capped the surface drag coefficient at 0.0023 for mean wind speeds greater than 27.85 m/s; the equivalent capped aerodynamic roughness length is 2.4 mm.

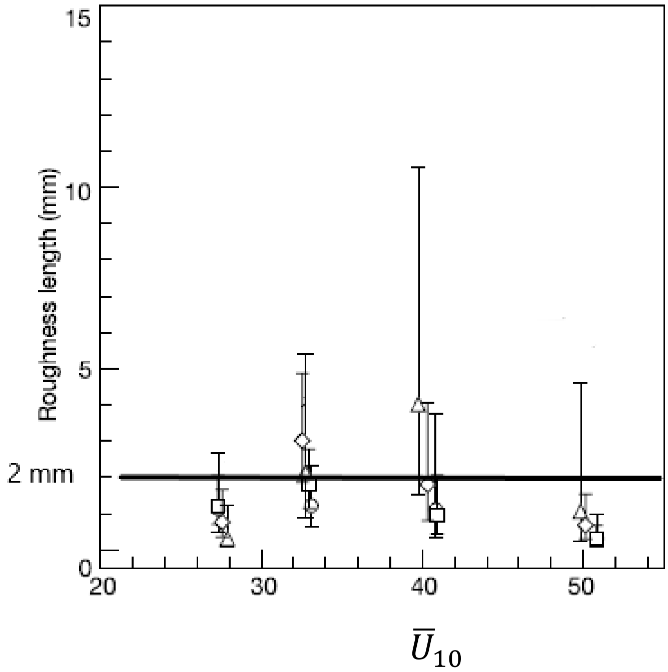

Figure 1. Roughness length in ocean winds from Atlantic hurricanes showing capping at ~2mm (Powell *et al*., 2003)

Some recent measurements using LIDAR profilers from three platforms, experiencing storms in the Gulf of Mexico, for heights above the surface of 60 to 160m, were described by Das *et al*. (2022). Some of the measured mean wind speeds at platform height exceeded 30 m/s. The mean wind profiles matched the logarithmic form, as used by both the ISO and API tropical cyclone models, quite well.

3. Turbulence intensities

The heights of some offshore structures, such as flare towers and the new generation of offshore wind turbine towers, are now approaching 200m above the surface. These are clearly dynamically wind-sensitive structures, for which along-wind buffeting by turbulence is a design consideration. Knowledge of the profiles of longitudinal turbulence intensity is therefore of some importance.

The turbulence intensity in an atmospheric boundary-layer over any surface is closely related to the surface roughness (C_d and z_o) and thus, in the case of winds over the ocean, is a function of mean wind speed. 'Capping' of the turbulence intensities at a mean wind speed in the range of 20-30 m/s, as with surface roughness, is also expected to occur.

Figure 2 shows measured values of longitudinal turbulence intensity at heights of 46 metres $\pm$ 13m above the surface, as a function of the mean wind speed at 10m, $\overline{U}_{10}$. These include some high-quality data from Frøya, but those were limited to values of mean wind speed of 26 m/s, as discussed in the previous section. Also shown are some unpublished values of lesser quality from the decks of oil or gas platforms in hurricanes. Also shown in Figure 2 is an empirical function from the ISO Metocean Standard (2015), in Equation (4), in which the height, z, has been taken as 46m.

$$I_u = 0.06[1 + 0.043\bar{U}_{10}](\frac{z}{10})^{-0.22} \tag{4}$$

As Eq. (4) is based on the Frøya data, it is a good fit to that data over the wind speed range of the measurements of 10 to 26 m/s. While there is some indication of 'saturation' or 'capping' above 28 m/s, the scatter in the data from the platforms does not allow definitive confirmation of this.

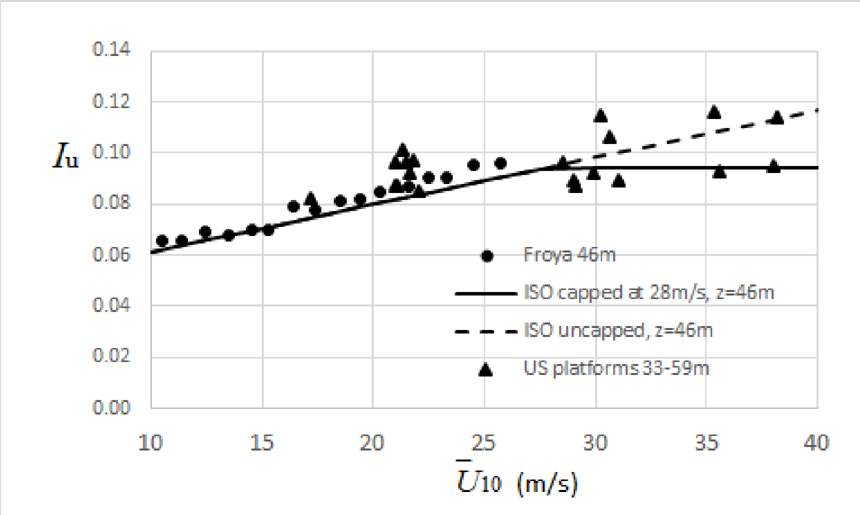

Figure 2. Longitudinal turbulence intensity as a function of mean wind speed (z= 46m ± 13m)

Figure 3 shows the available data on longitudinal turbulence intensity for mean wind speeds greater than 28 m/s, plotted against height above the surface. As well as the scattered data from the offshore platforms, values derived at 10m from 3sec/10 minute gust factors, recorded by the Bureau of Meteorology during Cyclone 'Yasi' (Holmes, 2017), are also shown in Figure 3.

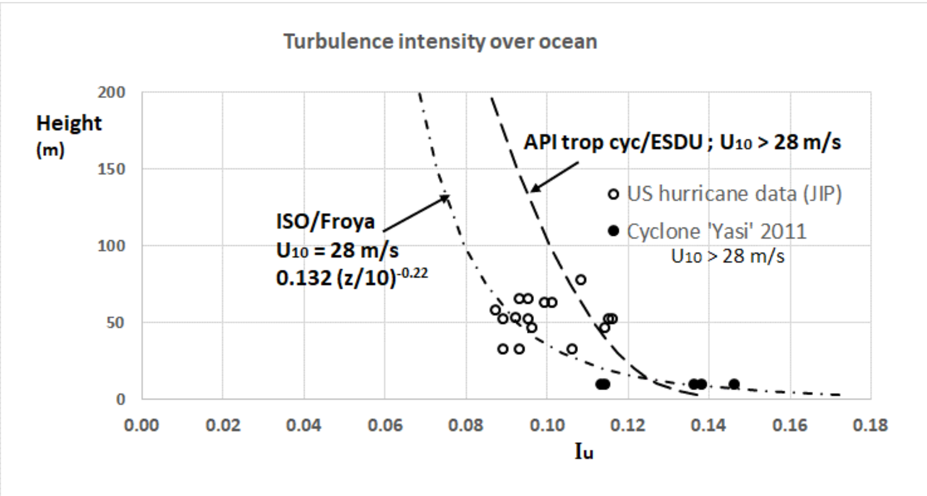

Figure 3. Longitudinal turbulence intensity profile for mean wind speeds greater than 28 m/s

Figure 3 shows the ISO profile based on the Frøya data of Equation (4), with the mean wind speed, $\bar{U}_{10}$, set equal (or 'capped') at 28 m/s. The fit is reasonable allowing for the scatter in the data.

Also shown in Figure 3 is the profile from the recent API Recommendations (2021) for 'tropical cyclones', ($\overline{U}_{10}$ > 28 m/s). Although this was nominally based on platform data (i.e. the open circles), it appears to be too high with respect to the data. The function is, in fact, based on one from an ESDU data item, which in turn was derived from the Deaves and Harris (1978) model for over-*land* winds, at much higher latitudes than those where tropical cyclones occur. Gradient heights from those models are also unrealistically high for lower latitudes. Hence the 'capped' ISO function based on the Frøya data is the preferred one for longitudinal turbulence intensities at design wind speeds.

Turbulence intensity measurements were also included in the recent measurements in the Gulf of Mexico described by Das *et al*. However, these data have not been plotted here, as there is some question about the errors resulting from the spatial resolution and effective averaging times resulting from use of the LIDAR profilers.

3. Turbulence spectra

The Frøya data included spectral densities of the longitudinal turbulence component (Andersen and Lovseth, 2006) – with particular emphasis on the low-frequency end, to cover the natural frequencies of tension leg platforms in deep water. These generally showed more low-frequency content, with larger turbulent length scales, compared to over-land winds. A complex function was fitted to the Frøya spectra, limited to the frequency range 0.00167 Hertz to 0.5 Hertz; this function appears in the ISO Metocean Standard (2015).

The recent API Recommendations (2021) for tropical cyclones uses the von Karman form with an integral length scale given by Eq. (5).

$$L_u = \frac{50\, z^{0.36}}{{z_o}^{0.063}} \qquad (5)$$

Equation (5) was derived from a similar empirical form in an early ESDU Data Item, with the 'constant' of 50 replacing 25 used by ESDU. The von Karman form, widely used in fluid mechanics and wind engineering (including in AS/NZS1170.2), with length-scale adjustment to match the available data, is the preferred form for over-ocean winds.

4. Discussion and Conclusions

This paper has reviewed available information on strong winds over the open oceans, with some emphasis on data and methods used by the offshore petroleum industry. Since about 1980, it has become very clear that 'saturation' or 'capping' of the surface roughness and turbulence intensity occurs at a mean wind speed at 10-metres height in the range of 20-30 m/s. This is convenient for structural design as it allows for invariant roughness lengths, surface drag coefficients, mean velocity and turbulence intensities to be assumed in the design range of wind speed. In fact, the recent change to AS/NZS1170.2 (Standards Australia, 2021), which designates over-water winds as Terrain Category 1, looks like a good decision, as the roughness length of 2 mm is very close to the observed 'saturation' values. It is also very clear that applying profiles and turbulence data from over-land winds to over-water situations is problematic, and will likely lead to significant errors.

The physical reasons for the 'capping' or 'saturation' phenomenon have yet to be explained satisfactorily. There appear to be two current explanations:

- At high wind speeds the 'tops of the waves are blown off…'. While this is a qualitative explanation, it may be supported by photographs from aircraft flights into hurricanes, which show large areas of relatively flat white water surface in the regions of maximum wind.

- Steep waves moving at a slower rate than the wind speed, act as bluff bodies with separated and reversing flow, with effectively negative contributions to the surface shear stress in between the travelling waves. This explanation was supported by laboratory experiments in a large wave tank, (Donelan *et al*., 2004).

These two explanations seem to be incompatible with each other, and clearly more research is required on the phenomenon.

The model of ocean wind and turbulence profiles in the ISO Metocean Standard (2015) has not yet recognized the capping or saturation of roughness and turbulence, even though it was apparent in the Frøya data, on which the Standard is based. However, this is likely to be a subject for revision in the next edition of that Standard. The 'tropical cyclone' model of the American Petroleum Institute (2021) *has* recognized the saturation phenomenon for wind speeds at 10 m height greater than 28 m/s, for both surface roughness and turbulence. However, the turbulence intensity profile in that model was derived from unrepresentative over-land winds (via ESDU and Deaves/ Harris); the expression is unnecessarily complex, and over-predicts the available data for over-ocean winds.

It is clear that reliable experimental data for *strong* winds over the ocean at greater than 26 m/s is lacking. A re-run of the good-quality Frøya experiments for a higher speed range would be very desirable.

The current push for large offshore windfarms, in Australia and elsewhere, with tall supporting towers for wind turbines (maximum of 199m at present), should take account of knowledge gained on strong winds over the ocean and reviewed in this paper.

References

American Petroleum Institute (2021), "Derivation of Metocean design and operating conditions", ANSI/API Recommended Practice 2Met, January 2021.

Amorocho, J., DeVries, J.J., 1980. A new evaluation of the wind stress coefficient over water surfaces. *Journal of Geophysical Research*, 85:433-442.

Andersen O.J., Lovseth, J., 2006. The Frøya database and maritime boundary layer wind description. *Marine Structures*, 19:173-192.

Charnock, H., 1955. Wind stress on a water surface. *Quarterly Journal Royal Meteorological Society*, 81:639-640.

Das, S., Maroju, S.S., Fan, S., Leung, P., Zwissler, C. (2022), Wind profile and structure during severe storms in the Gulf of Mexico. *41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2022)*, Hamburg, Germany, June 5-10, 2022.

Deacon E.L., Sheppard C., Webb, E.K., 1956. Wind profiles over the sea and the drag at the sea surface. *Australian Journal of Scientific Research, Series A: Physical Sciences,* 9:511-541.

Deaves D.M., Harris, R.I. (1978), "A mathematical model of the structure of strong winds", CIRIA Report 76.

Donelan, M.A., Haus, B.K., Reul, N., Plant, W.J., Stiassnie, M., Graber, H.C., Brown, O.B, Saltzman, E.S., 2004. On the limiting aerodynamic roughness of the ocean in very strong winds. *Geophysical Research Letters,* 31:L18306.

Holmes, J.D. (2017), Roughness lengths and turbulence intensities for wind over water. *9th Asia-Pacific Conference on Wind Engineering*, Auckland, New Zealand, Dec 3-7, 2017.

International Organization for Standardization (2015). "Petroleum and natural gas industries – specific requirements for offshore structures. Part 1. Metocean design and operating conditions", International Standard, ISO 19901-1, 2015.

Powell M.D., Vickery, P.J, Reinhold, T.A., 2003. Reduced drag coefficients for high speed winds in tropical cyclones. *Nature*, 422:279-283.

Standards Australia, (2021), "Structural design actions. Part 2 Wind actions", Australian/New Zealand Standard, AS/NZS 1170.2:2021.