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Review

Experimental investigation of turbulent transport of momentum and heat in the atmospheric surface layer

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ABSTRACT

In our study, turbulent transport of momentum and heat is investigated in the neutral and unstable atmospheric surface layer (ASL) over the edge of a desert. Our results reveal that with the increase of wind speed the transport efficiencies for momentum and heat increased, furthermore, transport efficiency of momentum increases faster than that of heat. In addition, the method of quadrant analysis and turbulent events were used to analyze the moment flux and heat flux. Experimental results show that the influence of wind speed on moment flux and heat flux can be quite different, which maybe has a great impact on the turbulent transport of momentum and heat in ASL.

1. Introduction

The turbulent transport of momentum and heat has been the subject of active research in many scientific fields, such as fluid mechanics, boundary layer meteorology, hydrology and air quality management, which directly affects the mass transport and energy transfer in the ASL where we live. Usually ASL is considered the lower part of the planetary atmospheric boundary layer (PBL) (usually about 1/10 of the PBL), where turbulent fluxes are constant, and velocity and temperature profiles are logarithmic (Metzger et al., 2007). The height of ASL in near-neutral condition represents the height at which the boundary layer velocity reaches 99% of the free-stream value, which is similar to the definition of boundary layer thickness used in the laboratory (Metzger et al., 2007). The ASL is the active link between the atmosphere and the surface. Thus its ability to transport momentum, heat, water vapor and other constituents is of great importance in all studies related to land surface atmosphere as well as ocean atmosphere exchange processes. In the bottom of ASL, the momentum, heat and water vapor fluxes are considered to be constant and the fluxes also can be regarded as the fluxes at the surface (Dyer and Hicks, 1970; Metzger et al., 2007). These fluxes are important in boundary layer meteorology because they represent the mass transport and energy transfer between the atmosphere and the land surface. The numerical model of atmosphere needs a means of estimating these fluxes (Avissar and Pielke, 1989; Louis, 1979; Zhao, 2002). So, the study of the characteristics of the near surface flux transport can not only reveal the atmospheric turbulence characteristics, but also helpful to the development of weather forecasting models.

Previous studies (Katul et al., 1997a) have assumed that turbulence transports all scalars similarly, such as temperature, humidity. This assumption is constantly extended to include momentum and referred to as the Reynolds analogy. However, it is recognized that this assumption is invalid in recently years (Li and Bou-Zeid, 2011). In the ASL, Reynolds analogy is considered to be only applied under neutral conditions. As buoyancy increases, the transport of momentum and scalars becomes increasingly different. Based on the measurements in Jodhpur, Rao and Narasimha (2006) show that the mean friction drag is zero in axisymmetric free convection and increases linearly with wind speed when it is low, which also strongly indicates that the Reynolds analogy cannot always hold. Some scholars (Li and Bou-Zeid, 2011) pointed out the dissimilarity between the turbulent transport of momentum and scalar under unstable conditions is likely caused by a change in the topology of turbulent structures. These turbulent structures are important to understand the mechanism of turbulence because of the important role they play in the processes of production and transport of turbulence (Abe et al., 2004; Barthlott et al., 2007).

However, it is difficult to obtain the three-dimensional topology of the turbulent structures in wall turbulence, especially in ASL, since the Reynolds number is high, the separation between large scale turbulent

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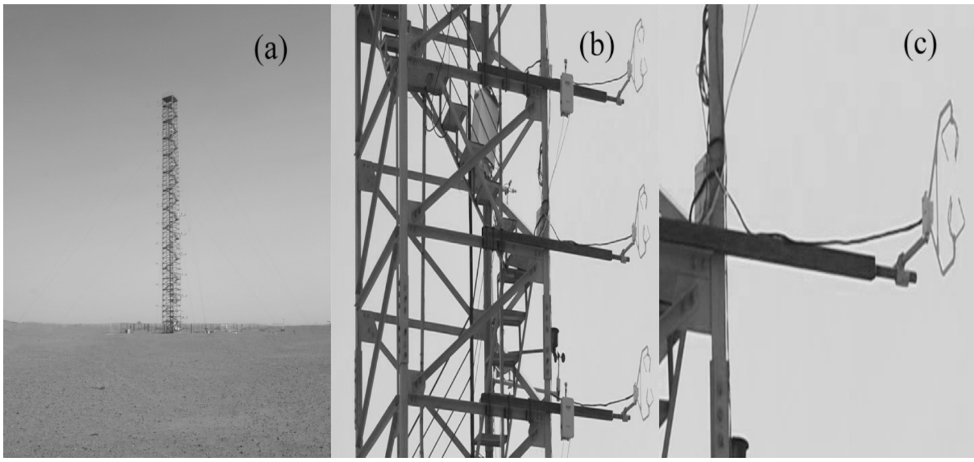

Fig. 1. (a) The meteorological observation tower. (b) The fixed manner of the sonic anemometers. (c) Set-up of a single sonic anemometer.

structure and small scale turbulent structure is significant (Smits et al., 2011), so detecting signatures of turbulent structures in time series data of velocity or other variables and getting quantitative conclusions about the turbulent transport of momentum and heat in ASL usually following conditional sampling techniques such as quadrant analysis (Katul et al., 1997b) or threshold method (Narasimha et al., 2007). One class of these researches is focus on the identification of turbulent events from time series data of velocity or other variables. Turbulent events are often associated with coherent structures such as eddies and bursting (Kline et al., 1967; Rao et al., 1971). Narasimha et al. (2007) used threshold method to convert flux time series to turbulent events and the turbulent event was defined as a series of turbulent fluctuations that contain more energy than the average turbulent fluctuations. Some time periods appear during the turbulent events take place and very strong transport occurs, while other time periods appear during very little transfer occurs. In addition, the transport of momentum and heat in the ASL does not occur continuously, so turbulent event analyses have been successfully applied to analyze the transport of momentum and heat in ASL (Katul et al., 1997b; Schols, 1984; Wang et al., 2014b).

The transport of momentum and heat in the ASL is complex due to the presence of vertical gradients in both wind and temperature. Atmospheric stability effects on the turbulent transport on momentum and heat in ASL has been studied by many scholars (Li and Bou-Zeid, 2011; Roth and Oke, 1995). However, the effects of wind speed on the turbulent transport on momentum and heat still remains unclear. Many studies show that Reynolds number has an influence on the characteristics of coherent structures (Adrian et al., 2000; Metzger and Klewicki, 2001; Robinson, 1991) and bursting (Blackwelder and Haritonidis, 1983; Rao et al., 1971), since the turbulent events are often associated with this structures and bursting, the influence of Reynolds number on turbulent events cannot be ignored. More complex turbulent features such as ejections and sweeps responsible for a significant component of the momentum and heat transport have received less attention, how they may affect the transport of momentum and heat in ASL still remains unclear.

The objective of our study is to investigate the transport of momentum and heat close to the ground in the ASL. First, the effects of wind speed on the correlation coefficient of momentum flux and heat flux, as well as the transport efficiencies for momentum and heat were investigated. Second, turbulent events techniques were applied to investigate the influence of wind speed on the transport of momentum and heat. The turbulent events are classified by quadrant analysis and the influence of the wind speed on the transport of momentum and heat was quantitatively investigated by analyzing the statistical characteristics of turbulent events. This paper is organized in the following way: Section 2 describes the experimental setup and data pretreatment. In Section 3, the correlation coefficient, transport efficiencies, quadrant analysis and turbulent flux events were introduced. In Section 4, the results are presented and discussed, and main conclusions were given in Section 5.

2. Experimental set-up and data pretreatment

2.1. Experimental set-up

The experimental site is located at the edge of Badain Jilin Desert and Tengger Desert (E: 103.08°, N: 38.62°) in Minqin, China, and the main wind direction was from the northwest. More details of the experimental site can be found in Liu et al. (2014) and Wang et al. (2014a). Experimental data were obtained in the meteorological observation tower. The tower belongs to Gansu Minqin Desert Experimental Station and the height of the tower (as shown in Fig. 1(a)) is 50 m and the cross section is a square truss structure with the side length of 2 m.

Measuring instruments were three component sonic anemometers (Campbell Scientific CSAT3) with a sampling frequency of 50 Hz ($f_c = 50$). The anemometers can provide three-dimensional wind velocities together with temperature, more details about the measuring techniques and experimental apparatus can be found in the work of Liu et al. (2014) and Wang et al. (2014a). In order to avoid the effect of the tower wake, the sonic anemometers were installed on a bar extended 2 m away from the tower and the sonic anemometer probe is pointing toward the main wind direction (northwest) (as shown in Fig. 1(b) and (c)).

2.2. Data pretreatment

The experimental data at fours heights (1 m, 2 m, 3 m, 4 m) were used to the study of the turbulent transport of momentum and heat close to the ground. In order to reduce the experimental error and ensure the streamwise velocity (u) is parallel to the incoming flow direction, spanwise velocity (v) is perpendicular to the incoming flow in the horizontal plane, vertical velocity (w) is in the vertical plane, pre-processing process were conducted for the turbulence data in this study, including noise exclusion process to exclude anomalous data (noise) in raw data and the wind direction adjustment (Liu et al., 2014). Friction velocity U_τ was obtained using the following formula:

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

where u', v' and w' describing the respective fluctuating velocity components, the upper line represents the ensemble average, we use 20 min averaging to define means and fluctuations.

The Obukhov length scale, L, is calculated using the