TOWNSEND'S HYPOTHESIS, COHERENT STRUCTURES AND MONIN–OBUKHOV SIMILARITY

K. G. McNAUGHTON
IERM, University of Edinburgh, Kings Buildings, Mayfield Road, Edinburgh EH9 3JU, Scotland

YVES BRUNET
Station de Bioclimatologie – INRA, BP81, 33883 Villenave d'Ornon cedex, France

(Received in final form 16 July 2001)

Abstract. Townsend's hypothesis states that turbulence near a wall can be divided into an active part that transports momentum, and an inactive part that does not, and that these two kinds of turbulence do not interact. Active turbulence is generated by wind shear and has properties that scale on local parameters of the flow, while inactive turbulence is the product of energetic processes remote from the surface and scales on outer-layer parameters. Both kinds of motion can be observed in the atmospheric surface layer, so Monin–Obukhov similarity theory, which is framed in terms of local parameters only, can apply only to active motions. If Townsend's hypothesis were wrong, so that active and inactive motions do interact in some significant way, then transport processes near the ground would be sensitive to outer-layer parameters such as boundary-layer depth, and Monin–Obukhov theory would fail.

Experimental results have shown that heat transport near the ground does depend on processes in the outer layer. We propose a mechanism for this whereby inactive motions initiate active, coherent ejection/sweep structures that carry much of the momentum and heat. We give evidence that the inactive motions take the form of streak patterns of faster and slower air, and argue that these are induced by the pressure effects of large eddies passing overhead. The streak pattern includes regions where faster streams of air overtake and engulf slower-moving streaks. Transverse vortices form across the spines of the streaks at these places and some of them develop into horseshoe vortices. These horseshoe vortices grow rapidly and are rotated forward in the sheared flow so they soon contact the ground, squirting the air confined between the legs of the horseshoe vortex outwards as a forceful ejection. This model is consistent with a wide range of results from the field and laboratory experiments. Heat transport is significantly affected, so undermining the dimensional assumptions of Monin–Obukhov similarity theory.

Keywords: Coherent structures, Inactive turbulence, Monin–Obukhov similarity, Townsend's hypothesis, Wall streaks.

1. Introduction

Monin–Obukhov similarity theory is an important foundation for much of our understanding of the atmospheric surface layer. The theory posits that the flow in uniform, steady atmospheric surface layers depends on only four local parameters: the height above ground, z, the friction velocity, u_* the kinematic virtual heat flux, $H_v/\rho c_p$, and the buoyancy parameter, g/T_v. That is, Monin–Obukhov theory rests on the assumption that the larger-scale motions in the boundary layer, and so the

Boundary-Layer Meteorology **102:** 161–175, 2002.
© 2002 *Kluwer Academic Publishers. Printed in the Netherlands.*

parameters that characterize them, have no significant influence on the flow near the ground. This means that all meteorological relationships between dimensionless local variables in the atmospheric surface layer must be functions of, z/L, where L, is the well-known Obukhov length scale.

While Monin–Obukhov similarity theory is almost universally accepted, it is not universally applicable. For example, it is known that the variances of horizontal wind velocities are not Monin–Obukhov-similar during the day and that the departure from such similarity is caused by the large-scale convective motions in the bulk of the boundary layer. Despite this, the variance of vertical velocity is often assumed to be Monin–Obukhov-similar, as are scalar variances and mean wind and scalar profiles. But all is not well even here because repeated experiments have failed to define the predicted universal gradient functions of z/L to better than half a decade (Högström, 1996).

Recent results from large-eddy simulation (Khanna and Brasseur, 1997) and analyses of profile data (Johanssen et al., 2001) in convective boundary layers now show that mean profiles near the ground also depend on an additional parameter: the inversion height. Indeed, Monin–Obukhov theory seems to be fully successful only in stable but fully turbulent night-time conditions when the larger-scale motions are absent. This is a remarkable situation.

Here we question Monin–Obukhov similarity theory at its most fundamental level: the assumption that its parameter set is complete for steady conditions over uniform ground. We point to the relationship between this assumption and Townsend's hypothesis that 'active' and 'inactive' components of turbulence do not interact, and to powerful evidence that such interaction does occur. The main part of the paper is then devoted to developing an hypothesis for how this might occur. We review evidence that the coherent structures that transport the majority of the momentum and scalars in the atmospheric surface layer are similar to those observed in laboratory flows over smooth walls, and we extend the correspondence by showing that structures analogous to wall streaks also exist in the atmospheric surface layer. On this basis we propose that inactive motions in the atmospheric surface layer (wall streaks) interact with the active turbulence by initiating the active coherent structures, in much the same way as they do in laboratory flows.

2. Townsend's Hypothesis and Similarity Laws for the Atmospheric Surface Layer

Historically, the Kansas experiment (e.g., Kaimal et al., 1972) established Monin–Obukhov similarity theory as the basic paradigm for describing the diabatic surface layer. However, results from this experiment can equally be interpreted as challenging the theory. Thus Kaimal et al. (1972) found that horizontal velocity spectra did not follow universal forms when normalized according to the rules of Monin–Obukhov similarity. Kaimal (1978) reported that the low-frequency parts of these spectra depend on z_i/L, where z_i is the height of the convective boundary layer, rather than on the Monin–Obukhov parameter z/L. That is, they are the product of large-scale convective motions that fill the whole boundary layer. In the atmospheric surface layer these large-scale motions, which obey outer-layer scaling (OLS), must somehow coexist with the small-scale turbulence that obeys inner-layer scaling (ILS), as prescribed by Monin–Obukhov similarity theory.

Bradshaw (1978) pointed out that Townsend (1961) and Bradshaw (1967) had observed the same phenomenon in laboratory boundary layers. They had noticed larger-scale motions near smooth walls, but found that these motions had no noticeable effect on the relationship between shear stress and the velocity profile there. Townsend (1961) had proposed the general hypothesis that there exist 'active' motions that transport momentum in such situations and that these are distinct from, and do not interact with, the 'inactive' motions that do not carry momentum. Interpreted according to Townsend's ideas, the Kansas wind spectra have an active component that describes the stress-carrying motions and scales on inner-layer parameters, and an inactive component that has no effect on mean wind profiles and scales on outer-layer parameters. Monin–Obukhov similarity theory, which is a form of ILS, can therefore apply only to the active parts of these spectra. Monin–Obukhov theory relies on Townsend's hypothesis because if the latter is not correct then active (transport) processes must depend on OLS parameters in addition to the ILS parameters accepted by Monin–Obukhov similarity theory. This reliance is largely unrecognized.

With its significance not widely appreciated, Townsend's hypothesis has not been tested in any systematic way. Even so, there is strong evidence to support it. Besides the insensitivity of the velocity profile to inactive turbulence, there is the remarkable insensitivity of the mean momentum cospectrum to even extreme disturbance by events in the outer layer. For example, Smeets et al. (1998) found that average momentum cospectra took the usual (Kansas) form on a mountain glacier despite the extreme gustiness caused by surrounding mountains disturbing the wind above.

3. Evidence for the Breakdown of Townsend's Hypothesis

So long as only velocity profiles, velocity spectra and momentum fluxes were considered Townsend's hypothesis seemed secure. However Laubach et al. (2000) and McNaughton and Laubach (2000) have reported an experiment that also provides extensive information on scalar transport, and the results obtained clearly challenge Townsend's hypothesis. The experiment was carried out over a paddy field at Warrawidgee, in Australia, in a situation that created wide separation and independence of the inner-layer and outer-layer scales for velocity, length and scalar concentrations. Here we summarize the results as they bear directly on Townsend's hypothesis.

The experimental rice field lay downwind of extensive dry rangeland, over which the atmospheric boundary layer was usually strongly convective. Thus the OLS length scale was z_i, while the OLS velocity scale was the Deardorff convective velocity scale

$$w_* = \left[\frac{g z_i \langle F_v \rangle}{\theta_v} \right]^{1/3},$$

where g is acceleration by gravity, z_i is the height of the capping inversion, θ_v is the virtual temperature and $\langle F_v \rangle$ is the virtual heat flux averaged over the dry upwind region. The OLS temperature scale was therefore F_T/w_*, where F_T is the large-scale (upwind) kinematic heat flux, and the scales for humidity and carbon dioxide concentrations were both close to zero because of the smallness of their fluxes from the brown upwind plain. The convective activity caused marked fluctuations in wind speed and direction over the rice crop. These are represented by the low-frequency parts of the spectra of horizontal wind components shown in Figure 1.

The wetness contrast produced an advective inversion over the paddy. Measurements were made at two levels, with ratios of fetch over the paddy to instrument height of 100:1 and 200:1. The measurements at the lower level were therefore made securely within an equilibrium sub-layer, free from any significant effects of local advection. The ILS length scale at this position was therefore height, z, the velocity scale was the local friction velocity, u_*, and scales for the various scalars were given by their respective fluxes divided by u_*. If Townsend's hypothesis were correct then all active processes within the equilibrium sub-layer would be expected to scale according to Monin–Obukhov similarity.

The separation and independence of the outer and inner scaling parameters achieved at Warrawidgee contrasts with most laboratory experiments where the ratio of length scales is often a decade less, and where the velocity and scalar scales are usually the same. The experimental conditions also differ from most field experiments by clearly differentiating the local and large-scale effects of buoyancy. Thus any local effects of instability on active processes (as described by Monin–Obukhov theory) could be distinguished from any effects of the OLS convective motions. Townsend's hypothesis says there should be no such effect.

Figure 1 shows averaged spectra for horizontal wind velocity at Warrawidgee. There is a separation in scale of the OLS and ILS motions, as evidenced particularly by the gap in the spectrum of the lateral velocity fluctuations, v. Kansas spectra for the same local stability are shown for reference. The spectral gap is far less evident in the u spectrum apparently because the OLS structures travel faster than the ILS structures.

Cospectra for the momentum and humidity fluxes at the lower height are shown in Figure 2. The averaged momentum cospectrum is similar to the Kansas cospectrum except for the spectral broadening caused by variability in u_* and stability

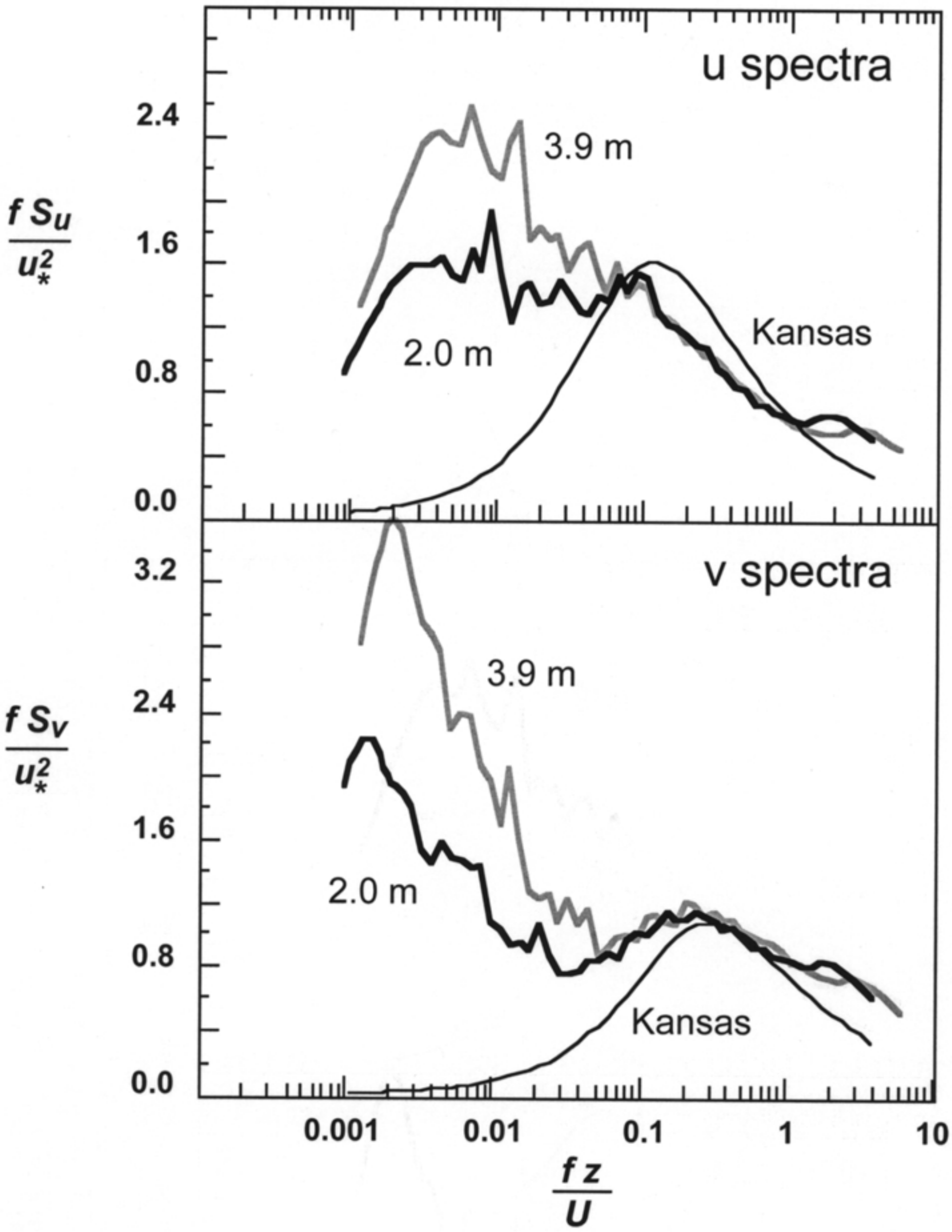

Figure 1. Averaged power spectra of the horizontal velocity fluctuations at Warrawidgee. Results from 31 individual runs were first normalized then averaged. (From McNaughton and Laubach, 2000.)

within runs. By contrast, scalar covariances are enhanced at low frequencies when compared with the corresponding scalar flux cospectrum from Kansas. Similar results have been obtained by Andreas (1987) and Smeets et al. (1998) in situations where topography produced strong motions in the outer part of the boundary layer, and in a wind tunnel with significant turbulence in the free stream above the boundary layer (Moss and Oldfield, 1996). The individual cospectra that make up the averages in Figures 1 and 2 are not shown, but they are highly erratic at lower frequencies. Apparently these erratic peaks make no net contribution to the averaged momentum spectrum, but a significant net contribution to the scalar flux cospectrum. The scalar gradients at Warrawidgee were about 20% smaller than predicted by the usual Monin–Obukhov relationships (Laubach et al. 2000), while the temperature gradients measured by Smeets et al. (1998) over the glacier were about half. Finally, McNaughton and Laubach (2000) argued that the low-frequency extensions to their scalar variance and flux spectra had characteristics consistent with a mixed ILS/OLS scaling regime.

Together, these results demonstrate that ‘inactive’ OLS motions do interact with ‘active’ ILS turbulence. A disconcerting feature of this interaction is that it occurred across a pronounced spectral gap (Figure 1). Spectral gaps are usually taken as a sure indication that the motions or structures represented on either side of the gap do not interact. The evidence for an interaction therefore challenges not only Monin–Obukhov similarity but also much of our understanding of turbulence processes in the atmospheric surface layer. The remainder of this paper addresses this challenge by proposing a mechanism for the interaction between inactive and active turbulence.

4. Turbulence Structure in the Atmospheric Surface Layer

The cospectra shown in Figure 2 were obtained by Fourier analysis. The information they give on the underlying turbulent structures is ambiguous in that covariance at low frequencies can represent either extensive structures with small amplitude, or powerful but more compact and widely separated structures. The experimental situation at Warrawidgee favours the second interpretation because the important processes occurred within an internal boundary layer that was far too shallow to accommodate continuous large eddies with periods of many minutes. This being so, the explanation that offers itself is that inactive motions interact with active turbulence by controlling the initiation or development of compact but widely separated coherent flux-carrying structures. Similar suggestions have been made by Schols et al. (1985) and by Mahrt and Gibson (1992) for turbulence in the atmospheric surface layer, and by many workers such as Rao et al. (1971) and Falco (1991) in laboratory flows. In this explanation the individual coherent structures obey ILS, but part of their spectral energy or cospectral flux is transferred to lower frequencies related to the intervals between the structures, so the averaged

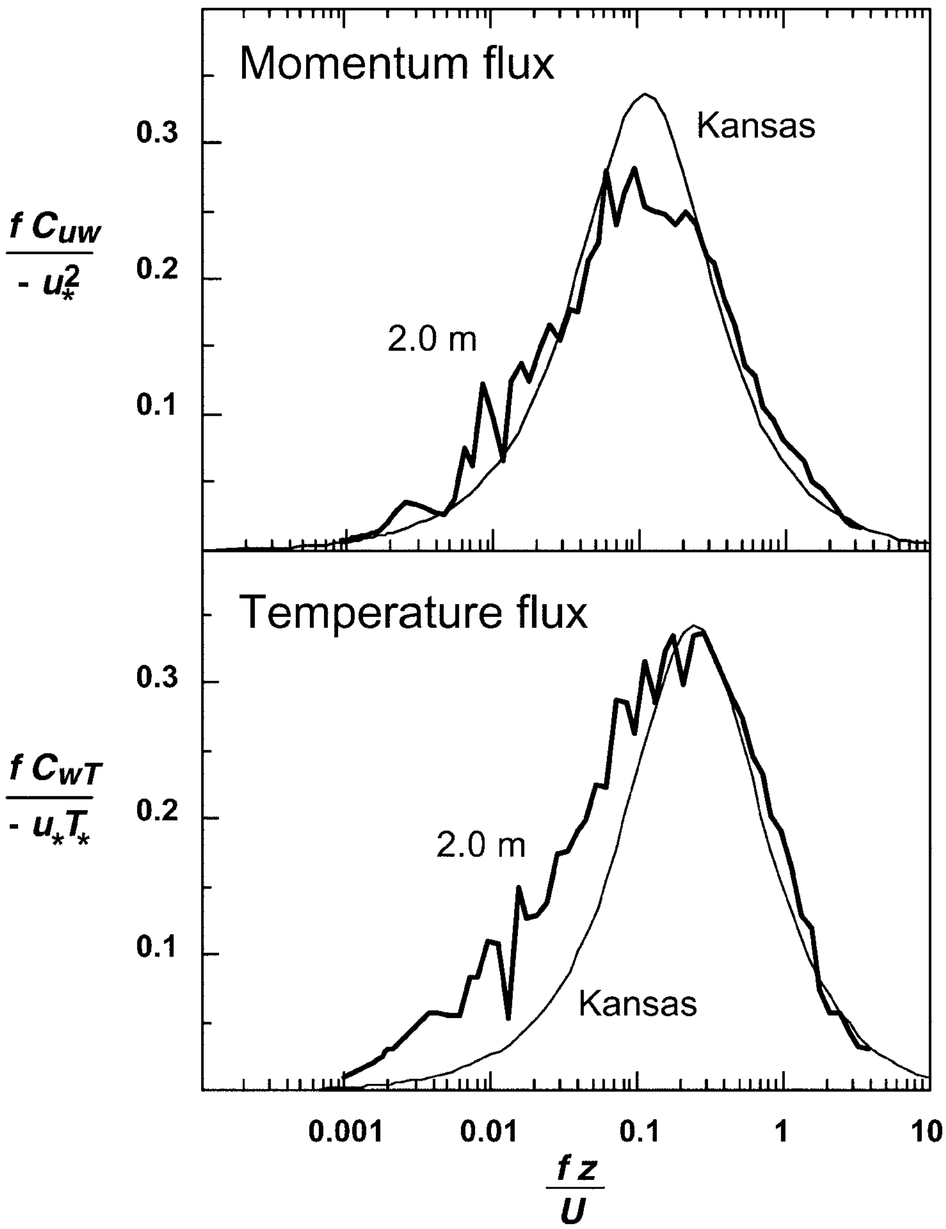

Figure 2. Momentum and humidity flux cospectra. Also shown is the Kansas spectrum. The Kansas temperature cospectrum has been adjusted down in amplitude to best fit the observed cospectrum in the inertial subrange and peak region. (From McNaughton and Laubach, 2000.)

spectrum displays mixed scaling. In this section we review evidence that active and inactive coherent structures near smooth walls in laboratory flows are structurally similar to those found at larger scale in the atmospheric surface layer. A discussion of the mechanism of the interaction follows in the next section.

It is known that active coherent structures in the atmospheric surface layer have many points of similarity with those found in laboratory flows over smooth walls. In both cases momentum is transported mainly by sharp upwards motions of air with small streamwise velocity, called ‘ejections’, and associated with these are ‘sweeps’ of faster, descending air which also transport momentum. Narasimha and Kailas (1990) have noted that the intervals between ejection/sweep events have similar bi-modal pattern in both cases. That is, ejection/sweep events are grouped into ‘bursts’ in both atmospheric and laboratory flows. The average interval between these bursts scales on the geometric mean of the ILS and OLS time scales for both smooth (Alfredsson and Johansson, 1984; Shah and Antonia, 1989) and rough (Antonia and Krogstad, 1993; Demare et al., 1999) walls. This agrees with the interpretation of McNaughton and Laubach (2000) that the low-frequency extensions of the scalar flux and variance spectra at Warrawidgee display mixed scaling. Also, similar-shaped ramps in scalar concentrations are observed near the surface when scalar flux issues from the wall or ground. These ramps are associated with ejection/sweep events and have similar properties in all flows (Antonia et al., 1979).

A missing point of similarity is the ‘wall streaks’ that have been observed only in laboratory flows over smooth walls. Wall streaks are ribbons of low-velocity fluid that are found next to smooth walls and are closely associated with the bursting phenomenon in laboratory flows (Kline et al., 1967; Robinson, 1991). They have not been observed over rough walls, and Antonia and Djendi (1997) think that they are unlikely to be found there. The origin of these streaks is itself controversial (Bradshaw, 1969). The dominant opinion is that they are a generated by the bursting process itself, but the alternative view – that they are caused or initiated by inactive turbulence impinging on the surface – has not been disproved.

There is evidence that wall streaks also occur in the atmospheric surface layer, and that they obey OLS. Thus Davison (1974) and Wilczak and Tillman (1980) have detected elongated temperature structures near the ground using arrays of towers. However, the best evidence is from the infra-red images of the surface taken from an aircraft by Derksen (1974). These show streaky patterns in crop-surface temperature, with the positions of the streaks changing with time, showing they are not related to surface features. A single infra-red image of pasture by Schols et al. (1985) shows the same phenomenon. Similar temperature streaks have been detected on smooth and rough walls in laboratory flows by Hetsroni et al. (1997), where they are associated with the streak pattern of near-surface velocity. These temperature patterns are a step away from the velocity patterns that define wall streaks, but McNaughton and Laubach (2000) found that the fluctuations in surface temperature closely followed variations in near-surface wind speed at Warrawidgee (op. cit. Fig. 10), and that the spectrum of surface temperature obeys OLS (op. cit. Fig. 9), like the inactive motions. Spectral results like these are not peculiar to the conditions at Warrawidgee since similar results have been obtained by Lagouarde et al. (1997) for a forest canopy and Katul et al. (1998) for grass in a forest clearing.

The significance of the Warrawidgee result is that scaling of the spectrum of infra-red surface temperature on OLS variables cannot be interpreted in any way but that the 'inactive' motions directly caused the observed variations in surface temperature. The OLS motions have an independent power source at large scale (buoyancy) and they imprint their spectral shape on the temperature fluctuations at the ground. If the spatial geometry associated with these fluctuations is a streak pattern, as shown in Derksen's images, then this pattern must be directly caused by the turbulent motions overhead. We may ask how this could happen, and for this there appears to be two options.

The first option is that large eddies from the outer layer penetrate the surface layer, sweeping up slow, near-surface air into ridges by their rotation. Such vortical motions would transfer momentum to the ground, enhancing the momentum cospectrum at the same OLS frequencies as observed in the spectrum of surface temperature. Such motions would not be inactive in momentum transport, and they were not observed at Warrawidgee (Figure 1).

The second option is that the OLS eddies of the effective scales are blocked by pressure reflection at the ground, so it is the reactive pressure pattern that induces the horizontal motions near the ground and creates the OLS streak pattern. Such horizontal motions would not transport momentum and so would be inactive. High-pressure areas would constitute zones of subsidence and horizontal divergence while low-pressure areas would constitute zones of local uplift and horizontal convergence. Because wind speed increases with height, subsided air is faster than the average at the new level while uplifted air is slower. The pattern of faster and slower air movement depends on both the form of the pressure-producing motions aloft and their movement relative to the near-surface wind. Now the OLS eddies travel with the wind aloft and so move faster than the air near the ground. This relative motion alone is sufficient to produce a streaky pattern of wind speeds near the ground. It is also probable that the pressure pattern itself has a streamwise alignment because shear in the lower boundary layer shapes the eddies there into quasi-streamwise vortices (Lee et al., 1990; Moeng and Sullivan, 1994).

It thus appears that turbulent transport processes are remarkably similar in laboratory and atmospheric surface layers. In both cases the majority of the momentum and scalars transport is by the active ejection/sweep structures, and in both cases there exist inactive streak patterns in the near-surface flow. It remains to show how the inactive streak motions might interact with the active ejection/sweep structures.

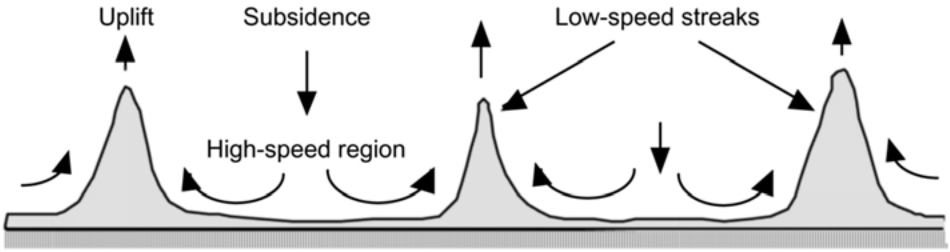

Figure 3. Schematic cross-flow section of the low-speed streaks near the ground. (After Smith and Walker, 1997.)

5. A Model for the Interaction of Active and Inactive Turbulence

We propose that the large-scale wall streaks in the atmospheric surface layer initiate bursts of ejection/sweep structures in exactly the same way as occurs at smaller scale against smooth walls in laboratory flows. Such a link is widely accepted for laboratory flows, though there is no agreed model of exactly what ejection/sweep structures are or exactly how they are initiated (Robinson, 1991). We also propose a model for how this might occur. The model is based primarily on laboratory observations because few suitable atmospheric observations are available. Rather than attempt to review the whole large literature on turbulent structure in wall-bounded shear flows, we proceed by asserting a plausible model followed by a summary of some key supporting results. Our intention is to show that such an interaction is possible, leaving a fuller account of the model for elsewhere.

We have described how the pressure fluctuations originating from above the surface layer cause streaky patterns of velocity variations to form, and that these are aligned with the surface wind. The high-speed streams of subsiding air spread laterally, creating sharp convergence lines of uplifted, slower air in the flow. The slow streaks are therefore narrower and more upright in form than the subsiding zones between them, as shown in Figure 3. The differences in speed of the various parts of the flow then creates convergence zones where the high-speed air streams overtake the slower-moving streaks.

In each of these zones the faster air stream at first simply passes about the slower streak, creating a zone of strong shear between the faster and slower air streams. The velocity profile along normals to this interface is strongly inflected and so forms a classic source of instability in the flow. It initiates a series of transverse roll vortices, just as similar inflexions do in plane mixing layers, but here the roll vortices are draped across the spine of the engulfed streak. These vortices describe gentle arcs where the streak is low and broad, but become croissant- or horseshoe-shaped over taller, more upright, parts of streaks. Well-formed horseshoe vortices can then assume a life of their own, continuing to grow by taking vorticity and turbulence kinetic energy from the mean flow itself. The mean shear also rotates these coherent vortices forward until, by a combination of growth and rotation, they contact the ground to form a dam with strong inflows along the ground produced by the rotation of the vortex arms and the main flow pressing in from behind. With nowhere else to go, the trapped air squirts backwards and outwards into the flow. This squirt is usually described as an ejection while the downwards flow around the outside of the vortex constitutes the sweep of the ejection/sweep event. The sequence then repeats along the streak for so long as conditions remain favourable, producing a burst of ejection/sweep events. A schematic diagram of the formation of the first ejection on a streak is shown as Figure 4.

This model of the bursting process is consistent with information from many sources. Theoretical arguments for the initiation of horseshoe vortices about slow-moving masses of fluid attached to the ground, with subsequent vortex and roll-up and ejection, were given by Theodorsen (1952), though he did not know of wall streaks nor appreciate the power of the ejection. Kline et al. (1967) described wall streaks and their oscillation and break-up with sudden ejection of fluid from very near the wall, though they did not detect the overtaking fluid or the horseshoe vortices. Corino and Brodkey (1969) showed the colliding masses of fluid and the power of the ejections, but their visualization methods did not detect the critical horseshoe vortices. A relationship between wall streaks and horseshoe vortices was first proposed by Hinze (1975) and Offen and Kline (1975), and shown experimentally by Swearingen and Blackwelder (1987), amongst others, but in flows where the Reynolds number was too small to promote vigorous ejections. The combination of horseshoe vortex and powerful ejection was first demonstrated experimentally by Hagen and Kurosaka (1993). A sequence of horseshoe eddies followed by a vigorous ejection, after which Figure 4 was partly modelled, has been deduced by Lin (2000) from a large-eddy simulation (LES) of the convective atmospheric boundary layer. The importance of pressure rather than vorticity in creating motions near the ground was shown from LES results by Moeng (reported by Peltier et al., 1996). The model described above is thus strongly foreshadowed in the literature, but the proposed pressure mechanism for streak formation is new as is the important consequence that wall streaks may form within fully-turbulent surface layers. Previously, wall-streak formation has been associated only with viscous sub-layers.

The above model shows that interaction between inactive and active turbulence is possible in principle, but it does not address the interesting question of why heat flux cospectra are sensitive to the scale at which coherent structures are initiated by large-scale streaks while momentum cospectra evidently are not (Figure 2). The answer to this question depends on the unique roles of pressure in the transport of momentum in ejection/sweep structures. That discussion is beyond the scope of the present paper.

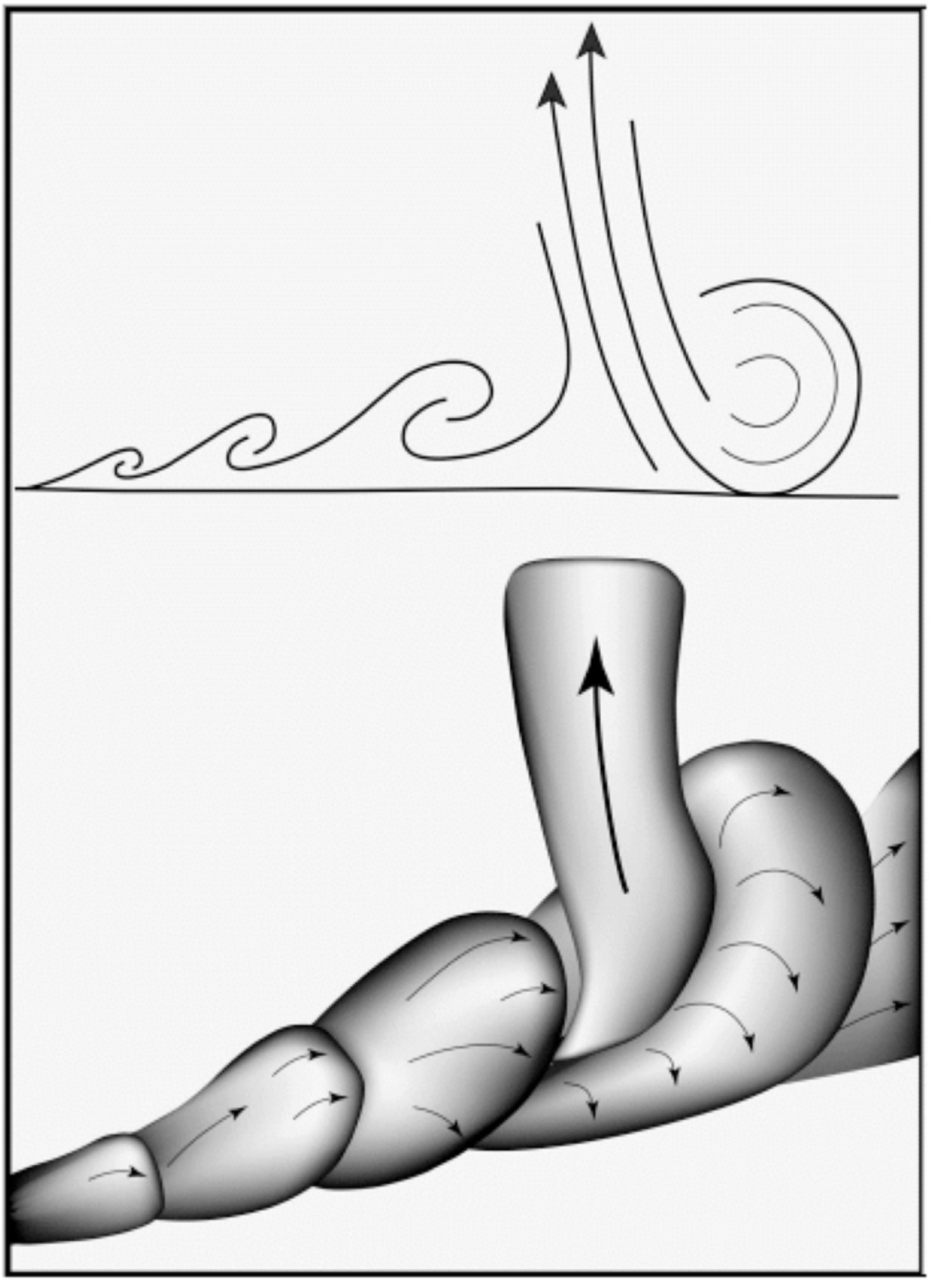

Figure 4. Schematic diagram of a series of vortices forming across the spine of a low-speed streak. The upper panel shows a longitudinal section down the streak while the lower panel represents to outline of the air of the streak as the vortices form. The vortices lying across the spine of the streak take on a ‘horseshoe’ or ‘hairpin’ shape where the streak is sufficiently upright, and these can grow to the point where they contact the ground and cause a vigorous ejection of fluid.

6. Conclusions

The arguments above have far-reaching implications. Firstly, inactive turbulence does interact with active turbulence near the ground so Townsend's hypothesis is not correct. The mechanism seems to be that inactive turbulence near the ground occurs as streaky patterns of horizontal velocity, and this pattern creates zones of sharp convergence that initiate bursts of active ejection/sweep events. This interaction apparently has little average effect on momentum transport, although it does affect its intermittence, and it clearly affects both the intermittence and the mean transport of scalar species. In particular it affects heat transport, which therefore does not observe Monin–Obukhov similarity. This failure of temperature to obey Monin–Obukhov similarity theory then undermines the whole of Monin–Obukhov theory, since the Obukhov length itself then depends on outer-layer parameters. Put succinctly, Monin–Obukhov theory fails because its basis set of parameters is incomplete.

Acknowledgements

This research was supported at the University of Edinburgh by the Natural Environment Research Committee under grant GR3/12545.

References

Alfredsson, P. H. and Johansson, A. V.: 1984, 'Time Scales in Turbulent Channel Flow', *Phys. Fluids* **27**, 1974–1981.

Andreas, E. L.: 1987, 'Spectral Measurements in a Disturbed Boundary Layer over Snow', *J. Atmos. Sci.* **44**, 1912–1939.

Antonia, R. A. and Djendi, L.: 1997, 'Reynolds Stress Producing Motions in Smooth and Rough Wall Boundary Layers', in R. L. Panton (ed.), *Self-Sustaining Mechanisms of Wall Turbulence*, Advances in Fluid Mechanics 15, Computational Mechanics Publications, Southampton, pp. 181–199.

Antonia, R. A. and Krogstad, P.: 1993, 'Scaling of the Bursting Period in Turbulent Rough-Wall Boundary Layers', *Exp. Fluids* **15**, 82–84.

Antonia, R. A., Chambers, A. J., Friehe, C. A., and Van Atta, C. W.: 1979, 'Temperature Ramps in the Atmospheric Surface Layer', *J. Atmos. Sci.* **36**, 99–108.

Bradshaw, P.: 1967, 'Inactive Motion and Pressure Fluctuations in Turbulent Boundary Layers', *J. Fluid Mech.* **30**, 241–258.

Bradshaw, P.: 1969, 'The Structure of Turbulent Shear Flows', in S. J. Kline, M. V. Morkovin, G. Sorovan et al. (eds.), in *Proceedings of the 1968 AFOSR-IFP-Stanford Conference on Computation of Turbulent Boundary Layers*, Stanford University, 1968, Stanford University, Dept. Mech. Eng., Palo Alto, pp. 403–423.

Bradshaw, P.: 1978, 'Comments on "Horizontal Velocity Spectra in an Unstable Surface Layer"', *J. Atmos. Sci.* **35**, 1768–1769.

Corino, E. R. and Brodkey, R. S.: 1969, 'A Visual Investigation of the Wall Region in Turbulent Flow', *J. Fluid Mech.* **37**, 1–30.

Davison, D. S.: 1974, 'The Translation Velocity of Convective Plumes', *Quart. J. Roy. Meteorol. Soc.* **100**, 572–592.

Demare, S., Labraga, L., and Tournier, C.: 1999, 'Comparison and Scaling of the Bursting Period in Rough and Smooth Walls Channel Flows', *ASME J. Fluids Eng.* **121**, 735–746.

Derksen, W. J.: 1974, 'Thermal Infrared Pictures and the Mapping of Microclimate', *Neth. J. Agric. Sci.* **22**, 119–132.

Falco, R. E.: 1991, 'A Coherent Structure Model of the Turbulent Boundary Layer and its Ability to Predict Reynolds Number dependence', *Phil. Trans. Roy. Soc. Lond. A* **336**, 103–129.

Hagen, J. P. and Kurosaka, M.: 1993, 'Corewise Cross-Flow Transport in Hairpin Vortices – The "Tornado Effect" ', *Phys. Fluids A* **5**, 3167–3174.

Hetsroni, G., Mosyak, A., and Yarin, L. P.: 1997, 'Thermal Streak Regeneration in the Wake of a Disturbance in a Turbulent Boundary Layer', *Int. J. Heat Mass Transfer* **40**, 4161–4168.

Hinze, J.: 1975, *Turbulence*, McGraw-Hill, New York, 790 pp.

Högström, U.: 1996, 'Review of Some Basic Characteristics of the Atmospheric Surface Layer', *Boundary-Layer Meteorol.* **78**, 215–246.

Johansson, C., Smedman, A-S., Högström, U., Brasseur, J. G., and Khanna, S.: 2001, 'Critical Test of the Validity of Monin–Obukhov Similarity during Convective Conditions', *J. Atmos. Sci.* **58**, 1549–1566.

Kaimal, J. C.: 1978, 'Horizontal Velocity Spectra in an Unstable Surface Layer', *J. Atmos. Sci.* **35**, 18–24.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y., and Coté, O. R.: 1972, 'Spectral Characteristics of Surface-Layer Turbulence', *Quart. J. Roy. Meteorol. Soc.* **98**, 563–589.

Katul, G. G., Schieldge, J., Hsieh, C. I., and Vidakovic, B.: 1998, 'Skin Temperature Perturbations Induced by Surface Layer Turbulence above a Grass Surface', *Water Resour. Res.* **34**, 1265–1274.

Khanna, S. and Brasseur, J. G.: 1997, 'Analysis of Monin–Obukhov Similarity from Large-Eddy Simulation', *J. Fluid Mech.* **345**, 251–286.

Kline, S. J., Reynolds, W. C., Schraub, F. A., and Runstadler, P. W.: 1967, 'The Structure of Turbulent Boundary Layers', *J. Fluid Mech.* **30**, 741–773.

Lagouarde, J. P., Dubreton, S., Moreau, P., and Guyon, D.: 1997, 'Analyse de l'Ergodicit, de la température de surface sur des couverts forestiers à diverse résolutions', in G. Guyot and T. Phulpin (eds.), *Physical Measurements and Signatures in Remote Sensing*, Balkema, Rotterdam, pp. 303–310.

Laubach, J., McNaughton, K. G., and Wilson, J. D.: 2000, 'Heat and Water Vapour Diffusivities near the Base of a Disturbed Stable Internal Boundary Layer', *Boundary-Layer Meteorol.* **94**, 23–63.

Lee, M. J., Kim, J., and Moin, P.: 1990, 'Structure of Turbulence at High Shear Rate', *J. Fluid Mech.* **216**, 561–583.

Lin, C-L.: 2000, 'Local Pressure Transport Structure in a Convective Atmospheric Boundary Layer', *Phys. Fluids* **12**, 1112–1128.

Mahrt, L. and Gibson, W.: 1992, 'Flux Decomposition into Coherent Structures', *Boundary-Layer Meteorol.* **60**, 143–168.

McNaughton, K. G. and Laubach, J.: 2000, 'Power Spectra and Cospectra for Wind and Scalars in a Disturbed Surface Layer at the Base of an Advective Inversion', *Boundary-Layer Meteorol.* **96**, 143–185.

Moeng, C. and Sullivan, P. P.: 1994, 'A Comparison of Shear- and Buoyancy-Driven Planetary Boundary Layers', *J. Atmos. Sci.* **51**, 999–1022.

Moss, R. W. and Oldfield, M. L. G.: 1996, 'Effect of Free-Stream Turbulence on Flat-Plate Heat Flux Signals: Spectra and Eddy Transport Velocities', *ASME J. Turbomachinery* **118**, 461–467.

Narasimha, R. and Kailas, S. V.: 1990, 'Turbulent Bursts in the Atmosphere', *Atmos. Environ.* **24A**, 1635–1654.

Offen, G. R. and Kline, S. J.: 1975, 'A Proposed Model of the Bursting Process in Turbulent Boundary Layers', *J. Fluid Mech.* **70**, 209–228.

Peltier, L. J., Wyngaard, J. C., Khanna, S., and Brasseur, J. G.: 1996, 'Spectra in the Unstable Surface Layer', *J. Atmos. Sci.* **53**, 49–61.

Rao, K. N., Narasimha, R., and Narayanan, M. A. B.: 1971, 'The Bursting Phenomenon in a Turbulent Boundary Layer', *J. Fluid Mech.* **48**, 339–352.

Robinson, S. K.: 1991, 'Coherent Motions in the Turbulent Boundary Layer', *Annu. Rev. Fluid Mech.* **23**, 601-639.

Schols, J. L. J., Jansen, A. E., and Krom, J. G.: 1985, 'Characteristics of Turbulent Structures in the Unstable Atmospheric Surface Layer', *Boundary-Layer Meteorol.* **33**, 173–196.

Shah, D. A. and Antonia, R. A.: 1989, 'Scaling of the "Bursting" Period in Turbulent Boundary Layer and Duct Flows', *Phys. Fluids A* **1**, 318–325.

Smeets, C. J. P., Duynkerke, P. G., and Vugts, H. F.: 1998, 'Turbulence Characteristics of the Stable Boundary Layer over a Mid-Latitude Glacier. Part I: C combination of Katabatic and Large-Scale Forcing', *Boundary-Layer Meteorol.* **87**, 117–145.

Smith, C. R., and Walker, J. D. A.: 1997, 'Sustaining Mechanisms of Turbulent Boundary Layers: The Role of Vortex Development and Interaction', in R. L. Panton (ed.), *Self-Sustaining Mechanisms of Wall Turbulence*, Advances in Fluid Mechanics 15, Computational Mechanics Publications, Southampton, pp. 273–308.

Swearingen, J. D. and Blackwelder, R. F.: 1987, 'The Growth and Breakdown of Streamwise Vortices in the Presence of a Wall', *J. Fluid Mech.* **182**, 255–290.

Theodorsen, T.: 1952, 'Mechanism of Turbulence', in *Proceedings of the Second Midwestern Conference on Fluid Mechanic*s, Columbus, Ohio, Ohio State University, pp. 1–18.

Townsend, A. A.: 1961, 'Equilibrium Layers and Wall Turbulence', *J. Fluid Mech.* **11**, 97–120.

Weske, J. R. and Plantholt, A. H.: 1953, 'Discrete Vortex Systems in the Transition Range of Fully Developed Flow in a Pipe', *J. Aerosol. Sci.* **20**, 717–718.

Wilczak, J. M. and Tillman, J. E.: 1980, 'The Three-Dimensional Structure of Convection in the Lower Atmospheric Surface Layer', *J. Atmos. Sci.* **37**, 2424–2443.