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A conditional analysis of spanwise vortices within the lower atmospheric log layer

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ABSTRACT

The current study is an initial step towards the full characterization of coherent structures within the turbulent atmospheric boundary layer (ABL). A conditional-analysis technique to identify spanwise vortices is applied on data acquired throughout January–August 2012. This study begins with an approximation of the ABL stability and thickness (δ). Subsequently the measured Reynolds stresses are compared to those measured by Klebanoff (1955) over a flat plate and similarity formulations developed by Marusic and Kunkel (2003). The ABL data is shown to be neutral with a thickness of approximately 1000 m. The statistical descriptors of the turbulent fluctuations are found to qualitatively agree with Klebanoff (1955) and Marusic and Kunkel (2003). From the conditional analysis, it is found that the height of spanwise vortices follows a Rayleigh-like distribution with a mean and standard deviation of 0.065δ and 0.038δ, respectively. The circulation distribution of spanwise vortices is found to be bimodal about $\Gamma/U_0\delta = 0$ with a standard deviation of $0.036U_0\delta$. The magnitude of the positive peak of the bimodal distribution tends to be 80–100% that of the negative peak, which demonstrates that prograde vortices are more frequent than retrograde vortices.

1. Introduction

This work is a first step in characterizing coherent structures within the lower atmospheric log layer, which is key towards further understanding turbulent fluctuations and coherent structures within this region. A more coherent understanding of turbulence within the lower log layer of the atmosphere is valuable for several applications such as wind-turbine control, managing gusts during the operation of small autonomous aircraft, such as micro aerial vehicles, and wind loadings on civil structures. The quantification of coherent structures within the log region of the ABL would also characterize the influence of the Reynolds number over several orders of magnitude. Coherent structures within canonical turbulent boundary layers (TBLs) have been typically quantified through the measurement of planar vortices such as spanwise vortices. The study of spanwise vortices has led to an improved understanding of turbulence mechanics and to improved computational models (Robinson, 1989). Thus, the current study looks to quantify the strength and orientation of ABL spanwise vortices to achieve similar ends.

Earlier research into atmospheric turbulence has generally focused on the time-averaged characteristics of the velocity fluctuations. For example, as demonstrated in Kaimal (1973), the power spectra of the velocity fluctuations and their cross-correlations follow normalized curves that are functions of the Richardson number. Similar relations involving the fluctuation spectra have been determined and are well documented in various texts such as Lumley and Panofsky (1964) and Kaimal and Finnigan (1994). A major drawback of time-averaging is that it is an indiscriminate filter such that quantification of the major energy-containing coherent structures within the wind field is not possible. The need to obtain a better temporal and spatial characterization of the flow has prompted a shift towards alternate measurement techniques to quantify the entire flow field. In meteorological studies, radar and lidar measurements have provided insightful data. For example, Lin et al. (2008) used lidar measurements, and Kropfli and Kohn (1978) used radar measurements, to characterize the nature of spanwise roller vortices within the ABL. However, meteorological studies such as these focus primarily on coherent structures that are on the order of the boundary layer thickness (δ), while the current study focuses on structures of a much smaller scale.

In contrast, using measurement techniques such as particle imaging velocimetry (PIV), studies on canonical TBLs have investigated turbulent coherent structures on orders much smaller than δ. One structure widely found within canonical TBLs is the hairpin vortex. The hairpin vortex is a ubiquitous coherent structure that explains several aspects of canonical TBL flow, and has been

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observed both experimentally and computationally at various Reynolds numbers; see Robinson (1989, 1991) for a review of the early research performed on hairpin vortices. Hairpin vortices were first observed three-dimensionally by Head and Bandyopadhay (1981). However, recent studies such as Christensen and Adrian (2001) have explained how early, qualitative, two-dimensional observations of turbulent coherent motions (Nychas et al., 1973 and Praturi and Brodkey, 1978) were in fact of hairpin vortices Hairpin vortices have been observed throughout the entire TBL and scale proportionally with the height of the head from the shearing flat surface; see Zhou et al. (1999), Adrian et al. (2000) and Adrian (2007).

It can be shown that the turbulent kinetic-energy budget of neutral ABLs is equal to that of canonical TBLs; see Lumley and Panofsky (1964). Furthermore, a similarity formulation developed in Marusic and Kunkel (2003) developed for canonical TBLs of high Reynolds number has been shown to accurately describe the Reynolds stresses of ABL flows; see Kunkel and Marusic (2006). It is expected that the Reynolds stresses measured in the current study will also agree with the similarity formulation from Marusic and Kunkel (2003).

The shared traits between ABLs and canonical TBLs would also give credence to our expectation of similar coherent structures within ABLs and canonical TBLs. One must, however, be careful in assuming that the characteristics of coherent structures within ABLs are comparable to characteristics of structures found within canonical TBLs. Due to the size of the atmosphere, entire coherent structures within the ABL have yet to be fully quantified. Studies that have visualized coherent structures within ABLs have had to compromise between qualitatively measuring full-scale structures, as done in Hommema and Adrian (2003) via smoke visualizations of full-scale hairpin packets, and quantitative measurements within a small (1 m $\times$ 0.5 m) field-of-view with PIV (Morris et al., 2007). Another issue is that studies focused on coherent structures within canonical TBLs have been performed at low Reynolds numbers ($Re_\theta = 10^2$–10^4) whereas ABL flow exhibits Reynolds numbers several orders greater ($Re_\theta = 10^6$–10^8). Thus it would be incorrect to draw connections from lab experiments as it remains unclear how the properties of turbulent flow scale with Reynolds number; see Degraaff et al. (1999) and Smits et al. (2011) for examples of Reynolds number scaling issues.

Since velocimetry techniques are still maturing for the measurement of time- and spatially-resolved velocity fields in ABLs, one must make do with wind masts to quantify coherent structures within ABLs in a meaningful way. Wind masts at best provide complete, high temporal resolution velocity measurements at only a limited number of data-acquisition points along their height. Scarabino et al. (2007) attempted to characterize hairpin vortices within a neutral ABL using data collected from a wind mast by Sterling et al. (2006). Using a conditional analysis (CA) technique, velocity fluctuations of extreme gust events were classified into three groups and were then ensemble averaged. One of the ensemble groups exhibited vortex-like flow, which led Scarabino et al. (2007) to fit a hairpin-vortex model onto the ensemble average. In this regard the study had limited success: although the hairpin-vortex model accounted for sharp changes in streamwise velocity, it failed to satisfactorily capture the simultaneous vertical fluctuations.

It is believed that the shortcomings of the hairpin-vortex model in Scarabino et al. (2007) were due to some oversimplifications. For example, it was assumed that the gust event coincided with the impingement of the center of the hairpin-vortex head on the mast. The study did not consider placing the impingement prior to or after the gust event. Furthermore, the assumption that the 6 s-long ensemble averages were comprised of a single hairpin vortex seems too basic. The ensemble averages observed by Scarabino et al. (2007) could have been induced by a series of hairpin vortices, which would induce a complicated flow field.

The wide range of structures within TBLs and the complex flow fields they induce compels the argument that coherent structures must be studied first in terms of their strength and orientation prior to investigating how they contribute to gust events and Reynolds stresses. Thus the current study takes an alternate approach to that in Scarabino et al. (2007). Rather than identifying gust events within the data and attempting to fit a certain coherent structure to their ensemble average, events that meet specific criteria consistent with a certain coherent structure are identified instead. Velocity fields are then determined for each specific event and are compared to experimental data. In this way, the orientation and strength of coherent structures within the lower log region of the ABL can be characterized, statistically analyzed and compared to those within canonical TBLs.

In the current study, high-speed velocity measurements from two ultrasonic sensors located on a wind mast are analyzed to characterize atmospheric spanwise vortices. Previous studies have shown that the occurrence-frequency distribution of spanwise vortex-center height is independent of Reynolds number. However, modest increases in Reynolds number have resulted in an increased ratio of retrograde to prograde vortices; see Wu and Christensen (2006). Since ABLs have characteristically high Reynolds numbers, it is expected that the occurrence-frequency distribution of spanwise vortex-center height will be comparable to lab studies, while the ratio of retrograde to prograde vortices will increase significantly in comparison to low Reynolds number studies.

Since spanwise vortices are but components of larger vortical superstructures, the superstructure itself can interfere with the detection of the spanwise vortex. Thus, a heuristic model drawn from canonical TBLs is presented in Section 2 to demonstrate that ABL spanwise vortices are detectable from the mast data in spite of the superstructure's presence. Afterwards, a CA technique is then developed to identify spanwise vortices using the two available ultrasonic sensors.

In Section 3 the measured Reynolds stresses are compared to measurements taken within a canonical TBL and subsequently to a similarity formulation from Marusic and Kunkel (2003). Finally, the results of the CA are presented. The occurrence-frequency distributions of normalized circulation ($\Gamma/U_0\delta$) and normalized vortex-center height (a/δ) of spanwise-vortex events are discussed, and the model's performance in identifying vortices is then evaluated.

2. Materials and methods

This section describes the wind site as well as the sensors fitted onto the wind mast. This is then followed by a heuristic model illustrating that spanwise-vortex events are identifiable despite the signal interference caused by the encompassing vortical superstructures.

2.1. Experimental setup

Eight data sets were acquired from January 2012 to August 2012 from a 50 m wind mast erected on university land. A schematic of the wind mast, with the approximate positioning of its sensors, is provided in Fig. 1(a). A photograph depicting the mast and the surrounding terrain is shown in Fig. 1(b). The mast is instrumented with five cup anemometers and wind vanes, as well as a two-component ultrasonic anemometer, which are all used to quantify the boundary-layer profile and mean wind direction. Spanwise vortices are characterized using the measurements