GL Garrad Hassan

TECHNICAL NOTE

Title	**Preliminary Turbulence Intensity and Wind Analysis at the Proposed Wainfleet Wind Project**
Client	**Wainfleet Wind Energy Inc.**
Contact	**Jordan Beekhuis**
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Revision	Date	Summary
A	13 June 2013	Original issue
B	23 August 2013	Updated to include expanded scope
C	29 August 2013	Minor edits

1 INTRODUCTION

Wainfleet Wind Energy Inc. (the "Client") is developing the Wainfleet Wind Project (the "Project") in Wainfleet Township, Ontario. The Project is located approximately 1.5 km west, at its closest point, from a skydiving facility (the "Facility"). The Client has requested that GL GH undertake an analysis of wind data statistics based on measurements recorded by a nearby measurement mast, including turbulence intensity and directional wind frequency predicted for the Project site. The scope of work is limited to a review and analysis of the Project wind data, and does not consider or make conclusions with respect to potential impacts of the proposed Project on the Facility. The results of the work are presented herein.

2 WIND ROSE, TURBULENCE INTENSITY AND WAKES

Several commonly-used wind energy terms are discussed in this brief technical note, which are defined and described below:

Wind Rose: A diagram indicating the average percentage of time that the wind blows from each direction sector. Wind roses are either presented as a "wind speed and direction frequency distribution" (see Figure 8 for an example) or as a "wind direction frequency distribution" (see Figure 9 for an example).

Wakes: An operating wind turbine creates a disturbance in the atmosphere known as a wake. The wake of a wind turbine is characterized by a downwind region of decreased mean wind speed and increased turbulence, as seen in Figure 1. GL GH uses the Eddy Viscosity wake model to predict the wind speed and turbulence intensity throughout the wake region. Additional information on wind turbine wakes can be found in the WindFarmer Theory Manual [1].

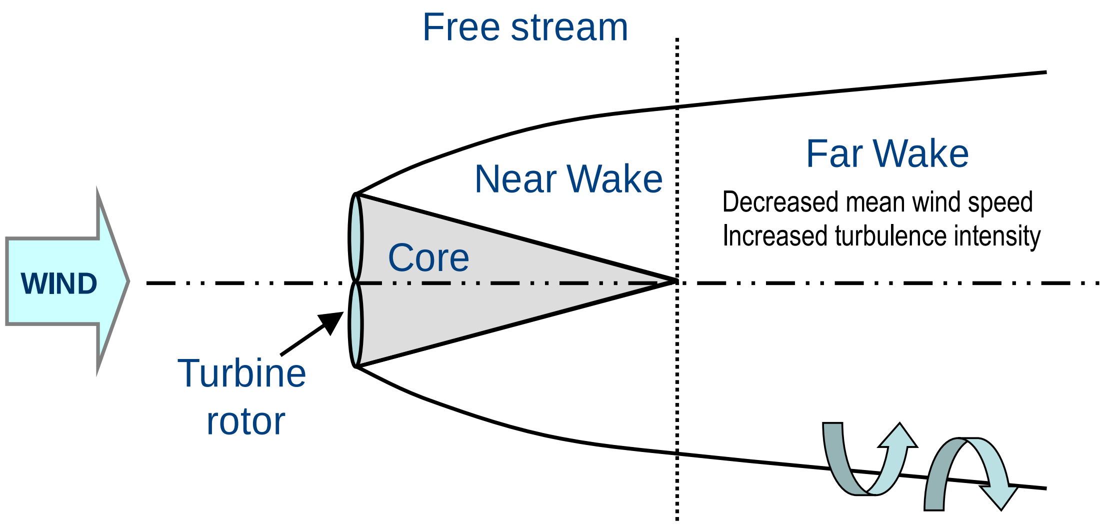

Figure 1 The wake of a wind turbine is divided into Near Wake and Far Wake.

The wake is assumed to spread equally in the horizontal and vertical directions. The EV wake model has been thoroughly validated by GL GH [2]. The wind speed in the near and far wakes of a single wind turbine are shown in Figure 2, as predicted using the EV model. In Figure 2, blue wind speeds represent free stream (in m/s), while waked wind speeds are presented in red. The wake width increases with downwind distance, while the magnitude of the wake effects decrease. The wake width at any downwind position is a function of the distance downwind, the turbine's thrust coefficient, and the ambient turbulence intensity [1]. GL GH has used site specific predicted values when modeling turbine wakes at the Wainfleet site.

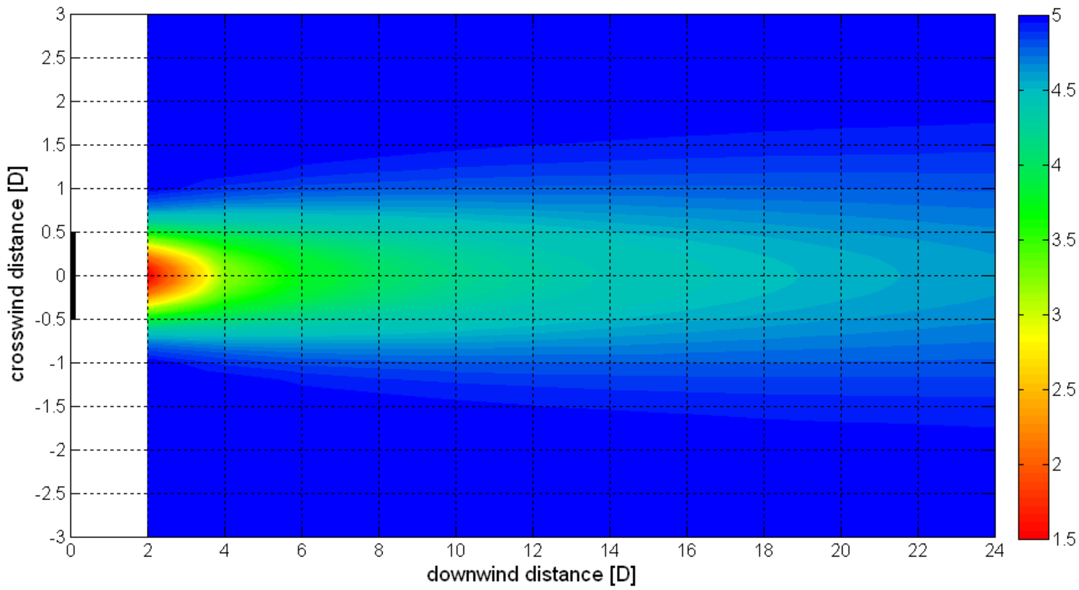

Figure 2 Wind speed behind a single turbine modelled with the Eddy Viscosity model.

Additional information on wind turbine wakes can be found in the WindFarmer Theory Manual [1] and the WindFarmer Validations Report [2].

Turbulence Intensity: In the field of wind power, fluctuations of the air flow in the seconds range around a 10-minute mean wind speed value are designated as turbulence intensity. The turbulence intensity, ***TI***, is expressed as a percentage, and defined as the ratio of the standard deviation ***σ*** of the wind speed to its mean value ***Uav***:

$$TI = \sigma / Uav$$

In this technical note, ambient (or “free steam”) turbulence intensity, as well as wake-induced (or “incident”) turbulence intensity are both discussed. Ambient turbulence intensity refers to the turbulence intensity associated with flow undisturbed by the presence of wakes from wind turbines, while wake-induced turbulence intensity refers to turbulence intensity which includes the presence of turbine wakes.

3 WIND DATA

GL GH has based the wind data analysis required for this study on wind speed and turbulence intensity data and statistics from a previously completed energy assessment applicable to this Project location [3]. The data period considered ranges from September 2002 to May 2004.

The resulting period of valid data available for the assessment of turbulence intensity at the Wainfleet Wind Project and surrounding area is presented in the table below:

Mast ID	Easting [m][1]	Northing [m][1]	Measurement Height [m]	Available Period [years]	Valid Period [years]	Data Coverage [%]
RC22502	632180	4747976	50	1.7	1.6	93

Note 1: UTM Zone 17T, NAD83 datum

It is noted that the assessment methodology used for obtaining the long-term wind speed has not been updated since the previous analysis, and should therefore be treated as preliminary, as GL GH methodologies have advanced since that assessment was completed. However, this point is not considered to have a significant impact on this assessment.

Reanalysis data from NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA) database have also been retrieved for use in this study, in order to check that wind direction distribution statistics generated for the site are representative of a longer reference period. This is considered to be a good sanity check on the site wind data considered, and was also necessary to assess how the predicted wind rose for the project varied over long-term expectations when data were filtered for specific periods (described further in Section 4.2). GL GH procured an hourly time series of reanalysis data, at a surface height of 50 m for a single grid point near the Project, as presented in the table below:

Grid Point	Easting [m][1]	Northing [m][1]	Height [m]	Distance From Site	Begin Date	End Date
MERRA 43N 79.3W	635851	4762162	50	15 km north	January 2000	June 2013

Note 1: UTM Zone 17T, NAD83 datum

The MERRA data retrieved were considered only in the wind direction analysis (Section 4.2) and were not used to generate turbulence intensity statistics.

4 METHODOLOGY AND RESULTS

4.1 Turbulence Intensity as a Function of Wind Speed

As discussed in Section 2, fluctuations of the air flow in the seconds range around a 10-minute mean wind speed value are designated as turbulence intensity. Ambient and wake-induced turbulence intensity statistics have been calculated and modeled for key wind direction and wind speeds for the Project, for several points of interest identified by the Client [4].

It is noted that the wake-induced (or "incident") turbulence in GL GH WindFarmer software is calculated using an empirical characterization developed by Quarton and Ainslie, which enables the added turbulence in the wake to be defined as a function of ambient turbulence, the turbine thrust coefficient, the distance downstream from the rotor plane, and the length of the near wake [1].

To assess the variation in ambient and wake-induced turbulence intensity across the area of interest, specific points of interest have been modeled between the Project and Facility, and several kilometers past the Facility. The Client provided GL GH with the turbine layout and a list of key points of interest to consider in this analysis, as shown in Tables 1 and 2, on the following page.

Turbine ID	Easting [m][1]	Northing [m][1]
WTG1	631359	4751252
WTG2	631758	4750750
WTG3	631911	4750551
WTG4	632750	4748389
WTG5	632706	4748817

Note 1: UTM Zone 17T, NAD83 datum

Table 1 Turbine Layout for the Wainfleet Wind Project

Points of Interest	Easting [m][1]	Northing [m][1]
Nearest Wind Turbine (WTG4)	632750	4748389
<1% difference in TI	*Based on Modelling*	
10x Turbine Height	634200	4748650
Skydive Boundary, West	634250	4748650
Skydive Boundary, East	634750	4748650

Note 1: UTM Zone 17T, NAD83 datum
Note 2 : TI difference [%] = wake-induced [%] – ambient [%]

Table 2 Key Points of Interest for Turbulence Intensity Modelling

The nearest wind turbine from the Project, with respect to the Facility, is WTG4, at approximately 1.5 km to the western boundary of the Facility. The Client has also requested turbulence intensity calculations for 10x the total turbine obstacle height (ie. hub height + rotor radius), which the Client has identified as a standard used by skydivers for avoiding turbulence [4]. Other key points include the Facility boundaries, as well a single reference point, representing differences between wake-induced and ambient turbulence intensity:

Note: TI difference [%] = wake-induced TI [%] – ambient TI [%]

These values were chosen to demonstrate the level of wake-induced turbulence dissipation as a function of distance from the Project. It is noted that GL GH does not consider there to be any specific physical phenomena associated with wake-induced to free stream differences of less than 1%; this difference is illustrated to serve as a reference point on the plots in Figures 3 to 7. GL GH notes that the turbulence intensity calculations presented herein are based on the mean turbulence intensity derived from a large number of 10-minute averages. For any particular period of 10 minutes the value can and will deviate from the statistical mean. The mean turbulence intensity does exclude consideration of fluctuations which may occur at a higher temporal resolution and does not represent situations with atmospheric conditions that may be especially favourable to wake persistence, such as stable flow.

The wind turbine model considered for the wind farm is the Vestas V100-1.8MW at 95 m hub height, for which information was provided by the Client. GL GH has modeled the ambient and wake-induced (or "incident") turbulence intensity from the Project on the points of interest east of the wind farm using the GL GH WindFarmer wind farm design software. The ambient and incident turbulence at each location was calculated and compared, to determine the magnitude of deviation from ambient conditions at each point. Given the location of the Facility, which is located east of the proposed wind farm, and based on input from the Client [4], GL GH has calculated the turbulence intensity from the western direction sectors only (260-deg to 280-deg). Winds from these sectors represent approximately 14% of all winds annually (see Section 4.2 for more detail).

It is noted that turbulence intensity changes as a function of wind speed. The Client has requested that GL GH calculate ambient and wake-induced turbulence intensity statistics for wind speed bins which it deems to be of interest to the operation of the Project and Facility. Specifically, the Client has requested that GL GH model turbulence intensity statistics for the following wind speed bins:

- **3 m/s** – corresponding to the cut-in wind speed of the turbine considered for the Project;
- **5 m/s** – corresponding to the maximum canopy height wind speed for "night and water jumps" according to the Client [4];
- **7 m/s** – corresponding to the maximum canopy height wind speed for "student parachutists" according to the Client [4];
- **9 m/s** – corresponding to the maximum canopy height wind speed for "Solo, A&B CoP holders" according to the Client [4]; and
- **11 m/s** – corresponding to the maximum canopy height wind speed for "C&D CoP holders" and "tandem jumps" according to the Client [4].

GL GH has calculated all average turbulence intensity statistics presented herein at the hub height of the Project's turbines (95 m). No analysis has been undertaken to correlate between "canopy height" winds, which are considered in skydiving, and winds at hub height. The results are presented graphically in Figures 3 to 7.

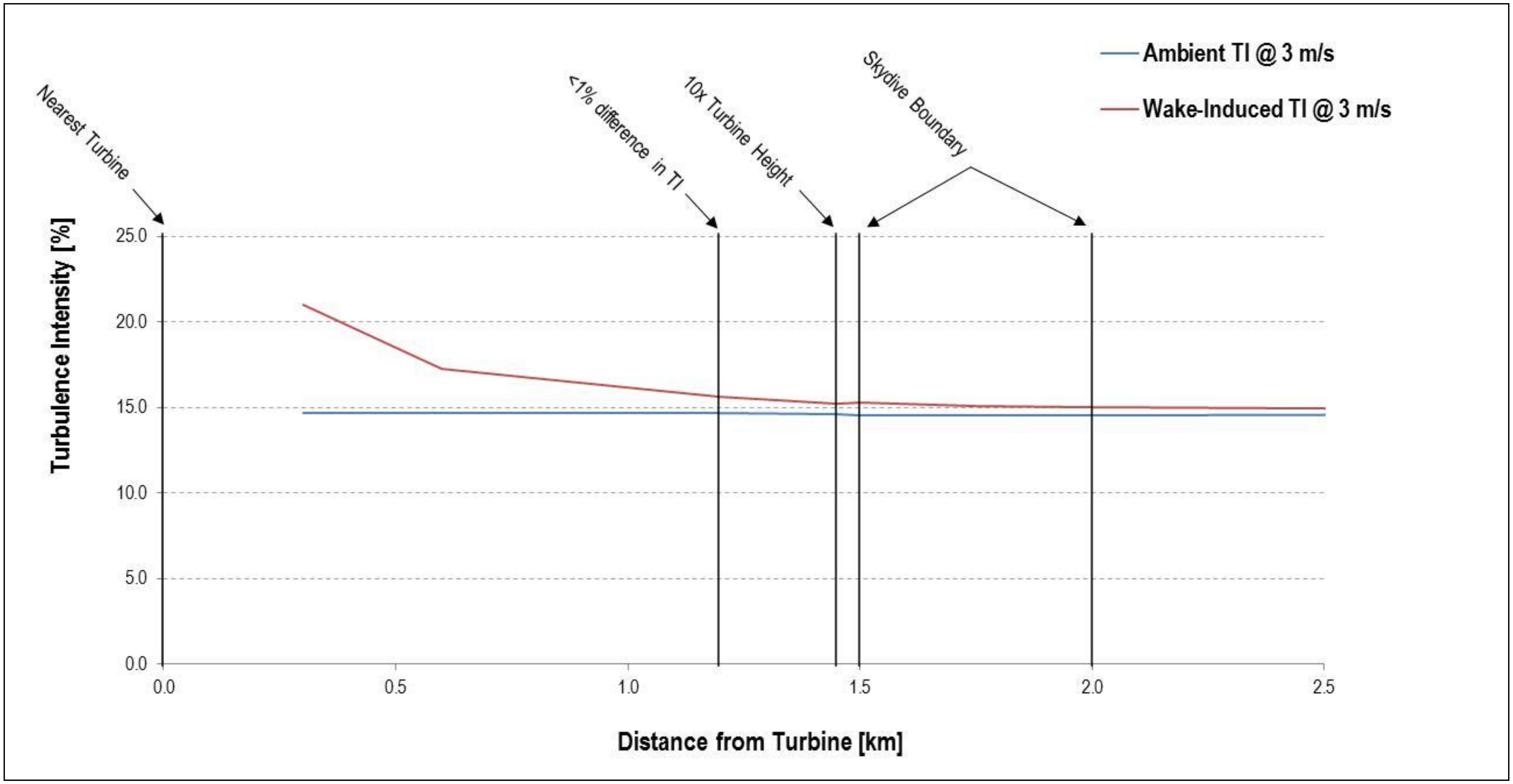

Figure 3 Ambient and Wake-Induced Turbulence Intensity Statistics at Points of Interest as a Function of Distance from Wind Farm, 3 m/s

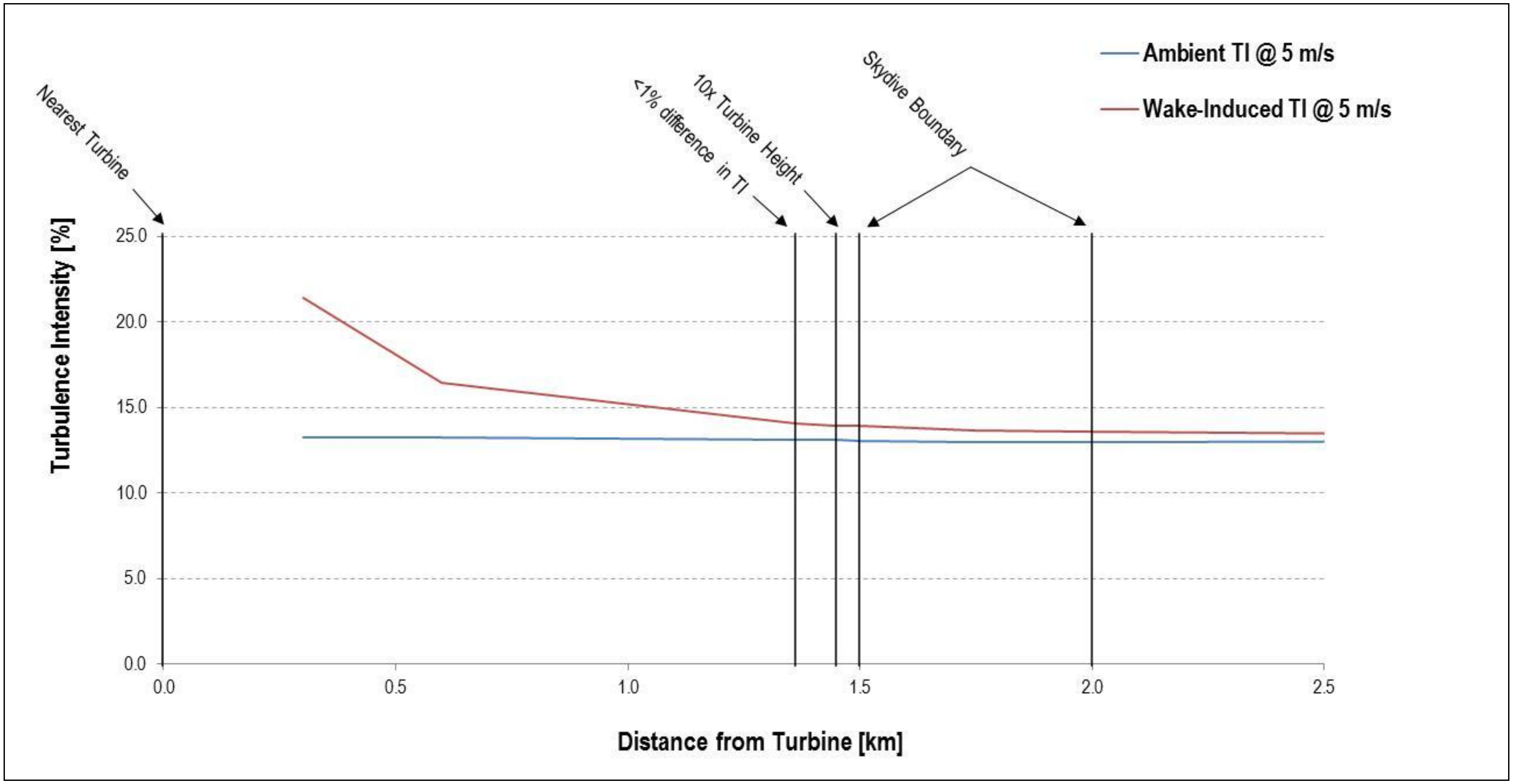

Figure 4 Ambient and Wake-Induced Turbulence Intensity Statistics at Points of Interest as a Function of Distance from Wind Farm, 5 m/s

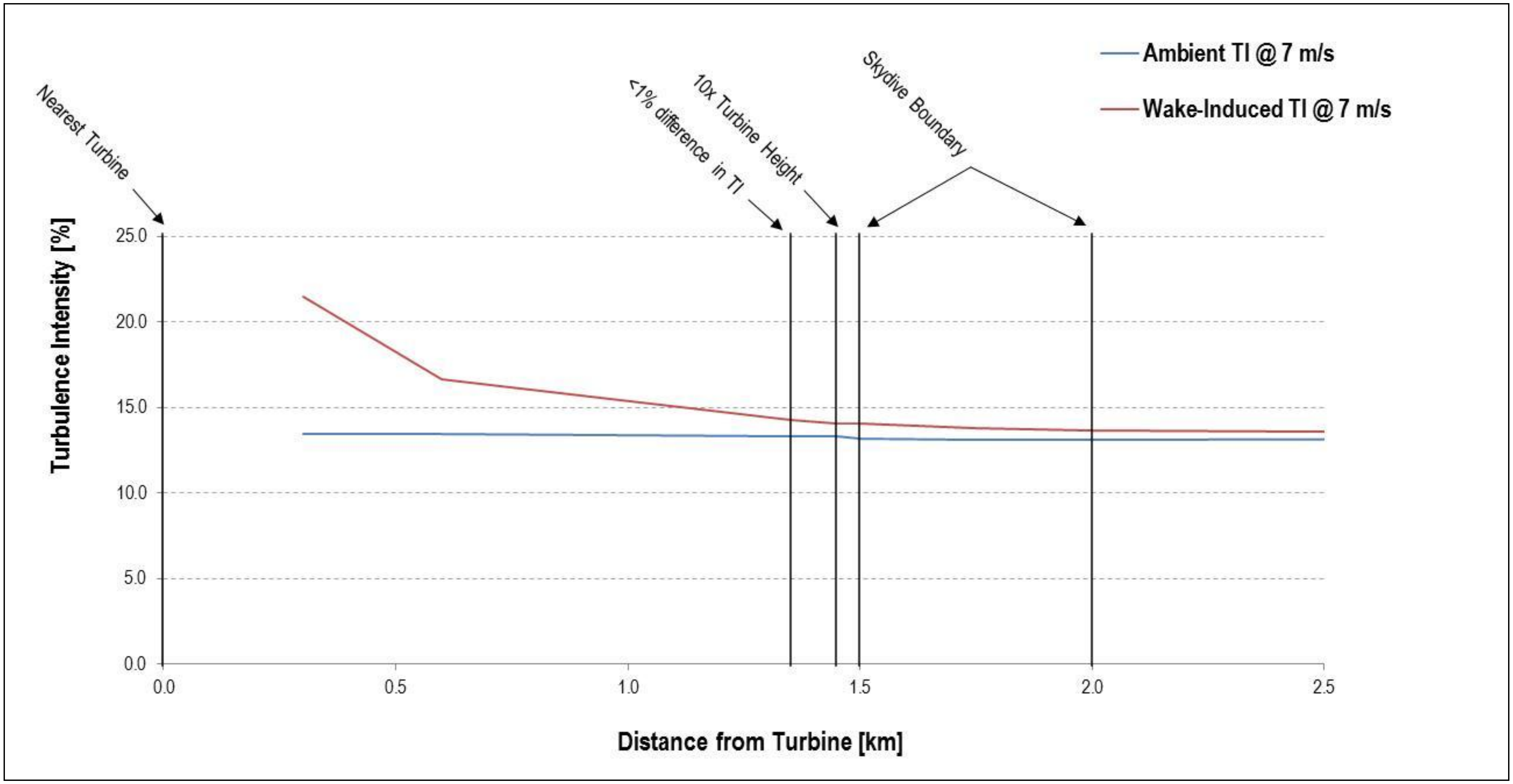

Figure 5 Ambient and Wake-Induced Turbulence Intensity Statistics at Points of Interest as a Function of Distance from Wind Farm, 7 m/s

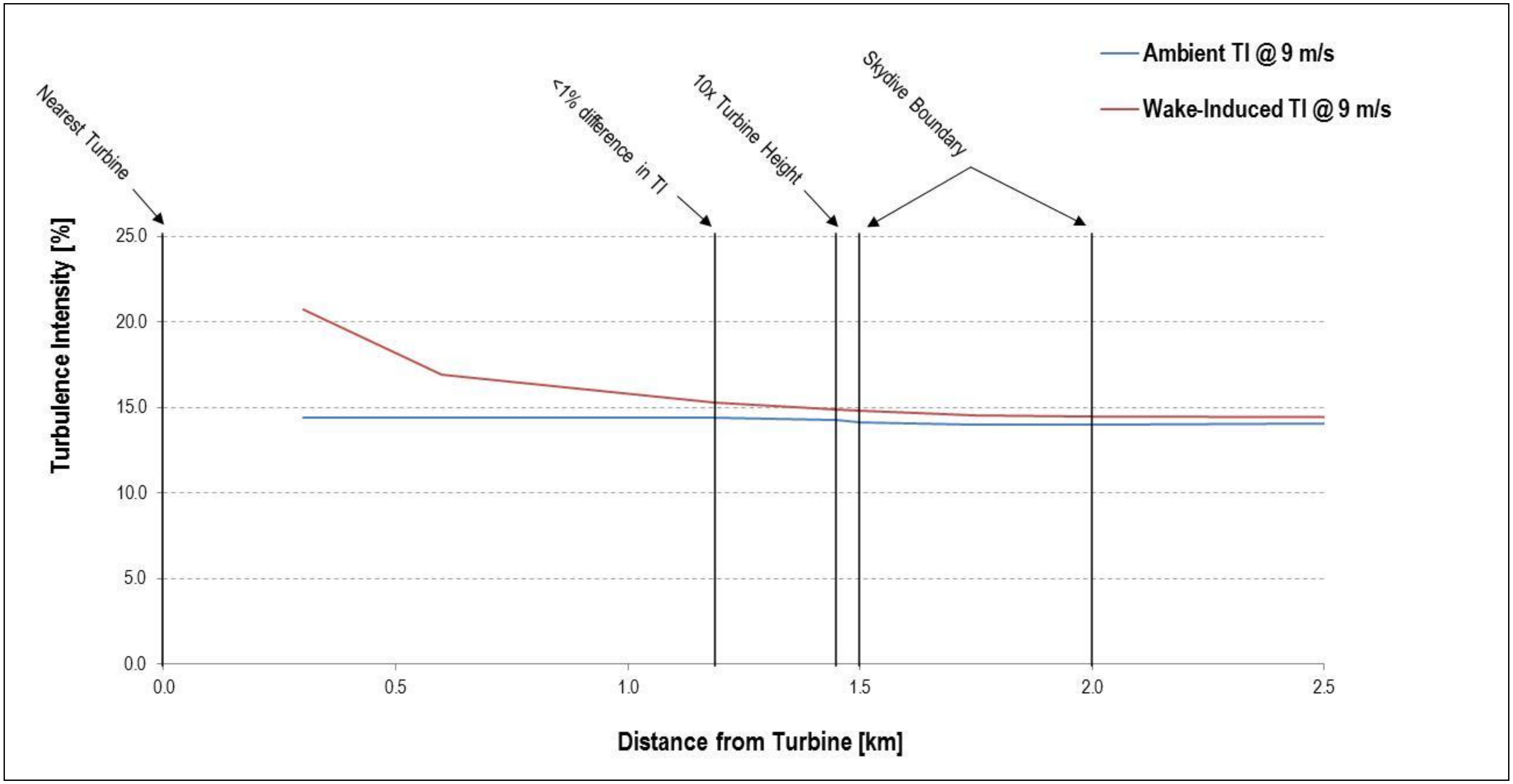

Figure 6 Ambient and Wake-Induced Turbulence Intensity Statistics at Points of Interest as a Function of Distance from Wind Farm, 9 m/s

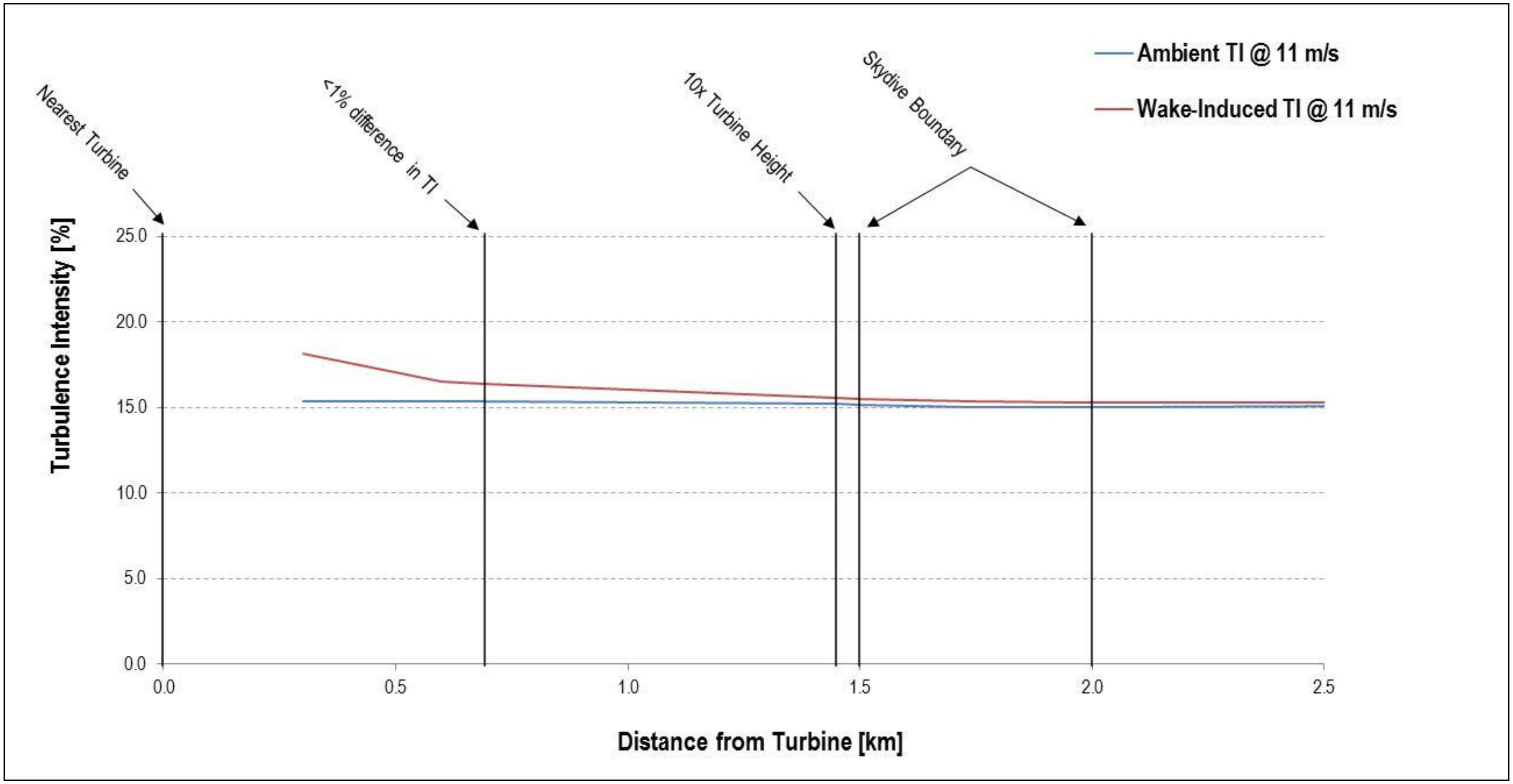

Figure 7 Ambient and Wake-Induced Turbulence Intensity Statistics at Points of Interest as a Function of Distance from Wind Farm, 11 m/s

4.2 Wind Direction Frequency Analysis

At the Client's request, GL GH has analyzed the wind direction frequency predicted for the Project to help provide a better understanding of the frequency with winds are expected to originate from each direction sector. Specifically GL GH has undertaken a high-level analysis of the wind direction frequency distribution expected for the Project as follows:

- Long-term annual average conditions for all wind speeds;
- Long-term annual average conditions for the wind speed range of interest to the client (3 – 11 m/s);
- Long-term conditions for the skydiving season, defined by the Client to range between Easter and Halloween [4], for all wind speeds; and
- Long-term conditions for the skydiving season, defined by the Client to range between Easter and Halloween [4], for the wind speed range of interest to the client (3 – 11 m/s);

As the wind data available from Mast RC22502 contains less than 2 years of valid data, GL GH has undertaken a high-level analysis to determine whether the shape of the wind rose represented by the mast is representative of longer-term climatic conditions. This was especially important for the seasonal analysis requested, to assess how the wind direction frequency distribution was expected to change between Easter and Halloween, as compared with the whole year.

To test this, GL GH created a wind rose based on concurrent data from the MERRA grid point, and compared it with the wind rose calculated for Mast RC22502 for the same period. If the MERRA data is a good representation of the mast data, then it should be expected that they would have similar wind roses for the concurrent period. The comparison, presented in Figure 8, suggested that the wind roses are, in fact, similar for the exact same period. The check also showed that each concurrent wind rose was similar to the wind rose associated with the full historical period of record at the MERRA grid point (13.5 years), meaning that each is also generally representative of long-term conditions. In other words, the wind speed and direction distribution of the MERRA wind data can also be considered a good representation of the onsite mast, and is therefore suitable for use as the basis for a long-term understanding of the wind direction distribution.

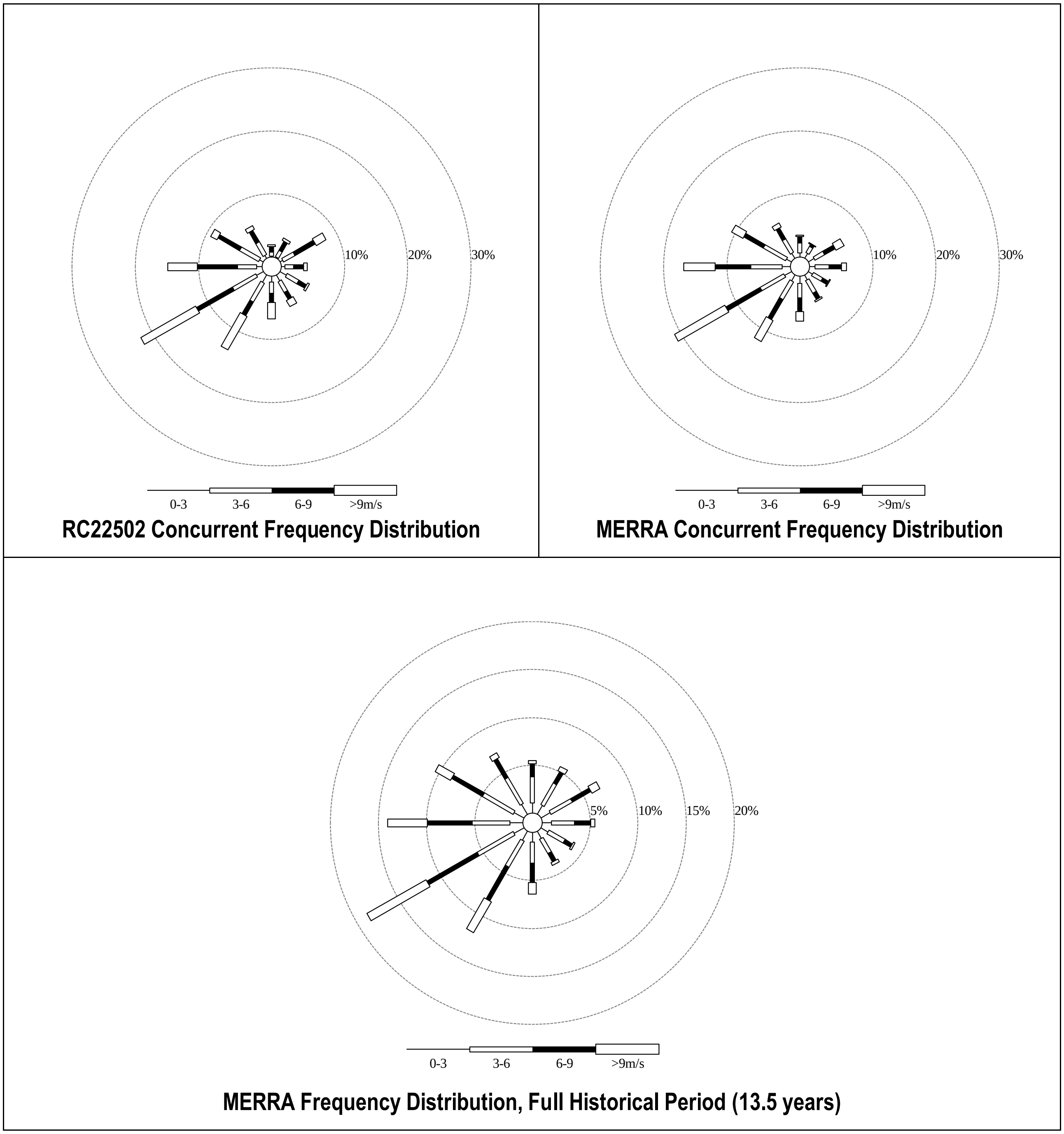

Figure 8 Comparison of Concurrent Wind Roses for Mast RC22502 and the MERRA Grid Point.

It is observed in Figure 8 that the wind direction distribution for the site is relatively omni-directional, meaning that winds originate for some not insignificant percentage of time from all direction sectors. That said, the wind rose does show a higher prevalence of wind from the southwest to west direction sectors, and smaller contributions from other sectors.

GL GH scaled the wind speed and direction presented in Figure 8, to be representative of predicted long-term wind speed conditions expected on site, based on the wind resource assessment completed in [3]. The wind rose derived was used to generate wind direction distribution statistics for two scenarios, presented graphically in Figure 9, and in tabular form in Table 3, as follows:

- For wind speeds ranging from 3 – 11 m/s; and
- Across all wind speed bins.

It is observed from Figure 9 that the wind rose represented by each scenario is virtually identical.

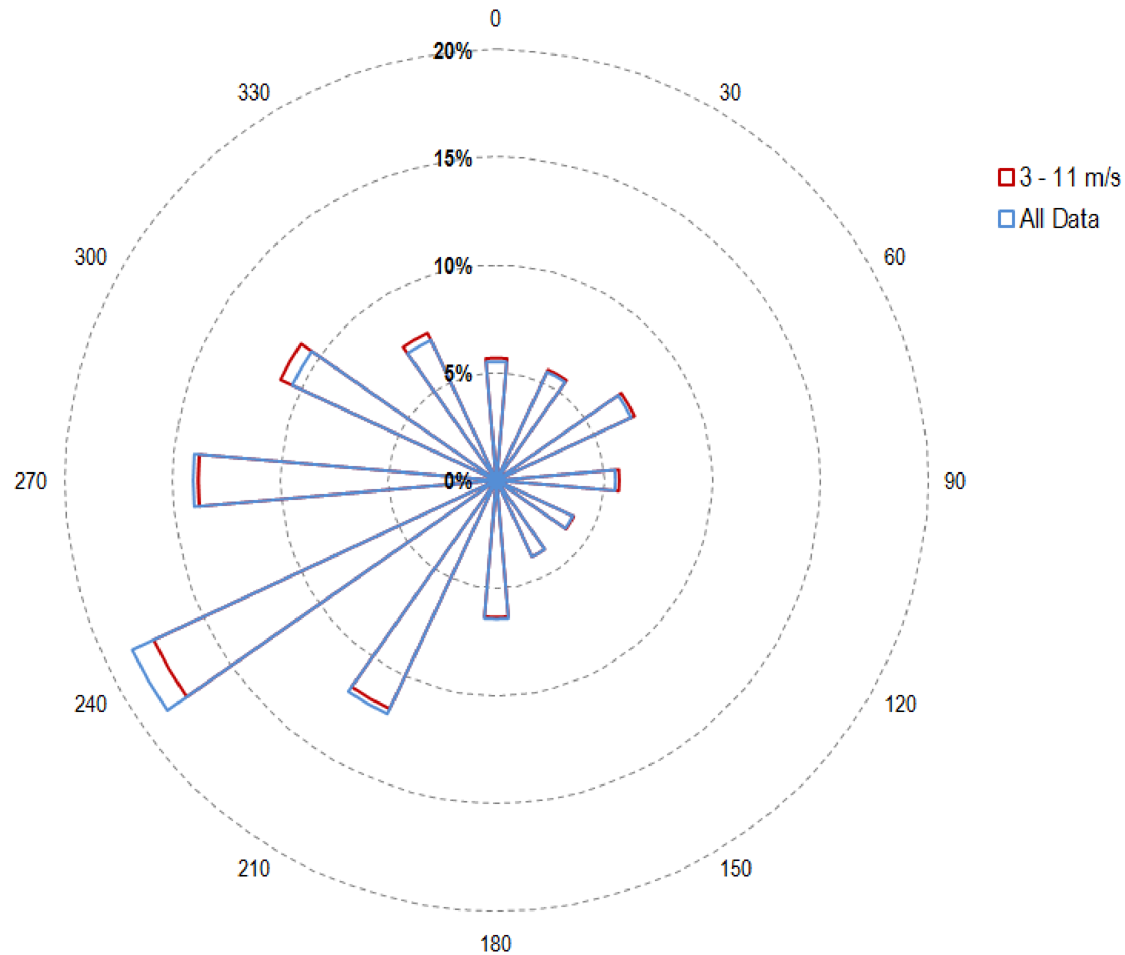

Figure 9 Predicted Long-Term Annual Wind Rose for the Wainfleet Project

Wind Speed	Direction Sector [deg]											
	0	30	60	90	120	150	180	210	240	270	300	330
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.3%	0.3%	0.2%	0.2%
2	0.5%	0.5%	0.5%	0.5%	0.4%	0.4%	0.4%	0.5%	0.5%	0.6%	0.5%	0.6%
3	0.7%	0.7%	0.7%	0.6%	0.5%	0.5%	0.6%	0.7%	0.8%	0.9%	0.8%	0.8%
4	0.9%	0.9%	0.8%	0.7%	0.8%	0.6%	0.7%	0.9%	1.2%	1.2%	1.1%	1.0%
5	1.0%	1.0%	0.9%	0.9%	0.7%	0.6%	0.8%	1.2%	1.6%	1.4%	1.3%	1.1%
6	0.9%	0.7%	1.0%	0.9%	0.5%	0.5%	0.8%	1.4%	2.0%	1.6%	1.6%	1.1%
7	0.5%	0.6%	0.9%	0.6%	0.3%	0.4%	0.7%	1.5%	2.2%	1.6%	1.4%	1.0%
8	0.3%	0.4%	0.6%	0.5%	0.2%	0.3%	0.6%	1.3%	1.9%	1.6%	1.1%	0.6%
9	0.2%	0.3%	0.4%	0.3%	0.1%	0.2%	0.5%	1.1%	1.9%	1.3%	0.8%	0.3%
10	0.1%	0.2%	0.3%	0.1%	0.1%	0.1%	0.3%	0.9%	1.7%	1.0%	0.6%	0.2%
11	0.1%	0.1%	0.2%	0.1%	0.0%	0.1%	0.2%	0.7%	1.3%	0.8%	0.4%	0.1%
12	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%	0.2%	0.6%	1.1%	0.6%	0.3%	0.1%
13	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.4%	0.8%	0.4%	0.1%	0.0%
14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.6%	0.3%	0.1%	0.0%
15	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%	0.2%	0.1%	0.0%
16	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.1%	0.0%	0.0%
17	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%
18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Frequency, 3-11 m/s [%]	6%	6%	7%	6%	4%	4%	6%	12%	18%	14%	11%	8%
Frequency, all data [%]	6%	6%	7%	6%	4%	4%	6%	12%	19%	14%	10%	7%

Table 3 Predicted Long-Term Annual Wind Rose for the Wainfleet Project

The Client has informed GL GH that skydiving tends to occur between Easter and Halloween, and has therefore requested that an analysis be undertaken to assess how the wind direction distribution predicted for that period compares to a full-year distribution. Consequently, GL GH has filtered out the wind speed and direction statistics for this period for every year in the 13.5 year MERRA dataset, to establish a wind rose for this specific period.

The wind rose derived was used to generate wind direction distribution statistics for two scenarios, presented graphically in Figure 10, and in tabular form in Table 4:

- For wind speeds ranging from 3 – 11 m/s; and
- Across all wind speed bins.

It is observed from Figure 10 that the wind rose represented by each scenario is virtually identical for both each wind speed scenario considered. Furthermore, it is noted that the wind rose is also virtually identical to the predicted distribution generated for the full seasonal period. In other words, it is expected that the annual wind direction distribution between Easter and Halloween will compare closely with the overall long-term annual distribution for the full year.

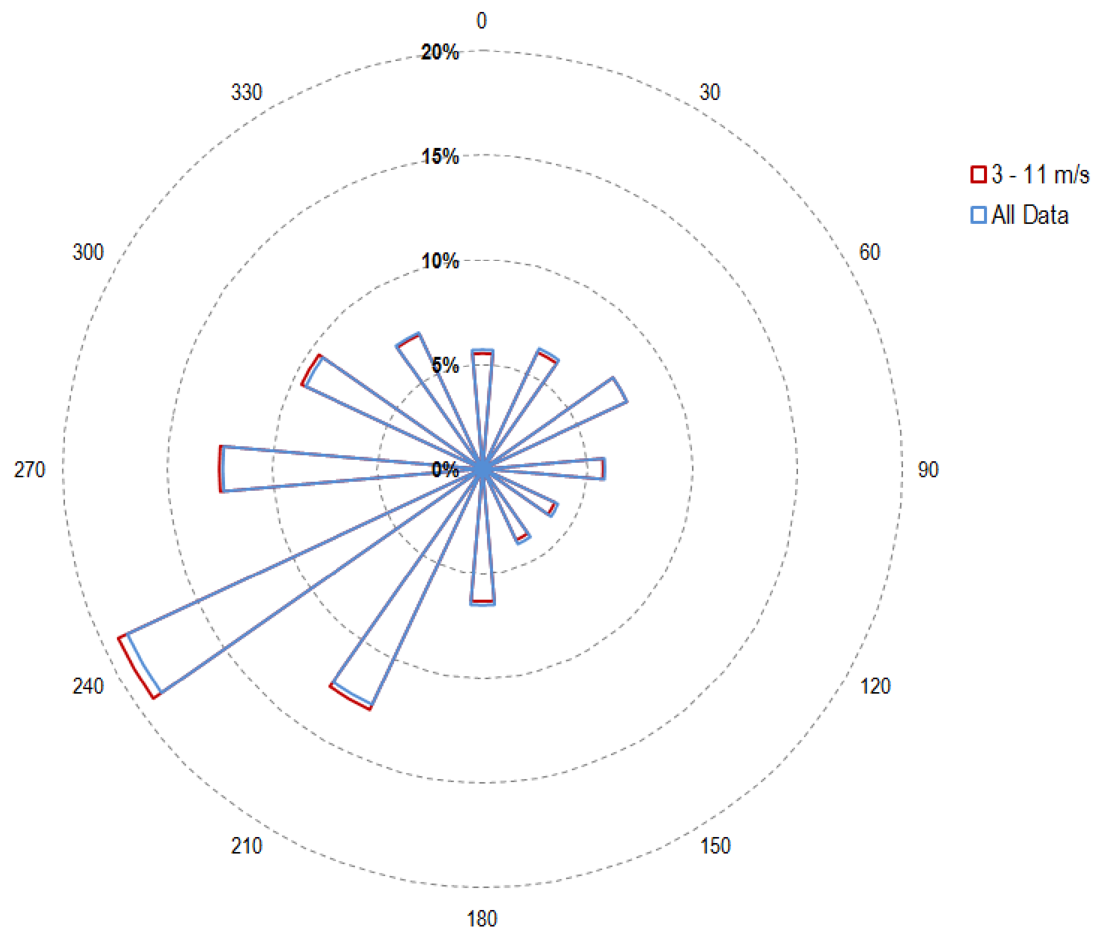

Figure 10 Predicted Annual Wind Rose for the Wainfleet Project from Easter to Halloween

Wind Speed	Direction Sector [deg]											
	0	30	60	90	120	150	180	210	240	270	300	330
0	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
1	0.3%	0.3%	0.3%	0.3%	0.2%	0.2%	0.3%	0.3%	0.3%	0.4%	0.3%	0.3%
2	0.6%	0.6%	0.6%	0.6%	0.4%	0.4%	0.5%	0.6%	0.6%	0.7%	0.7%	0.7%
3	0.9%	0.8%	0.9%	0.7%	0.6%	0.6%	0.7%	0.8%	1.0%	1.1%	1.0%	1.0%
4	1.0%	1.1%	1.0%	0.9%	0.9%	0.8%	0.9%	1.2%	1.5%	1.5%	1.3%	1.1%
5	1.1%	1.2%	1.2%	1.1%	0.8%	0.7%	1.0%	1.6%	2.2%	1.7%	1.5%	1.2%
6	1.0%	0.7%	1.2%	1.0%	0.5%	0.4%	0.9%	1.7%	2.6%	1.8%	1.7%	1.2%
7	0.5%	0.6%	1.0%	0.6%	0.3%	0.4%	0.7%	1.7%	2.7%	1.5%	1.2%	0.9%
8	0.2%	0.4%	0.6%	0.3%	0.1%	0.1%	0.6%	1.5%	2.2%	1.2%	0.7%	0.4%
9	0.1%	0.3%	0.4%	0.2%	0.1%	0.1%	0.4%	1.1%	1.9%	0.9%	0.4%	0.1%
10	0.0%	0.1%	0.2%	0.1%	0.1%	0.1%	0.2%	0.7%	1.5%	0.6%	0.3%	0.1%
11	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.1%	0.5%	0.8%	0.4%	0.1%	0.0%
12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.5%	0.2%	0.1%	0.0%
13	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.3%	0.1%	0.0%	0.0%
14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.1%	0.0%	0.0%
15	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
16	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
17	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Frequency, 3-11 m/s [%]	6%	6%	8%	6%	4%	4%	6%	13%	19%	13%	10%	7%
Frequency, all data [%]	6%	6%	8%	6%	4%	4%	7%	12%	19%	12%	9%	7%

Table 4 Predicted Long-Term Annual Wind Rose for the Wainfleet Project from Easter to Halloween

It is noted that the wind rose for the full annual period, and the period from Easter to Halloween, when skydiving is understood to occur at the facility of interest, are virtually identical over the 13.5 year period represented by the MERRA reanalysis data set considered.

4 CONCLUSIONS

GL GH has undertaken an analysis of wind data statistics based on measurements recorded by a nearby measurement mast, including turbulence intensity and directional wind frequency predicted for the Project site. The scope of work was limited to a review and analysis of the Project wind data, to provide a high-level understanding of how average turbulence intensity and wind direction frequency statistics vary in the vicinity of the proposed Wainfleet Wind Project, and a nearby skydiving Facility. No analysis was undertaken to assess the potential level of impact of the wind farm Project on the Facility, and no conclusions are made regarding safety. GL GH notes that the turbulence intensity calculations presented herein are based on 10-minute average turbulence intensity statistics and do not consider turbulence conditions which may occur at a higher temporal resolution, or in atmospheric conditions especially favorable to wake persistence, such as stable flow.

5 REFERENCES

1. WindFarmer V5.2 Theory Manual, Garrad Hassan & Partners Ltd., August 2013.
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