Coherent Structures and the Dissimilarity of Turbulent Transport of Momentum and Scalars in the Unstable Atmospheric Surface Layer

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Abstract Atmospheric stability effects on the dissimilarity between the turbulent transport of momentum and scalars (water vapour and temperature) are investigated in the neutral and unstable atmospheric surface layers over a lake and a vineyard. A decorrelation of the momentum and scalar fluxes is observed with increasing instability. Moreover, different measures of transport efficiency (correlation coefficients, efficiencies based on quadrant analysis and bulk transfer coefficients) indicate that, under close to neutral conditions, momentum and scalars are transported similarly whereas, as the instability of the atmosphere increases, scalars are transported increasingly more efficiently than momentum. This dissimilarity between the turbulent transport of momentum and scalars under unstable conditions concurs with, and is likely caused by, a change in the topology of turbulent coherent structures. Previous laboratory and field studies report that under neutral conditions hairpin vortices and hairpin packets are present and dominate the vertical fluxes, while under free-convection conditions thermal plumes are expected. Our results (cross-stream vorticity variation, quadrant analysis and time series analysis) are in very good agreement with this picture and confirm a change in the structure of the coherent turbulent motions under increasing instability, although the exact structure of these motions and how they are modified by stability requires further investigation based on three-dimensional flow data.

Keywords Coherent structures · Hairpin vortices · Quadrant analysis · Reynolds analogy · Thermal plumes · Transport efficiencies

1 Introduction

The turbulent transport of momentum and scalars has been the subject of active research in many disciplines such as fluid mechanics, boundary-layer meteorology, eco-hydrology and...
air quality. It has long been assumed that turbulence transports all scalars such as temperature, water vapour and trace gases similarly (the Lewis analogy for turbulence, Kays et al. 2005). This analogy is often extended to include momentum and referred to as the Reynolds analogy. The Reynolds analogy has important applications in turbulent flow simulations, parametrizations and measurements; but it is recognized that this analogy is generally invalid. In the atmospheric boundary layer (ABL), the Reynolds analogy is considered to be applicable only under neutral conditions. As the role of buoyancy increases, the flux–profile relationships (Brutsaert 2005) and the transport efficiencies (De Bruin et al. 1993; Choi et al. 2004; Bou-Zeid et al. 2010) for momentum and scalars become increasingly different. The need to understand the physical causes of this dissimilarity and the role of atmospheric stability in the failure of the Reynolds analogy motivates this study.

Previous studies revealed a number of reasons for dissimilarity among scalars in the ABL such as advection (Lee et al. 2004; Assouline et al. 2008); unsteadiness (McNaughton and Laubach 1998); entrainment at the top of the ABL (Mahrt 1991a; Sempreviva and Hojstrup 1998; De Bruin et al. 1999; Semperviva and Gryning 2000; Asanuma et al. 2007; Katul et al. 2008; Cava et al. 2008) and differences in sources and sinks (Moriwaki and Kanda 2006; Williams et al. 2007; Detto et al. 2008; Moene and Schuttemeyer 2008). The dissimilar transport of momentum and scalars, on the other hand, has been linked to the canopy effect (Katul et al. 1997a). Though our focus here is on the effect of atmospheric stability on the dissimilar transport of momentum and scalars, not among scalars, we note that these non-local effects could also potentially play a role in momentum–scalar flux dissimilarity.

If atmospheric stability is found to play a role in momentum and scalar flux dissimilarity (as expected), then one physical explanation would be the one related to turbulent coherent structures and how they are modified by buoyancy. These structures are of interest because they have been shown to be responsible for a large fraction of the transport of momentum and scalars (Robinson 1991; Marusic et al. 2010a), leading to a paradigm shift in the studies of turbulent transport in the atmosphere, which is no longer viewed as resulting from random turbulent fluctuations across a velocity or scalar gradient. Many laboratory and numerical studies revealed that various forms of coherent structures such as low-speed streaks, hairpin vortices and large-scale motions exist in pipe flows, channel flows and turbulent boundary layers (e.g. Kline et al. 1967; Head and Bandyopadhyay 1981; Kim and Adrian 1999; Monty et al. 2007; Ringuette et al. 2008; Marusic et al. 2010a). It is now generally recognized that hairpin vortices (first proposed by Theodorsen 1952) and the streamwise packets they form are the primary coherent structures forming in the logarithmic layer of the neutral turbulent boundary layer under laboratory conditions (Adrian 2007). Coherent structures have been also investigated in the ABL through numerical simulations, scale model experiments, and field experiments (e.g. Hommema and Adrian 2003; Carper and Porte-Agel 2004; Kanda 2006; Huang et al. 2009; Inagaki and Kanda 2010; Horiguchi et al. 2010). Such investigations, focusing mainly on the neutral ABL, found turbulent structures similar to laboratory structures, such as hairpins, hairpin packets and cross-stream vortices (which might be the leading edges of hairpin vortices) and large-scale organized motions (e.g. Boppe et al. 1999; Horiguchi et al. 2010). In addition, recent review articles have compiled studies that indicate that turbulence and the pressure field in the atmospheric surface layer (ASL) scale similarly to canonical wall-bounded flows (Marusic et al. 2010a), further suggesting that the coherent structures responsible for this scaling are similar. Thus, despite studies suggesting that detached eddies from the outer layer can intrude and be active (i.e. produce fluxes and not only contribute to variances) in the surface layer of the high Reynolds number ABL (Hunt and Morrison 2000; Hunt and Carlotti 2001; Hogstrom et al. 2002; McNaughton and Brunet 2002; Drobinski et al. 2004; Smedman et al. 2007; Drobinski et al. 2007), the classic and more