Engineering and Effective and Economic Measure of Atmospheric Stability

R. Cotton*
Strathclyde University
Glasgow, United Kingdom

Abstract

An investigation has been carried out to determine atmospheric stability in the context of wind energy. Assessment of various classification techniques was carried out using data collected on a 50m meteorological mast installed at the Myres Hill turbine test site near Eaglesham, Scotland. The campaign enabled various schemes which categorize atmospheric stability to be determined including Sigma Theta (Standard Deviation of Wind Direction) method, Solar Radiation Temperature Gradient method, Obukhov Length, Flux Richardson method and the Temperature Gradient method. The Obukhov Length was assumed to be most appropriate method to measure stability and was taken as the datum to which all other schemes were compared. The Flux Richardson method agreed closely with the Obukhov scheme across all wind speeds however all other schemes had significant disagreement particularly at low wind speeds.

Introduction

Knowledge of wind conditions across a site is very important for assessing wind energy resource and turbine suitability. Typically, measurements are taken at discrete points in space by mast mounted in-situ instruments and extrapolated to characterise the site. This extrapolation process can be carried out in various ways using flow models (linear, non-linear, empirical etc). A fundamental assumption of this modelling is that flows are not affected by atmospheric stability, which is not always the case and it is anticipated that by factoring in a stability-related correction, improvements can be made to the model. Examples of situations where this neutral assumption is not appropriate include low wind speed sites with high solar insolation, and very cold sites where little surface heating exists. At some sites it is observed that stability rarely approaches neutral conditions and it is within this area that the motivation for this work lies.

Atmospheric stability can be thought of as a condition of the surface layer which influences turbulence behaviour and eddy size. Where warm air exists above cold surface air, the atmosphere acts to suppress turbulence intensity and is termed stable. Conversely warm air at the surface will rise buoyantly thought the atmosphere to achieve thermal equilibrium. This convective process will induce large recirculations and heighten turbulence intensity and is known as unstable. When stability is considered to have little influence on turbulence the atmosphere is said to be neutral.

There are various stability corrections to some flow models however these are considered 'make-shift' and as such a more robust measure is sought.

Methods

Schemes selected to measure stability included:

- Temperature Gradient Method
- Solar Insolation and Wind Speed Method (SRdt)
- Standard Deviation of Wind Fluctuation Method (Sigma Theta)
- Flux Richardson Number
- Obukhov Length.

Fig 1 shows the installation configuration to satisfy the measurement criteria for each stability scheme. In addition to this non-essential instrumentation was installed such as rain gauge, naturally aspirated temperature probes etc which allowed performance analysis to be carried out with a view to optimising the system in future campaigns.

Logging of data was made by way of 2 independent data loggers which synchronised clocks twice daily. Data was recorded at 1 minute averages and processed in MS Excel. In all the data gathered encompassed approximately 5 months between April and September 2009.

The site was a turbine test facility and as such 'noise' could be seen in the data from the surrounding instalments. The terrain was reasonably flat and the mast situated away from any inclined topography to the south west corner of the site, as shown in Fig 2.

* Author Address: Richie Cotton, Department of Mechanical Engineering, University of Strathclyde, Glasgow G1 1XJ email: richie.cotton@strath.ac.uk

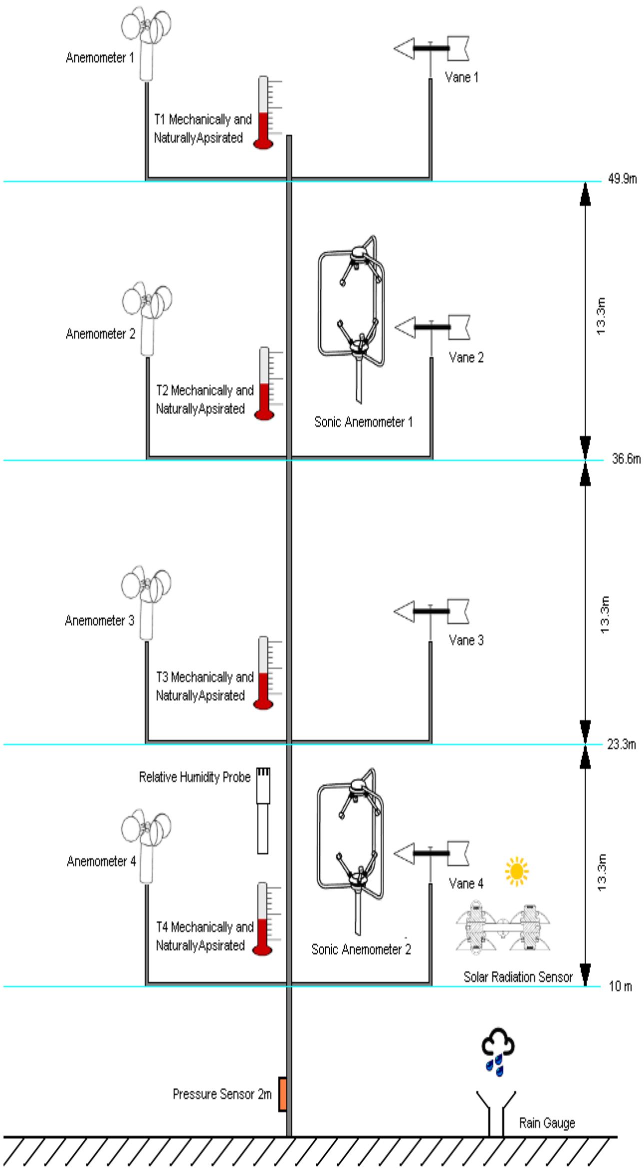

Fig 1. *Schematic of installed observation system*

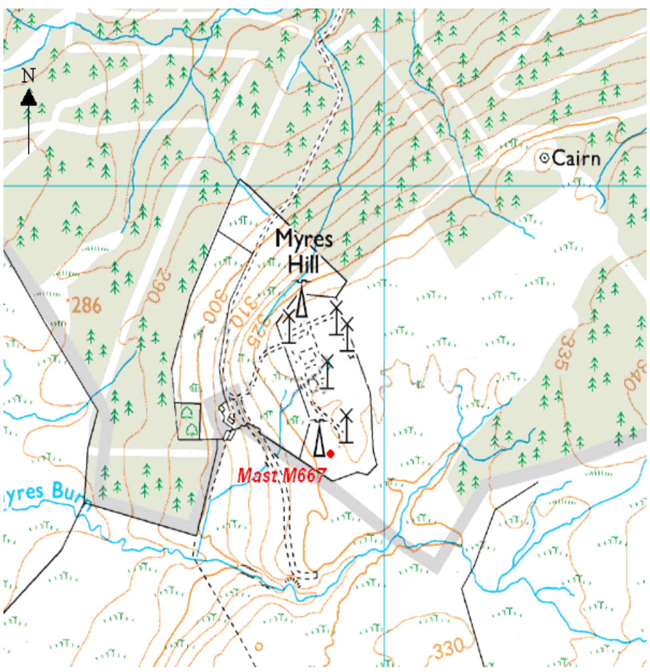

Fig 2 *Test Site Layout*

Censoring of data was carried out in accordance with the useful data region determined in Fig 4.

Results

The Obukhov Length was calculated using Eq (1). This definition is an approximation to the original Obukhov Length as defined in Eq (2).

$$L = \frac{T.u_*^2}{g.k.\theta_*} \qquad \text{Eq (1)}$$

$$L = -\frac{-\overline{\theta}_v * u_*^{\ 3}}{k * g * \overline{(w'\theta_v')}_s} \qquad \text{Eq (2)}$$

This approximation was made using the relationship $\left(\overline{w'\theta_v'}\right) \approx -u_*\theta_*$, Middleton (2001), where:

T= Ambient Temperature
u_* = Surface Friction Velocity
g = Gravitational Constant
k = Von-Karmen Constant
θ_* = Temperature Scale
w = Vertical Wind Component
θ_v = Virtual Potential Temperature

A site specific calibration of the Obukhov Length was determined by establishing the bounds for 1/L which encompassed the known neutral turbulence intensity values at high wind speeds.

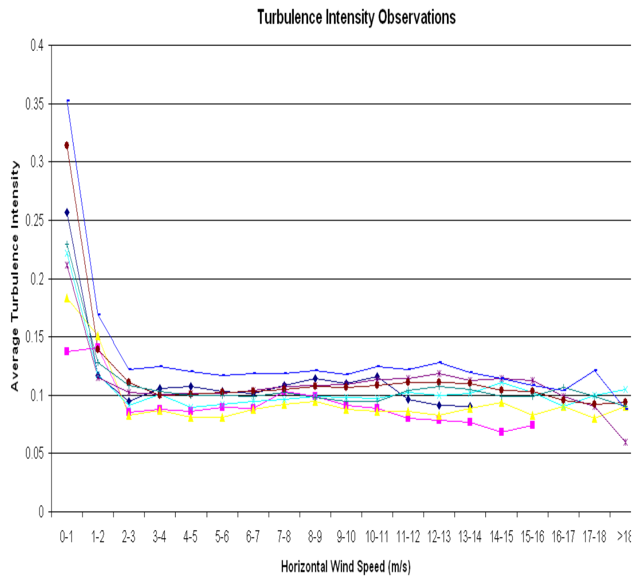

Fig – 3 *Turbulence Intensity based site specific calibration for known neutral condition, established from all data collected and directionally censored*

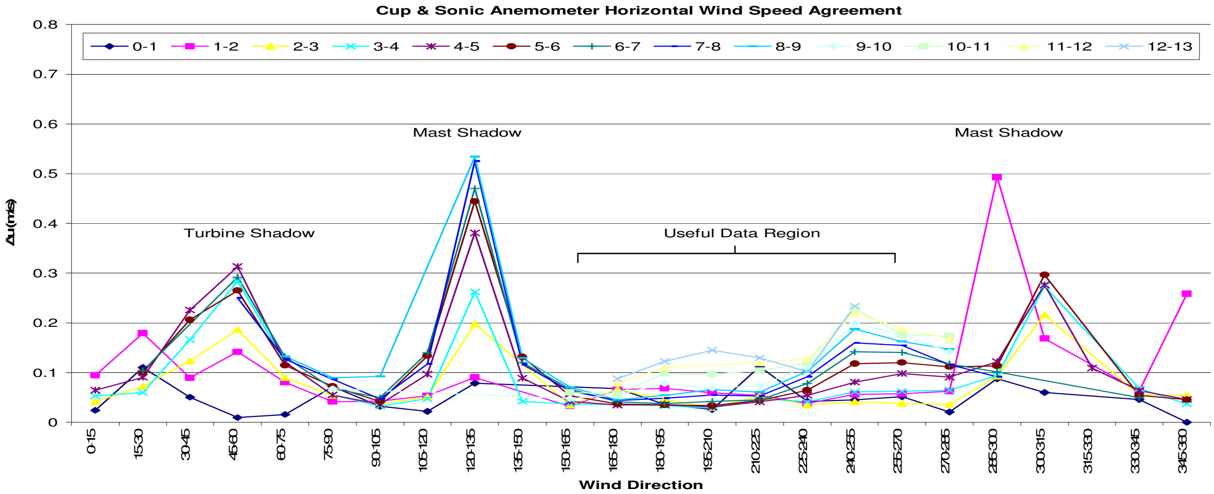

Fig 4 – *Horizontal wind speed agreement between 36.6m instruments for all wind speeds as given in the legend.*

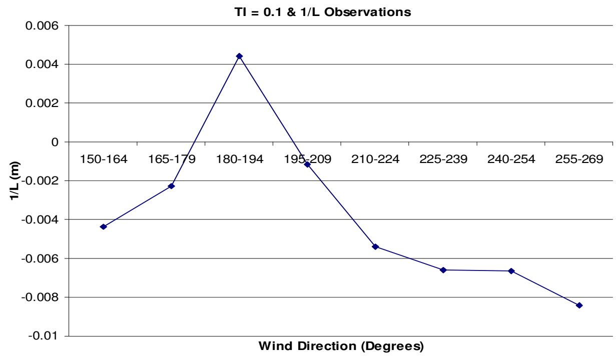

Fig 4 – *Establishing the 1/L values which bound the neutral region categorised by turbulence intensity =0.1*

From this criterion the site stability was categorised as a function of wind speed which formed the basis for inter-scheme comparison. The Obukhov results conformed well to what was expected in that neutral conditions were much less frequent at low wind speeds and steadily increased with wind speed. Interestingly, unstable conditions were observed to exist up to wind speed of around 12 m/s.

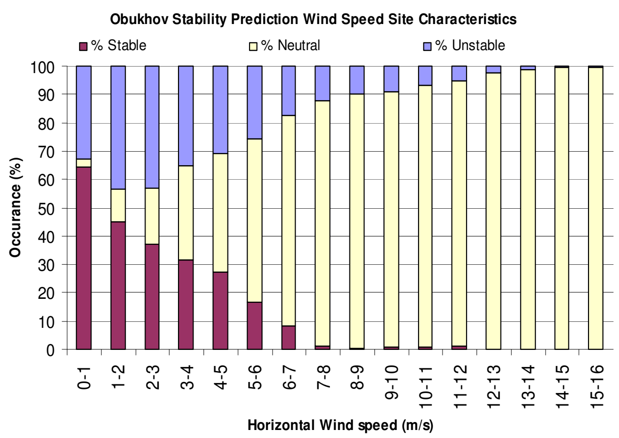

Fig – 5 *Thermal Stratification as a function of horizontal wind speed, measured using the Obukhov technique*

The Flux Richardson method was determined from the relationship Eq (3) which is an approximation to the Flux Richardson number given in Eq (4). This approximation was made using the same relation as described for the Obukhov Length.

$$R_f = \frac{\left(\frac{g}{\theta_v}\right) u_* \theta_*}{(\overline{u'w'})\frac{\partial \overline{U}}{\partial z} + (\overline{v'w'})\frac{\partial \overline{V}}{\partial z}} \qquad \text{Eq (3)}$$

$$R_f = \frac{\left(\frac{g}{\theta_v}\right)(\overline{w'\theta_v'})}{(\overline{u'w'})\frac{\partial \overline{U}}{\partial z} + (\overline{v'w'})\frac{\partial \overline{V}}{\partial z}} \qquad \text{Eq(4)}$$

The remaining schemes were processed by applying the corresponding Pasquill stability classes and filtering the classes into neutral, stable and unstable categories.

Stable agreement across all schemes was poor with the exception of the Flux Richardson number which had good conformance with the Obukhov technique. The greatest disagreement was between Obukhov and Temperature gradient methods. The Sigma Theta method over predicted stable conditions by some margin.

also.

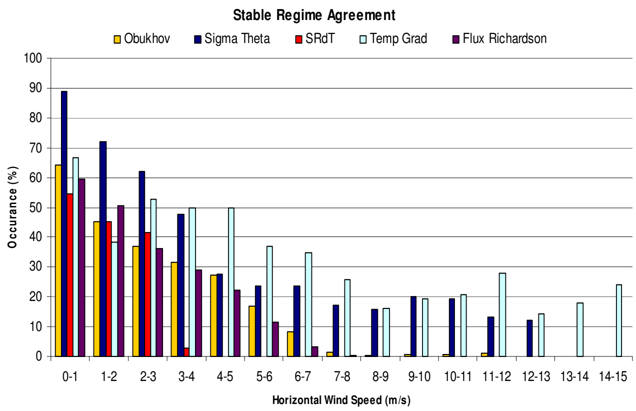

Fig – 6 *Stable regime agreement between all schemes*

Unstable category agreement was similarly poor across all schemes with the exception of the Flux Richardson number. All other schemes had significant disagreement the most so being the Temperature Gradient method and the sigma theta method, the later under predicting unstable conditions by a significant margin.

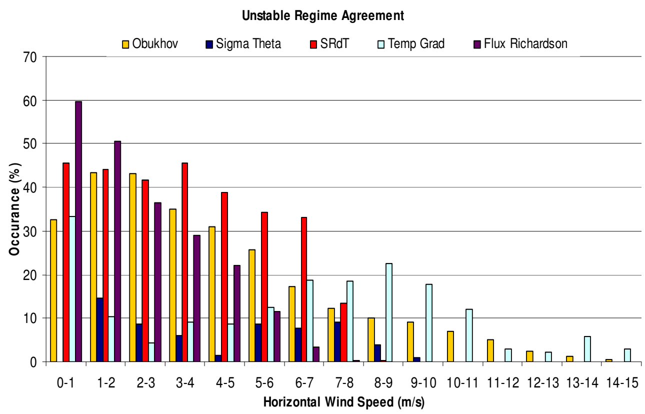

Fig – 7 *Unstable regime agreement between all schemes*

Neutral conditions agreed well across wind speeds in excess of 5 m/s, although at lower wind speeds the spread in categories was greater.

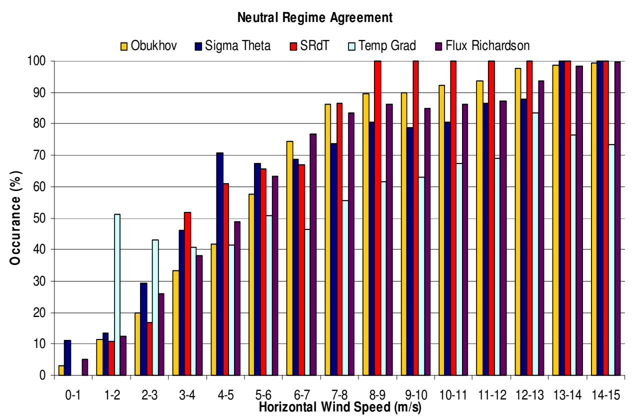

Fig – 8 *Neutral regime agreement between all schemes*

Summary and Conclusions

The SRdT, Sigma Theta and Temperature Gradient schemes are not robust and effective ways to measure atmospheric stability in this context. It was found that whilst occasionally these techniques agreed with the more comprehensive Obukhov method, in the areas of interest they conformed poorly. Unfortunately these schemes make up the economical alternatives to measuring stability and as such it was found no economical system for such measurements existed within the bounds of this investigation.

It is recommended that future attention is focused on attaining the Obukhov Length or Flux Richardson Number by more economical means through similarity theory or approximations such as the Bulk Richardson Number.

With regard to stability measurement using the Obukhov technique, it was found the vertical kinematic heat flux approximation, Middleton (2001) produced repeatable and, as far as was discernable robust results. However establishing the true vertical kinematic heat flux from the eddy correlation $\left(\overline{w'\theta_v'}\right)$ is recommended which will allow verification of this assumption.

References

Middleton, D R and Thomson, D J (2001) *Uncertainties in met pre-processing for dispersion models*, ADMLC Workshop at NRPB