9.10 A MODEL OF THE LARGE-SCALE RAMP STRUCTURES OBSERVED IN THE ATMOSPHERIC SURFACE LAYER

K.G. McNaughton* and R.E. Blundell
University of Edinburgh, Scotland

1. INTRODUCTION

Potentially, a better understanding of turbulent structure can provide better closures for Reynolds-averaged Navier-Stokes (RANS) models and better sub-grid schemes for large-eddy simulation (LES) models. Taking an optimistic view, such understanding might even lead to a new class of 'structural dynamics' models: models based on the macroscopic dynamics of the coherent structures themselves. Unfortunately the mechanism, or mechanisms of turbulence remain obscure so little of this potential has been realized. The main obstacle to progress has been the very complexity of fully turbulent flows themselves. This makes direct observations extremely difficult and full numerical simulations unachievable for most flows. The atmospheric boundary layer (ABL) is particularly difficult to study both because it is large and because it is extremely complex, with Reynolds numbers typically greater than 10^6. High Reynolds numbers in the ABL, however, provide opportunities as well as obstacles because the deep log layers that are so difficult to obtain in the laboratory are commonplace in the ABL. This paper is concerned with the structure of turbulence in the log layer. In particular, it is concerned with the large-scale ramp-like structures that have been observed in log layers, both in the laboratory and in the lowest part of the ABL.

2. LARGE-SCALE RAMP-LIKE STRUCTURES

Large-scale ramp-like structures were first observed by Head & Bandyopadhyay (1981) in a wind tunnel with $Re_\theta > 10^4$. They released smoke from the floor of the tunnel and illuminated x-z sections through it with a plane of laser light. They saw ramp-like structures that contained a series of vortex centres. Head & Bandyopadhyay interpreted these structures as groups of hairpin vortices, of the kind predicted by Theodorsen (1952). The hairpins individually leaned forward at 45˚ and were contained within a linear envelope inclined upwards at about 20˚.

This model of larger-scale ramps was taken up and developed over many years by Perry and his collaborators (Perry & Chong, 1982; Perry & Marusic, 1995; Chong et al. 1998). They were able to reproduce a number of the statistical properties of the turbulence by proposing suitable forms and properties for the hairpins, but their model lacked a mechanistic foundation and so was unable to explain why the hairpins behave in such fashion. The most recent contribution to this line of development is by Marusic (2001), who has shown that the two-point velocity correlation function observed in a laboratory flow can be reproduced by a model of this kind. This adds to the evidence that these ramp-like structures not only exist in surface-layer turbulence, but are a principal component of it, but it leaves unanswered the basic question of mechanism.

Recent observations of large-scale ramp-like structures have confirmed the earlier results and have given new detail on their structure. Thus Adrian ***et al***. (2000) used particle image velocimetry (PIV) to produce complete maps of velocity in the x-z plane of a channel flow. They confirmed the ramp-like structures and even found ramps within ramps. In search of higher Reynolds numbers, Hommema & Adrian (2001) went outdoors and released smoke from a slot cut into the ground in flat desert. They illuminated the smoke with a sheet of laser light and observed ramp structures like those seen by Head & Bandyopadhyay (1981). Ramp structures more than a meter high were observed but maximum size was limited by the experimental setup rather than the availability of larger structures in the flow.

Evidence that these ramp structures can be much larger comes from Mayer et al. (1994), who used wavelet transforms to analyse momentum flux data from an instrument at 4m over land. They found frequent sequences in which a large structure arrived first, followed by a series of associated and progressively smaller structures. The largest structures were more than 100 m long.

3. GROWTH OF A DISTURBANCE IN PLANE-PARALLEL FLOW

Large-scale ramp-like structures appear to be isolated disturbances that grow autonomously under the action of the mean shear. Their exact forms vary, being influenced by the turbulent variations in the local environment in which each one develops. To study them it is convenient to simplify the background flow to a steady, plane-parallel flow. Consider then a disturbance growing into a steady inviscid flow over a smooth wall and take the initial velocity profile to be logarithmic. A flow like this could not be achieved in a real

---

***Corresponding author address:** K.G. McNaughton, University of Edinburgh, Institute of Ecology and Resource Management, Edinburgh EH9 3JU, Scotland. E-mail keith.mcnaughton@ed.ac.uk

experiment because small imperfections of the wall or small residual turbulence in the flow would quickly initiate turbulence in the whole flow. However, this flow is consistent with the inviscid Navier-Stokes equations and it provides a useful initial condition for mathematical analysis and computer simulations.

If a suitable disturbance is introduced into such a log flow at the wall then shear in the flow causes the disturbance to grow and change form as it is carried downstream. Its form soon becomes independent of the initial disturbance so the growing disturbance quickly develops a coherent dynamic in which the scales of its various parts are all related. In particular it has a single length scale given by the height of the structure, $\boldsymbol{h}$. The shear of the main flow, which propels its development, then provides an evolutionary time scale, $\partial \boldsymbol{u}/\partial \boldsymbol{z}|_{z=h}$,, and together the length and time scales provide the velocity scale, $\boldsymbol{u}_s = (1/\boldsymbol{h})\partial \boldsymbol{u}/\partial \boldsymbol{z}|_{z=h}$, This velocity scale is independent of the height of the eddy.

We can now draw some simple deductions. The rate of height growth of this eddy, $d\boldsymbol{h}/d\boldsymbol{t}$, must scale on $\boldsymbol{u}_s$, and so be constant, as must its lateral growth rate. Meanwhile the structure advects downstream, at a speed that also scales on $\boldsymbol{u}_s$, so the whole disturbance must grow within a linear envelope with origin at a fixed point on the wall: the virtual origin of the disturbance. The active part of the coherent structure, and all of its residual effects (tracer redistribution, for example) must lie within this envelope.

4. THE TEA STRUCTURE

Implicit in the above account is that the disturbance soon achieves a characteristic form, or ‘coherent structure’ that it is 'attached' to the wall. This section outlines a model for the growth of such a disturbance.

In their model of the ejection/sweep structure, McNaughton & Brunet (2002) proposed that an initial streak of low velocity air against the ground could cause an instability in the flow and initiate the roll-up of a hairpin eddy. This hairpin vortex would then grow under the action of the mean shear, confining air within its arms and squirting it outwards and backwards into the flow as an ejection. The combination of hairpin vortex and ejection then constitutes an ejection/sweep structure. The conjecture here is that such an ejection can initiate another hairpin vortex which can lead to another ejection and so on, creating an up-scale, or inverse cascade of ‘ejection amplifier’ structures. Support for this idea comes from Levinski & Cohen (1995) who initiated hairpin vortices experimentally in couette flow by injecting pulses of fluid from a port in a smooth wall. Unfortunately the Reynolds number of their flow was too shallow to allow powerful ejections.

Theodorsen (1952) was the first to propose that hairpin (or horseshoe) vortices are the major momentum-transporting structures in shear turbulence. His diagram is given here as Fig. 1.

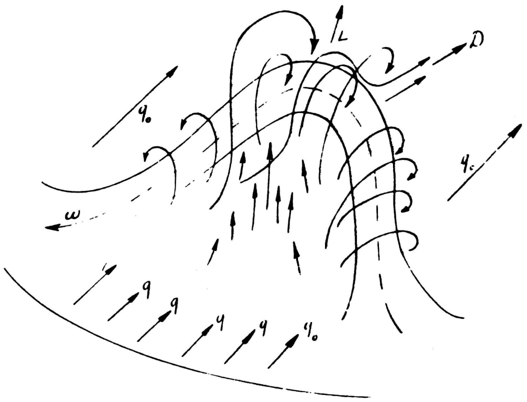

Figure 1. Primary structure of wall-bounded turbulence. Note concentrated current through centre-region of horseshoe representing the “Reynolds stresses” and giving the “mixing lengths” of Prandtl. Figure and caption are from Theodorsen (1952).

Theodorsen proposed that a hairpin vortex is initiated by the inflexional instability that forms when the flow passes about a low-speed mass of fluid against the wall. This hairpin vortex then rolls up and grows under the action of the mean shear, and in doing so induces an outflow from between its arms. Theodorsen did not know of wall streaks. This outflow, or ejection, was not detected in the experiments done by Weske & Plantholt (1953) though they did confirme the hairpin structures. Theodorsen omitted the ejection from later versions of his diagram (Theodorsen, 1955). This tracer experiment, and most tracer experiments since, used flows with small Reynolds numbers to avoid rapid dispersal of the tracer. Unfortunately this severely limits the power of the ejections. Full numerical simulations (e.g. Singer & Joslin, 1994) are also restricted to small Reynolds numbers by computer capacity. Because of these limits to experiments, Theodorsen’s scenario of hairpin roll-up leading to powerful ejection was largely forgotten. The best direct experimental support so far is by Hagen & Kurosaka (1994) who traced fairly powerful ejections originating within the arcs of hairpin vortices by injecting dye at two levels to mark separately the hairpins and the ejections. It is in high-Reynolds-number flows that powerful ejections (often called plumes or updrafts) are commonly observed (e.g. Boppe et al., 1999).

Accepting that powerful ejections exist, and putting together the known ejection-to-hairpin and hairpin-to-ejection associations then gives an ejection-to-ejection structure, which we call a ‘Theodorsen ejection amplifier’, or TEA structure. A sketch of its stages of development is given as Fig. 2. A series of TEA structures constitutes an up-scale cascade, which we call a TEA cascade. Such cascades can grow autonomously under the action of the mean shear and have all of the characteristics needed to identify them with the large-scale ramp-like structures found in log layers. Of course real background flows are not plane-parallel, so real TEA-like (TEAL) structures will be somewhat irregular in form, and competition for space means that neighbouring TEAL cascades will almost certainly interact. Such interaction and resulting termination of cascades is necessary if the overall process is to attain the size distribution of TEAL structures necessary for the ensemble to observe inner scaling.

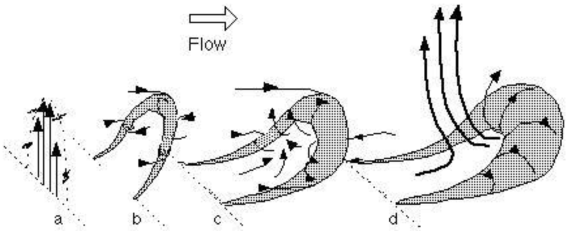

Figure 2. Stages in the evolution of a TEA structure. The dotted diagonals represent the same reference line, shown displaced successively at each stage of development. The cycle starts with an ejection of fluid from against the wall (a). This produces an inflexional instability traced out in the form of a ∩, which initiates the roll-up of a hairpin vortex (b). The vortex grows and rotates under the action of the mean shear, producing an outflow from within its arc (c). This process continues until the hairpin contacts the wall, increasing the power of the ejection (d), which then initiates a new cycle.

---

5. NUMERICAL SIMULATIONS

In principal TEA structures and TEA cascades can be simulated numerically. The chief problem is that several growth cycles are necessary before the form of the ejection amplifier becomes independent of the form of the initiating ejection, and so before the amplifier becomes a true TEA structure as we have defined it. The preliminary results presented here (Fig. 3) are for just the first cycle and are heavily influenced by the form of the initial ejection. Even so, the results confirm our general expectation that an ejection into a log profile leads through the formation and growth of a hairpin vortex to a new, larger ejection.

Our simulations used the CFD software FLUENT to simulate Navier-Stokes flow with constant density and zero viscosity. Parallel flow with a log profile was injected at the upstream boundary and zero vertical velocity was imposed at the upper and lower boundaries. A 96x32x64 grid was used for the half volume of the flow. The solver was run until a stable log profile was achieved, then a disturbance was introduced by injecting fluid at 45˚ back into the flow through a slot in the wall while withdrawing an equal volume of

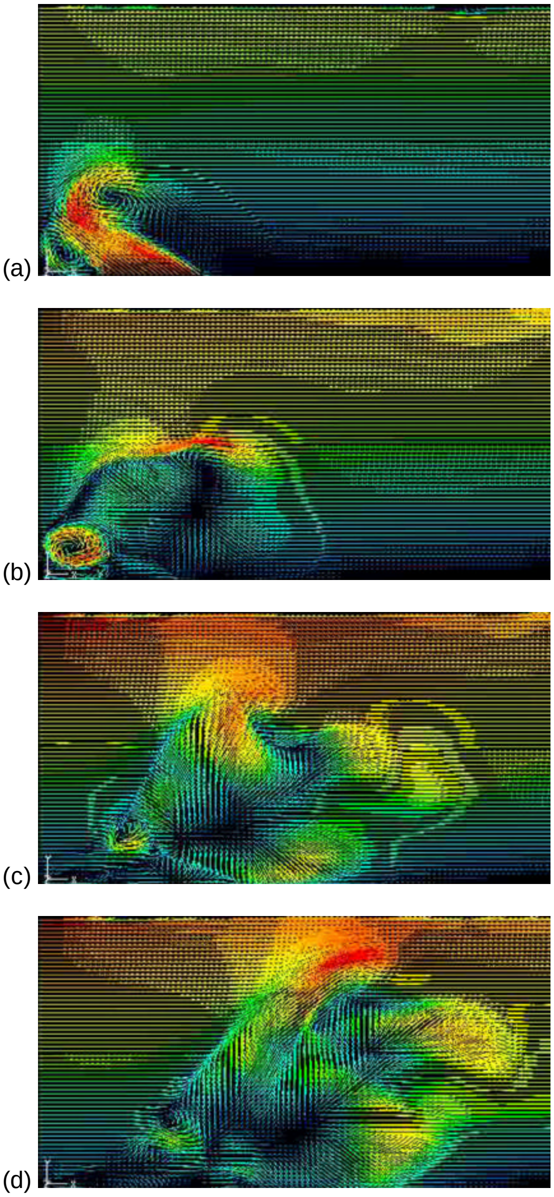

Figure 3. Stages of an exploratory simulation of a TEA structure at four times. All frames show velocity vectors at the median x-z plane. (a): Initial ejection has just stopped. Hairpin roll-up has begun. (b): Hairpin has grown and moved downstream. A new ejection is forming with velocity vectors angled 45˚ back into the flow. (c): New ejection has emerged and is rolling over at the top, indicating the start of a second hairpin vortex. (d): Ejection reaches maximum extent. Results by this time are distorted by proximity to boundaries. Shading is rescaled for each image and has no quantitative meaning.

fluid through flanking slots. This procedure combined elements of the slot ejection used by Singer & Joslin (1994) in DNS experiments, and of the ejection port with the balancing suction ports on either side used by Levinski & Cohen (1995) in physical experiments. The 45° angle was chosen to mimic ejections in turbulent flow. Hairpin vortices were successfully initiated in the flow and these developed to produce larger ejections.

Fig. 3 shows successive stages from an exploratory simulation. The simulation could not be pursued far enough to follow more than one cycle. Also, the results show effects of nearness to upstream and overhead boundaries, and to the particular form of the initial ejection. An example is the rotor seen between the ejection and the forced inflow at the upstream boundary. Despite these limitations, the results do conform remarkably well to the expected behaviour (Fig. 2). They do not properly define the TEA structure but, along with the scale analysis and the expectation that long-time results must become independent of the initial conditions, they are enough to say confidently that the TEA structure exists. The only significant (i.e. not an artifact) difference between the structure sketched in Fig. 2 and the simulation results is that a distinct roll-up stage is not apparent. Instead it seems that the TEA structure continuously tumbles over itself without tightly-rolled vortices being formed along the way.

6. CONCLUSION

We have presented a model of the large-scale ramp-like structures observed in the ASL. We propose that these ramps are inverse cascades of ejection amplifier structures, each stage very much like an archetypal "Theodorsen ejection amplifier" (TEA) structure. The TEA structure is defined for a plane-parallel inviscid flow. It develops autonomously under the action of the mean shear, is initiated by an ejection which leads to the development of a hairpin vortex and then to another ejection. Preliminary simulations confirm the general features of this process. Cascades of TEA-like (TEAL) structures are strong candidates to be the principal agent of turbulent transport in the ASL. TEAL cascades also provide a mechanism for the 'backscatter' that must be introduced into LES models through the sub-grid parameterization. An interpretation of spectra in the ASL that is consistent with TEAL cascades being the main active structures is given in a companion paper at this meeting.

7. REFERENCES

Adrian, R.J., C.D. Meinhart & C.D. Tomkins. 2000. Vortex organization in the outer region of the turbulent boundary layer. ***J. Fluid Mech.*** 422:1-54.

Boppe, R.S., W.L. Neu & H. Shuai. 1999. Large-scale motions in the marine atmospheric surface layer. ***Bound.-Layer Meteor.*** **92:**165-183.

Chong, M.S., J. Soria, A.E. Perry, J. Chacin, B.J. Cantwell & Y. Na. 1998. Turbulent structures of wall-bounded shear flows found using DNS data. ***J. Fluid Mech.*** **357:**225-247.

Hagen, J.P. & M. Kurosaka. 1993. Corewise cross-flow transport in hairpin vortices- the "Tornado effect". ***Phys. Fluids A*** **5:**3167-3174.

Head, M.R. & P. Bandyopadhyay. 1981. New aspects of turbulent boundary layer structure. ***J. Fluid Mech.*** **107:**297-338.

Hommema, S. & R.J. Adrian. 2001. Structure of wall-eddies at $Re_\theta \geq 10^6$. Pp. IV.9 in ***Laser Techniques for Fluid Mechanics. Selected Papers 10th Int. Symp., Lisbon Portugal 10-13 July, 2000***, Eds R.J. Adrian, D.F.G. Durão, M.V. Heitor, M. Maede, C. Tropea & J.H. Whitelaw.

Levinski, V. & J. Cohen. 1995. The evolution of a localized vortex disturbance in external shear flows. Part 1. Theoretical considerations and preliminary experimental results. ***J. Fluid Mech.*** **289:**159-177.

McNaughton, K.G. & Y. Brunet. 2002. Townsend's hypothesis, coherent structures and Monin-Obukhov similarity. ***Bound.-Layer Meteor.*** **102:**161-175.

Marusic, I.. 2001. On the role of large-scale structures in wall turbulence. ***Phys. Fluids*** **13:**735-743.

Mayer, M.E., L. Hudgins & C.A. Friehe. 1994. Wavelet spectra of buoyant atmospheric turbulence. ***Wavelets: Theory, Algorithms and Applications. Volume 5***, eds C.K. Chui, L. Montefusco and L. Puccio. Academic Press, San Diego.

Perry, A.E. & M.S. Chong. 1982. On the mechanism of wall turbulence. ***J. Fluid Mech.*** **119:**173-217.

Perry, A.E. & I. Marusic. 1995. A wall-wake model for the turbulence structure of boundary layers. Part 1. Extension of the attached eddy hypothesis. ***J. Fluid Mech.*** **298:**361-388.

Singer, B.A. & R.D. Joslin. 1994. Metamorphosis of a hairpin vortex into a young turbulent spot. ***Phys. Fluids*** **6:**3724-3736.

Theodorsen, T.. 1952. Mechanism of turbulence. Pp. 1-18 in ***Proceedings of the Second Midwestern Conference on Fluid Mechanics***, Columbus, Ohio, March 17. Ohio State University.

Theodorsen, T. 1955. The structure of turbulence. Pp. 55-62 in ***50 Jahre Grenzschichtforschung***, editors H. Görtler & W. Tollmein. Braunschweig: Friedr. Vieweg & Sohn.

Weske, J.R. & A.H. Plantholt. 1953. Discrete vortex systems in the transition range of fully developed flow in a pipe. ***J. Aeron. Sci.*** **20:**717-718.