1.8 TOWNSEND'S HYPOTHESIS, COHERENT STRUCTURES AND MONIN-OBUKHOV SIMILARITY

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1. INTRODUCTION

Monin Obukhov (MO) similarity theory is an important foundation for much of our understanding of the atmospheric surface layer (ASL). The theory posits that the flow in uniform, steady ASLs depends on only four parameters: the height above ground, $\boldsymbol{z}$, the friction velocity, $\boldsymbol{u}_*$, the kinematic virtual heat flux, $\boldsymbol{H}_V/\rho\boldsymbol{c}_p$, and the buoyancy parameter, $\boldsymbol{g}/\boldsymbol{T}_V$. This means that all meteorological relationships between dimensionless variables must be functions of, $\boldsymbol{z}/\boldsymbol{L}_V$, where $\boldsymbol{L}_V$, 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 MO-similar during the day because they are affected by large-scale convective motions, which are not MO-similar. On the other hand, the variance of vertical velocity is often assumed to be MO-similar, as are scalar variances and mean wind and scalar profiles. Even so, repeated experiments have failed to define precisely the predicted universal functions. Spectra of wind and scalar fluctuations also are not fully MO-similar in unstable conditions (Kaimal et al., 1972). Indeed, Monin-Obukhov theory seems to be fully successful only in stable but fully turbulent night-time conditions. This is a remarkable situation.

Here we question MO similarity theory at its most fundamental level: the assumption that its parameter set is complete for steady conditions over homogeneous ground. We point to the relationship between this assumption and Townsend's hypothesis, and to evidence for the failure of Townsend's hypothesis. We then propose a mechanism to explain how this comes about.

2. TOWNSEND'S HYPOTHESIS AND SIMILARITY LAWS FOR THE ASL

Historically, the Kansas experiment established MO similarity theory as the basic paradigm for modelling the diabatic ASL. However, 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 MO similarity. Kaimal (1978) reported that the low-frequency parts of these spectra depend on $\boldsymbol{z}_i/\boldsymbol{L}$, where $\boldsymbol{z}_i$ is the height of the convective boundary layer, rather than on the MO parameter $\boldsymbol{z}/\boldsymbol{L}$. That is, they represent large-scale convective motions that fill the whole boundary layer. In the ASL 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 MO 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 the wall in boundary layers, 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 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 that scales on inner-layer variables, and an inactive component that has no effect on mean wind profiles and obeys outer-layer scaling (OLS). MO similarity theory, which is based on inner-layer scaling (ILS), can therefore apply only to the active parts of these spectra.

MO 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 those accepted by MO 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. In addition to the insensitivity of the velocity profile to inactive turbulence, there is the remarkable insensitivity of the mean momentum spectrum to even extreme disturbance by events in the outer layer. For example, Smeets et al. (1998) found that average momentum spectra took the usual (Kansas) form on a mountain glacier

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despite the extreme gustiness caused by surrounding mountains disturbing the wind above.

3. THE WARRAWIDGEE EXPERIMENT

Laubach et al. (2000) and McNaughton and Laubach (2000) have reported an experiment that provides a strong test of Townsend's hypothesis. It was carried out over a paddy field at Warrawidgee, in Australia, in a situation that created wide separation and independence of the inner and outer-layer scales for velocity, length and scalar concentrations.

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, $\boldsymbol{z}_\mathrm{I}$, while the OLS velocity scale was the Deardorff convective velocity scale

$$w_* = \left[\frac{g\, z_\mathrm{I} \langle F_\mathrm{v} \rangle}{\theta_\mathrm{v}}\right]^{1/3}$$

where θ_v is the virtual temperature and $\langle \boldsymbol{F}_\mathrm{v} \rangle$ is the virtual heat flux averaged over the dry upwind region. The OLS temperature scale was therefore $\boldsymbol{F}_\mathrm{T}/\boldsymbol{w}_*$ and the scales for humidity and carbon dioxide concentrations were both close to zero because of the smallness of their fluxes from the brown 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 surface layer was free from any significant effects of local advection at the lower level. The ILS length scale at this position was therefore height, $\boldsymbol{z}$, the velocity scale was the local friction velocity, $\boldsymbol{u}_*$, and scales for the various scalars were given by their respective fluxes divided by $\boldsymbol{u}_*$.

The scale separation and independence achieved at Warrawidgee contrasts with most laboratory experiments where the ratio of length scales is often a decade less, where the outer and inner layers often share the same velocity scale, $\boldsymbol{u}_*$, and the same scalar scales based on the identical surface flux. The 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 MO-theory) could be distinguished from any effects of the OLS convective motions. Townsend's hypothesis implies that the latter should not exist.

Figure 1 shows averaged spectra for horizontal velocity at Warrawidgee. There is marked separation of the spectral peaks for OLS and ILS motions, particularly for the lateral velocity fluctuations, $\boldsymbol{v}$. Kansas spectra for the same local stability are shown for reference. The spectral gap is far less evident in the $\boldsymbol{u}$ spectrum

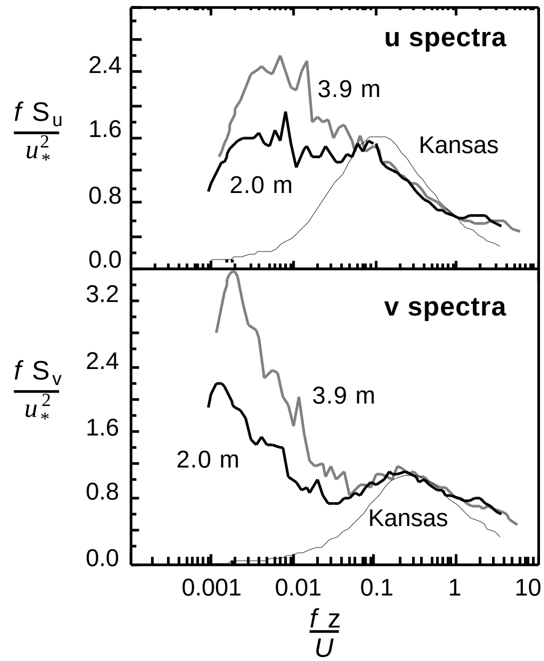

Figure 1. Averaged power spectra of the horizontal velocity fluctuations at Warrawidgee. Results from 31 individual runs were first normalized then averaged.

apparently because the ILS structures are elongated in the $\boldsymbol{u}$ direction, and the OLS structures travel faster than the ILS structures.

Cospectra for momentum and humidity fluxes at the lower height are shown in Figure 2. The averaged momentum cospectrum is similar to the Kansas spectrum except for the spectral broadening caused by variability in $\boldsymbol{u}_*$ and stability 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 layer. The individual cospectra, which 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, while they make a significant net contribution to the scalar flux. The shapes of scalar power spectra at Warrawidgee (not shown) were also biased towards lower frequencies, though total variance was little affected (McNaughton and Laubach, 2000; Laubach et al. 2000).

Together, these results demonstrate that 'inactive' OLS motions do interact with 'active' ILS turbulence. The question is how they can do so across the spectral gap evident in Figure 1.

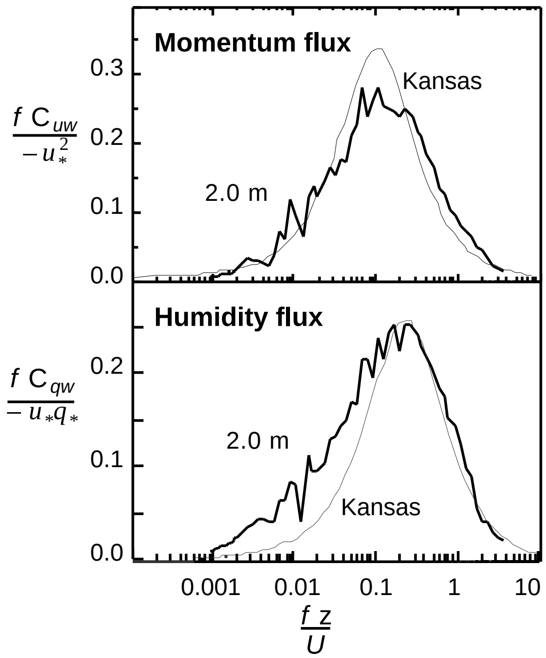

Figure 2. Momentum and humidity flux cospectra. Also shown is the Kansas spectrum, adjusted only in amplitude to best fit the observed average cospectra.

4. INTERACTION OF OLS MOTIONS AND COHERENT STRUCTURES

The cospectra shown in Figure 2 were obtained by Fourier analysis. They are 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 Warrawidgee results favour the second interpretation because the important processes occur within an internal boundary layer that is far too shallow to accommodate continuous large eddies with periods of many minutes. This being so, the Warrawidgee results strongly suggest that the OLS motions interact with the ILS motions by controlling the initiation or development of coherent flux events. 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) in laboratory flows.

It is known that coherent structures in the atmospheric surface layer have many similarities to those found in laboratory flows over smooth walls. Thus momentum is transported mainly by sharp upwards motions of air with small streamwise velocity, called 'ejections'. 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 bimodal pattern in both situations. That is, 'ejection/sweep' events are grouped into 'bursts' in both atmospheric and laboratory flows. The intervals between bursts observe OLS in flows with high Reynolds numbers (Antonia and Krogstad, 1993). Also, ramps in the concentration of transported scalars can be observed when a scalar flux issues from the wall or ground. These are associated with ejection/sweep events and have similar properties in all flows (Antonia et al., 1979).

The only disputed point of similarity concerns 'wall streaks'. These are ribbons of low-velocity fluid adjacent to the wall that are closely associated with the bursting phenomenon (Kline et al, 1967; Robinson, 1991). Wall streaks have not been observed over rough walls, and Antonia and Djenidi (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 by inactive turbulence impinging on the surface—has never been disproved.

There is evidence that wall streaks do occur in the ASL, and that they obey OLS. Thus Davison (1974) and Wilczac and Tillman (1980) have detected elongated structures like wall streaks using arrays of towers. However, the best evidence is from the infra-red images of surface temperature taken from an aircraft by Derksen (1974). These show streaky patterns in crop-surface temperature, and the positions of these streaks changed 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. At Warrawidgee it was found that fluctuations in surface infra-red temperature closely follow variations in near-surface wind speed, and that the spectrum of surface temperature obeys OLS. These spectral results 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 that time scale on the temperature fluctuations. 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 inactive motions. In this way we resolve the controversy about the origin of wall streaks in boundary layers. We agree with Sternberg (see Bradshaw, 1969) that they are a product of the OLS turbulence impinging on the ground.

5. 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 controls the formation of wall streaks, and that these affect the disposition of the bursts of ejection/sweep events. This interaction apparently has little average effect on momentum transport, though it does affect its intermittency, and it clearly affects both the intermittency and the mean transport of scalar species. In particular it affects temperature transport, which therefore does not display MO similarity. This failure of temperature to obey MO similarity theory then undermines the whole of MO theory, since the Obukhov length itself depends on outer-layer parameters.

Put succinctly, Monin-Obukhov theory fails because its set of basis parameters is incomplete. The practical significance of this has yet to be determined.

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