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Installation, Commissioning and Operation of the Atmospheric Boundary Layer Research Facility (ABLRF)

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Abstract

This paper describes a recently installed and commissioned atmospheric boundary layer research facility (ABLRF) for high-fidelity field measurements of atmospheric turbulence and wind loads on structures. The goal is to characterise gust wind events and three-dimensional turbulence length scales, which are driving factors for dynamic effects such as torsional flutter and galloping on flexible structures, the turbulent transport and diffusion of dust and particle concentrations for heliostat mirror soiling, herbicide spray drift and propagation of pollutants in plumes. The ABLRF provides increased precision and resolution of near-surface turbulence data in the lowest 10 metres, with high-frequency measurements of the intensities and length scales of horizontal and vertical turbulence components. Preliminary analysis of mean wind velocity and turbulence data during a high-wind afternoon shows that the site is characterised by an open country terrain with logarithmic roughness height between 0.01 m and 0.03 m and friction velocity of 0.3 m/s.

1. Introduction

This paper presents the installation, commissioning, and operation of the Atmospheric Boundary Layer Research Facility (ABLRF) established at the University of Adelaide in 2022. The high-fidelity field-scale measurements at the ABLRF provide an insight into the spatial and temporal turbulence characteristics and their relationships with thermal gradients, surface fluxes and stability parameters in the atmospheric surface layer. The development of a field-scale facility would provide a platform for investigation of research projects with a focus on significant energy savings and increased productivity in a wide range of applications in rural and urban environments including wind loads on structures, renewable energy, agriculture, and numerical weather predictions. Furthermore, the field measurements provide valuable extensive data sets for fundamental research of high Reynolds number boundary layer flows. Turbulent eddies in the lower region of the atmospheric surface layer play an important role in the diurnal development of turbulent frictional forces and the exchange of momentum and heat due to velocity and temperature fluctuations. These turbulent eddies which are characterised by a large range of scales have been shown to impact the aerodynamics and wind loads on small-scale structures (Emes *et al.* 2021), renewable energy yield (Porté-Agel *et al.* 2020) and agricultural production (Himel *et al.* 1990). The dynamic stability combining the effects of wind shear and three-dimensional turbulence components impacts the horizontal and vertical transfer of energy and airborne particle dispersion (Tepper 2017) and the production of turbulence kinetic energy in the atmospheric surface layer (Träumner *et al.* 2011). Furthermore, the near surface turbulence fluxes are critical for reliable numerical models for weather predictions (Huang *et al.* 2021).

The proposed facility, which is unique in Australia, is one of the few facilities for lower-surface atmospheric measurements in the world. There are two such research facilities that exist. The first one is the Surface Layer Turbulence and Environmental Science Test (SLTEST) facility in the western Utah Great Salt Lake desert (Hutchins *et al.* 2012, Hutchins and Marusic 2007, Marusic and Hutchins 2008) in the USA, which is equipped with 9 CSAT3 ultrasonic anemometers on a vertical tower array and 10 sonic anemometers in a spanwise mast array to measure the wind velocity components and temperature in the spanwise direction at heights of 2.4 m above the ground (Metzger *et al.* 2007). This facility has recently been adapted using high-resolution nanoscale thermal anemometry probes (NSTAPs) to measure wall-resolved streamwise velocity and temperature data within the first metre above the ground to develop an understanding of heterogeneities in topography, land cover, stability, and their effects on the flow field, scalar transport and spectral behaviour to improve modelling approaches in wall-bounded flows (Huang *et al.* 2021). The second one is the Qingtu Lake Observation Array (QLOA) facility in China, which is equipped with 31 three-component sonic anemometers installed on 21 towers (one 32 m high and the remaining 5 m high) which collect the wind data along 240 m, 60 m and 32 m in the prevailing wind direction, spanwise and vertical directions for analysis of dust storms and effect of terrain roughness on synoptic-scale separations between signals and large-scale coherent structures (Li *et al.* 2021, Wang and Zheng 2016).

The ABLRF field site has a unique topography characterised by grassland in a flat rural landscape over several kilometres. The facility offers an increased spatial resolution at the response time of surface layer turbulence to accurately resolve surface-layer turbulent eddies and the distribution of small-scale flow features, temperature gradients and surface fluxes for understanding of stability parameters, surface roughness, and three-dimensional turbulence spectra and length scale distributions. Development of cross-validation techniques to characterise streamwise and spanwise distributions of three-dimensional wind velocity and temperature measurements in the near-surface region with the existing arrays will be progressed with the addition of high-frequency multi-hole pitot tubes, hot-wire anemometers, temperature, humidity and dust sampling sensors. Furthermore, expansion of the ABLRF to increased resolution of the turbulent wind fluctuations in the order of kilometres in the longitudinal direction and at increased elevations above 50 metres and up to several kilometres in the outer region of the atmospheric surface layer is being investigated using long-range remote sensing instruments including SODAR with information on turbulence intensity and the gradients of temperature and wind velocity in the lowest few hundred metres of the ABL, wind profiling LIDAR for high temporal and vertical resolutions of three-dimensional turbulence structure in the ABL, PIV to investigate turbulence structure and spatial distribution of turbulence statistics in field environments, and radiosondes for in-situ observations of temperature, pressure, humidity and wind velocity and most accurate information of troposphere in ABL study (Dang *et al.* 2019). Such techniques will develop understanding on turbulence structure in the outer region and near-surface energy fluxes, temperature gradients, flow dispersion and turbulence parameters.

A heliostat is installed as a model structure in the ABLRF as part of a funded Australian Solar Thermal Research Institute (ASTRI) heliostat aerodynamics and wind load project. The work is led by the University of Adelaide in collaboration with CSIRO and funded by the Australian Renewable Energy Agency (ARENA) with the goal to investigate the discrepancies between heliostat wind loads in wind tunnel experiments and full-scale field environments. Characterization of gust wind events and verification of heliostat wind load correlations with ABL turbulence parameters are crucial to further develop and refine heliostat design wind load predictions and guidelines. Flow field and load measurements at the facility will be applied to investigate dynamic wind loads and tracking error of heliostats, and the turbulent transport and diffusion of dust and particle concentration in the development of heliostat soiling, herbicide spray drift and propagation of pollutants in plumes.

2. Experimental Facility Establishment

2.1 Field site fencing and foundation preparation

Figure 1 shows a panoramic view of the outdoor atmospheric boundary layer research facility (ABLRF) to the north-west of the piggery at the University of Adelaide Roseworthy Campus. which has been set up with wired rural fencing around the 50 m × 50 m fenced area (34°30'37.0"S 138°40'37.3"E) and a double access gate (Figure 2). Following the excavation, trenching and installation of six 450 mm square diameter and 500 mm depth concrete pads (for five 3-m masts and a heliostat model) and a bored pier and post foundation (for 12 m tower) were carried out by a construction company, followed by installation of conduit and water pipe between a series of pits along the trench line by the University of Adelaide (Figure 2). Backfill of the excavated soil and installation of chem-set anchors on the heliostat pad foundation were then completed by a construction company.

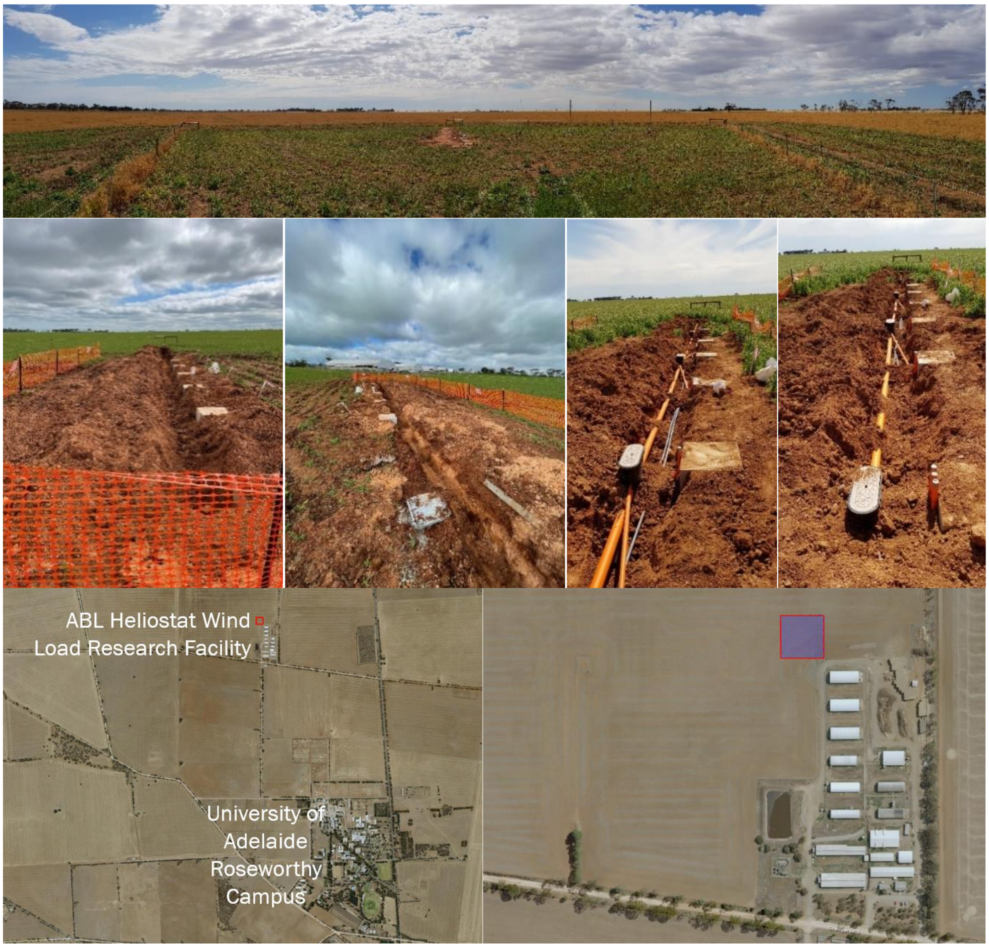


Figure 1. Site preparation stages including fencing, trench excavation, installation of mast foundations, water pipe and pits within the 50 m × 50 m fenced area of the Atmospheric Boundary Layer Research Facility (ABLRF) at the University of Adelaide Roseworthy Campus field site (34°30'37.0"S 138°40'37.3"E).

2.2 Installation of mast arrays, 12-m tower and underground pits

Figure 2 shows a sequence of photos taken during the installation and commissioning stages of the ABLRF for outdoor full-scale field measurements of ABL turbulence and heliostat wind loads. Installation included raising the longitudinal and lateral arrays of 3-m masts with guy wires (Figure 2a), assembling the 3-m lattice sections (Figure 2b), mounting junction boxes, conduit and cross-arms on the 3-m masts and the 12-m tower (Figure 2c), and laying power and communication cables in the underground conduit between the pits (Figure 1). In collaboration with CSIRO on wind load and tracking error of heliostats, installation and assembly of the heliostat model and PV control panel (Figure 2d) were undertaken at the ABLRF site following freight transport coordinated by the University of Adelaide to Roseworthy campus from CSIRO Energy in Newcastle.

The University of Adelaide project team completed the wiring and cable terminations to 14 ultrasonic anemometers, 9 cup anemometers, and 4 security cameras on the 12-m tower, laying power and communication cables in conduit between the array of masts and coordinating the raising of the 12-m tower with a Franna crane. Fourteen 3D Campbell Scientific 81005 ultrasonic anemometers and junction boxes for cabling to the 3-m masts were configured for serial communication and commissioned. Three of the ultrasonic anemometers and four tripod masts were delivered to the University of Adelaide by Conditions Over the Landscape (COtL). Commissioning of the wind anemometers and load sensors was completed in July 2022.

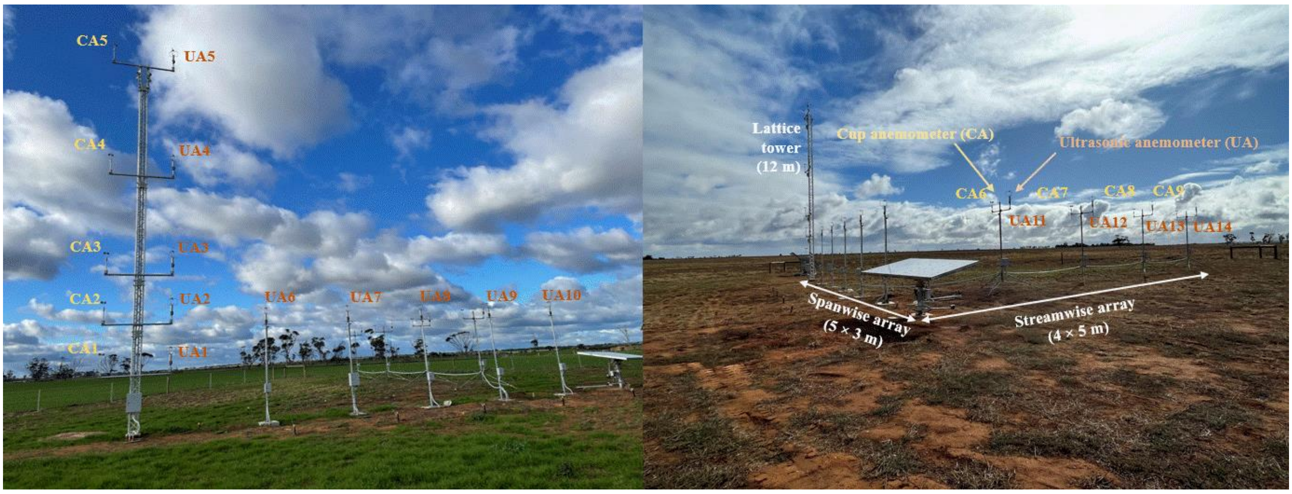
(a) (b) (c) (d)

Figure 2. Field test setup stages including (a) installation of conduit, junction boxes and guy wires on longitudinal and lateral arrays of 3-m masts, (b) assembly of lattice sections and mounting of cross-arms and conduit on 12-m tower, (d) configuration, installation and alignment of anemometers and security cameras prior to raising of 12-m tower, (d) laying of electrical, network and communication cables underground between pits for termination in junction boxes and control panel.

2.3 Establishment and commissioning of ABLRF instrumentation

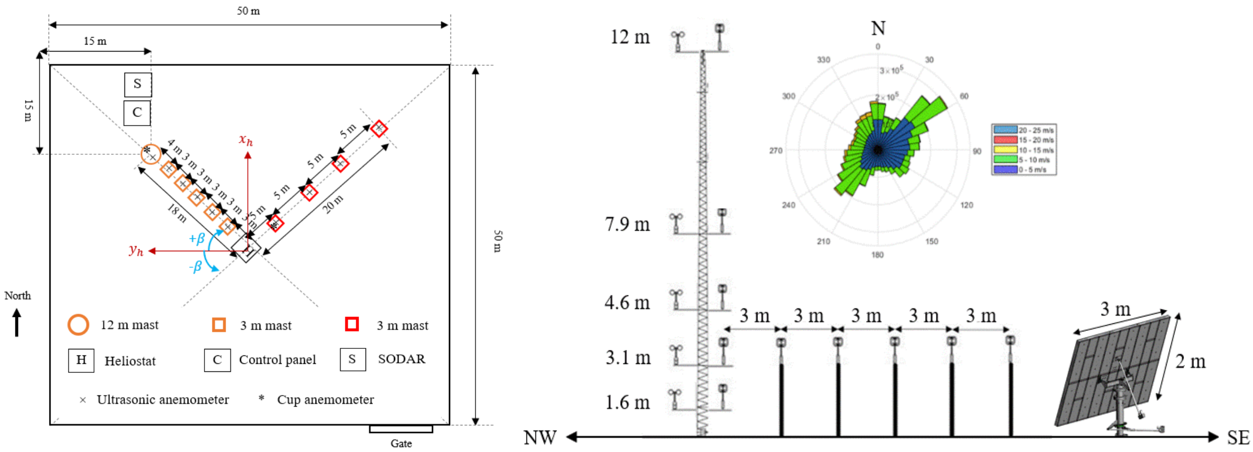
Figure 3 illustrates the ABLRF instrumentation, consisting of a 12-m height cantilevered lattice mast containing five ultrasonic anemometers to measure three components of wind velocity and temperature at a 32 Hz sampling frequency, and five cup anemometers at 1 Hz sampling frequency to verify the mean wind profiles, at logarithmically spaced heights above the surface. A horizontal array of five 3-m tilt-over masts spaced 3 metres apart span the crosswind with the prevailing wind direction from the south-west. An additional four ultrasonic and cup anemometers on tripod masts, are spaced 5 metres apart in the longitudinal direction of the prevailing wind. The mast arrays were positioned in the north-western corner of the fenced site (Figure 1) at a distance greater than 10 building heights from the piggery shed buildings to minimise the flow disturbances by the buildings. Nevertheless, winds approaching from the south or south-easterly directions are expected to be impacted by the presence of the buildings to the south-east of the site.

The rectangular heliostat model contains 48 high-frequency (differential) pressure sensors and a six-axis load cell to measure load distributions and calculate aerodynamic coefficients at different tracking angles controlled using two linear actuators for comparison with UoA wind tunnel experiments. The heliostat model is remotely controlled and monitored through cellular networks and a standalone self-contained power system, consisting of two 315 W photovoltaic panels and four 102 Ah batteries.



(a) (b)

Figure 3. Completed installation of lattice tower, streamwise and spanwise mast arrays and instrumentation including ultrasonic anemometers (UA), cup anemometers (CA) and heliostat model at the ABLRF: (a) view looking north-east, (b) view looking north-west.



(a) (b)

Figure 4. Field layout schematic of (a) plan view and (b) instrumentation at the ABLRF including ultrasonic and cup anemometers on a 12-m height lattice tower, five 3-m height tilt-over masts and a heliostat model in the lateral direction, and four 3-m height tripod masts in the longitudinal direction of the prevailing wind from the south-westerly direction. Inset shows the wind rose of 1-minute wind data between 2013 and 2019 at Bureau of Meteorology Roseworthy Agricultural College weather station 023122.

3. Wind measurements on the 12-m tower at the ABLRF

Figure 5 shows time series wind data from the 12-m tower on the afternoon of 24 May 2022 of three velocity components (blue u, red v and green w) and temperature measured at 32 Hz sampling frequency by the ultrasonic anemometers UA1 to UA5 in Figure 5(a-e). The 10-minute averaged wind direction, calculated as $\tan^{-1}(u/v)$ using the horizontal velocity components in Figure 5(f), is north-easterly during the afternoon. This corresponds to the prevailing wind direction for high wind speeds above 10 m/s based on Bureau of Meteorology (BoM) weather station 023122 cup anemometer observations from 2013-2019. The 10-minute averaged wind speed (Figure 5g) exceeds 8 m/s in unstable convective conditions during high daytime temperatures (Figure 5h) that diminish by late afternoon, as characterised by Monin-Obukhov similarity parameter z/L (Figure 5i) decreasing from -2 at 12:30 to -0.07 at 15:30. The transition period from convective to stable boundary layer conditions, approaching sunset from 15:30 to 16:30, corresponds to decreasing temperature and strong winds. However, wind speeds rapidly decline as a stable boundary layer develops from 16:30 into the evening. The collected data has an accuracy of ± 0.05 m/s, ± 2°, and ± 2° C, with a resolution of 0.01 m/s, 0.1°, and 0.01° C, for wind velocity, direction, and temperature, respectively. The required sampling frequency will be investigated to identify the minimum required frequency to realise turbulence profiles and length scales.

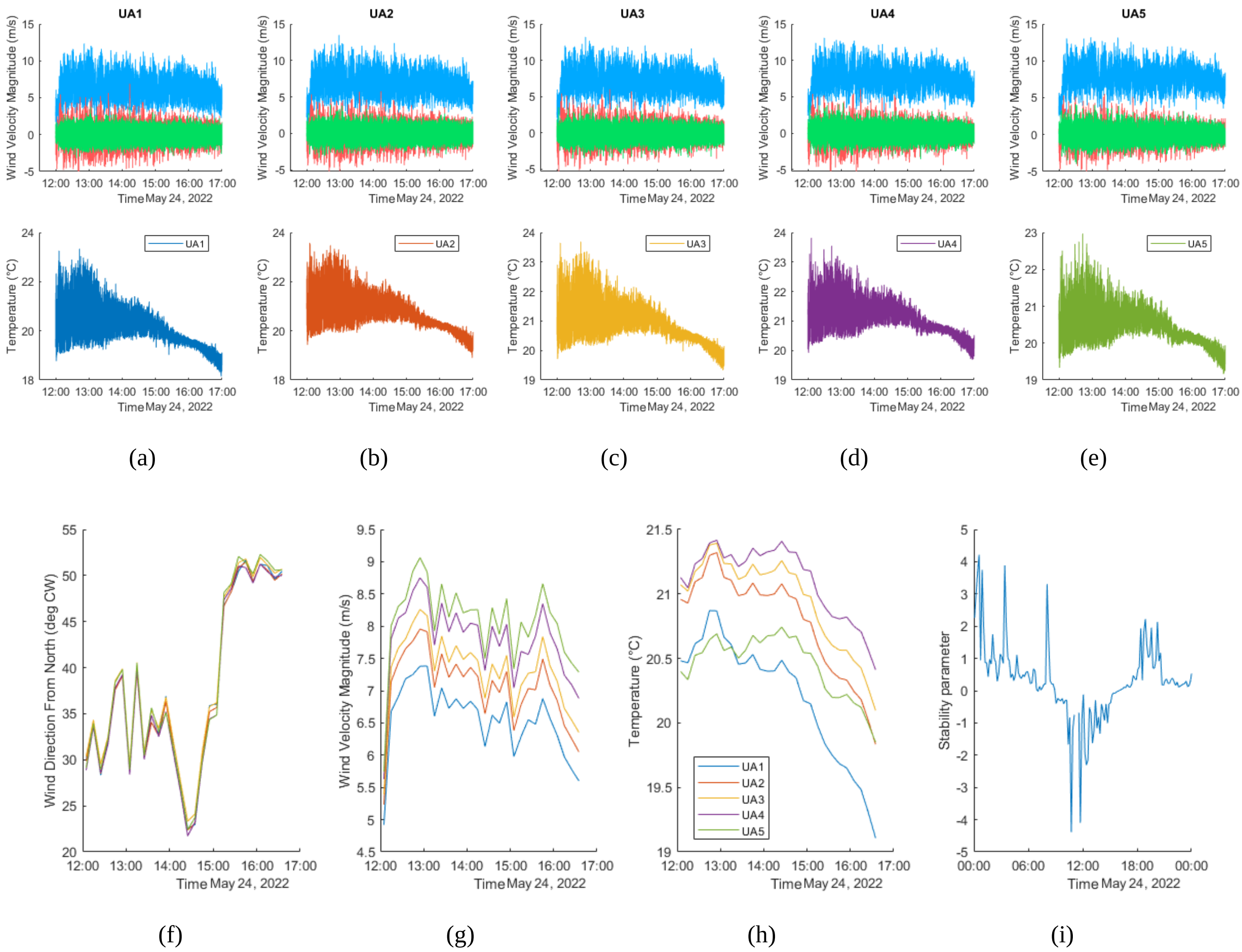


Figure 5. Time series of 32 Hz velocity data and temperature data on 24 May 2022 measured by five ultrasonic anemometers (a-e) UA1-UA5 on the 12-m tower. Blue, red and green lines indicate the u, v and w velocity components, respectively. Calculated 10-minute averages of (f) flow direction, (g) velocity magnitude, (h) temperature, (i) stability parameter.

Figure 6 shows the mean velocity and turbulence intensity profiles during a 10-minute period from 14:14 on 24 May 2022, where the error bars indicate the standard deviation of the fluctuating velocity component at the five measurement heights on the 12-m lattice tower. The mean velocity profile is consistent with a log law profile (Marusic *et al.* 2013)

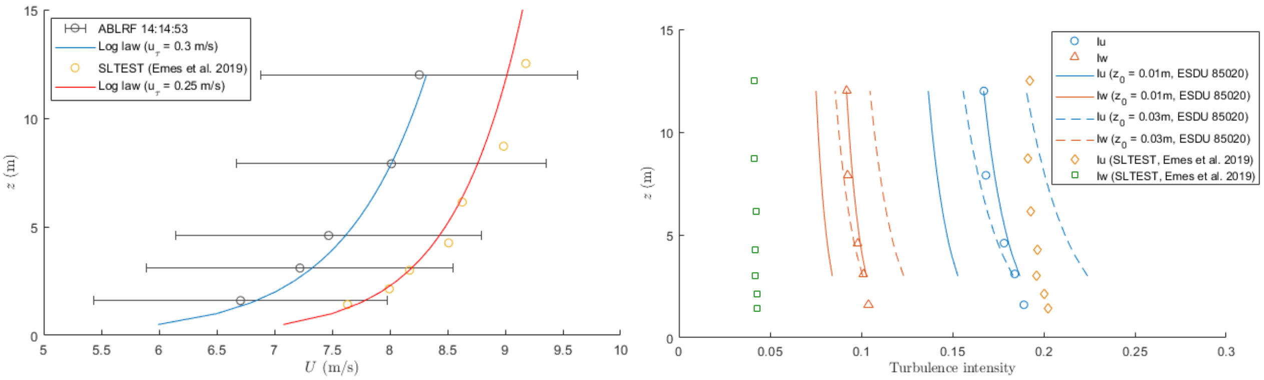
$$U(z) = \frac{u_\tau}{k} \ln z + A, \tag{1}$$

where $A = 6.5$ and the friction velocity is calculated as 0.3 m/s at the lowest measurement height of 1.6 m (Stull 1988)

$$u_\tau = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}. \tag{2}$$

The turbulence intensity profiles of the longitudinal velocity component $I_u = \sigma_u/U$ and vertical velocity component $I_w = \sigma_w/U$ in Figure 6(b) have been plotted against the ±10% uncertainty bands of ESDU 85020 (2001) profiles for ABL with surface roughness heights $z_0 = 0.01$ m and 0.03 m. The turbulence intensities recorded on the 12-m tower are within the lower range of $z_0 = 0.03$ m and the upper range of $z_0 = 0.01$ m at heights of 3 m and above. This indicates that the ABLRF site is representative of terrain between flat, open country and grassy plains. The gradients of U and I_u profiles and magnitudes of I_w are smaller at the ABLRF with estimated boundary layer thickness of 1.3 km, compared with SLTEST data over low-roughness salt flats in western Utah with an estimated surface layer thickness of 60 m (Emes *et al.* 2019, Hutchins *et al.* 2012).

As part of the project, the spectral analysis of the fluctuating velocity component in the frequency domain and spatio-temporal analysis of the vertical tower, spanwise and streamwise mast arrays using autocorrelation and cross-correlation techniques will be undertaken in future to characterise the distribution of energy-containing turbulent eddies and identify the dominant frequencies of wind instabilities in the lower atmospheric surface layer, Cross-validation of the mast array turbulent statistics with SODAR and LIDAR measurements further aloft in the atmospheric surface layer thickness at heights above 100 m will be used to investigate the vertical exchange of turbulent kinetic energy, dust dispersion and stability effects and their functional dependence on near-surface atmospheric turbulent eddies.



(a) (b)

Figure 6. Analysis of 10 minutes of velocity data from 14:14 on 24 May 2022: (a) Mean velocity profile compared with log law profile with $u_\tau = 0.3$ m/s and $A = 6.5$, (b) turbulence intensity profiles compared with ESDU 85020 (2001) data over range of measurement heights on the 12-m tower. The error bars in (a) show the standard deviation of wind velocity fluctuations. The ESDU profiles in (b) show the lower and upper bounds for ±10% in turbulence intensity data at $z_0 = 0.01$ m and $z_0 = 0.03$ m in ESDU 85020 (2001). Velocity and turbulence intensity profiles are also compared with near-neutral SLTEST data from Emes *et al.* (2019).

4. Conclusions

This study outlined the phases of field preparation, setup, installation, and commissioning of high-frequency wind measurement instrumentation for study of near-surface atmospheric turbulence intensities, length scales, surface fluxes and atmospheric stability at the University of Adelaide Atmospheric Boundary Layer Research Facility (ABLRF). The high-fidelity measurements allow for the ABL to be accurately characterised. Preliminary analysis of mean wind velocity and turbulence intensity profiles during a high-wind afternoon and comparison with log law and ESDU 85020 data indicates that the site is characterised by an open country terrain with logarithmic roughness height between 0.01 m and 0.03 m and friction velocity of 0.3 m/s.

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