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ASPECT RATIO EFFECTS IN THE DEVELOPMENT OF A WIND TUNNEL MODEL OF THE ATMOSPHERIC CONVECTIVE BOUNDARY LAYER

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ABSTRACT

This paper discusses the development of a wind tunnel model of the atmospheric convective boundary layer (CBL) in the Environmental Working Section of the 1MW Wind Tunnel at Monash University. Data showing the development of quasi-stationary longitudinal horizontal rolls (spirals) is presented. The results of attempts to minimise or eliminate the spirals from the flow by increasing the aspect ratio are presented and discussed.

INTRODUCTION

Atmospheric convective boundary layer (CBL) flows are developed over the earth's surface when a positive heat flux exists from the ground (or surface) into the atmosphere, generally due to solar heating of the surface. Under suitable conditions they show strong diurnal development with an adiabatic layer developing close to the surface from early morning and increasing in depth with time. A deep well mixed boundary layer is developed by mid to late morning which is capped by an elevated inversion at a finite height, z_i, of the order 1 - 2*km*. The turbulence field within the CBL is dominated by large, buoyancy driven eddies extending vertically over the entire depth of the of the CBL. The eddies can have lifetimes of the order 10 to 20 minutes with vertical scales of the order z_i and horizontal scales of order $1.5z_i$. The large turbulence structures present within CBL flows, together with a positively skewed distribution of the vertical velocity, significantly alter the dispersion characteristics of plumes emitted into such flows from those of the standard final rise height and Gaussian spread assumptions generally used in regulatory models. In their numerous heated water tank studies, Willis and Deardorff (1974, 1976, 1978 & 1981) discovered a very unusual behaviour of the average plume centre line (locus of maximum concentration). For surface releases ($z_s < 0.1z_i$) the plumes were found to lift from the surface, while for elevated releases the plume centre lines were found to descend to the surface, where they remained for a considerable time before ascending in a similar manner to a surface source. This unusual behaviour produced significantly higher impact at the surface than predicted by standard Gaussian plume models. Numerical simulations (Lamb 1978 & 1979, Mirsa 1982) also exhibited a similar behaviour, with a field experiment (Moninger et al. 1983, Briggs 1993a & b) confirming this behaviour in the atmosphere. The diffusion characteristics were found to be very dependent upon release height, but increasing the release height did not necessarily reduce the surface or ground level concentrations. In fact, at certain down wind distances, elevated releases could result in three times the ground level concentration of similar surface released plumes.

Although water tanks have been used to model CBL phenomena for over 20 years (Willis and Deardorff 1974, Kumar and Adrian 1986, Ohba et al 1991, Cenedese and Querzoli 1991, Hibberd and Sawford 1994), they lack a mean flow and thus cannot model shear effects at the surface or across the entrainment region between the mixed layer and capping inversion. Their use is restricted to the most convective conditions with very low wind speeds, when only very shallow surface layers exist and shear effects can be considered to be negligible. Due to the presence of a mean wind flow, wind tunnels offer the possibility of modelling terrain effects such as surface roughness changes or topographical features, as well as the effects of surface heat flux variations. They also offer the ability to obtain reliable measurements of the fluctuating concentration statistics with the use of high frequency gas samplers such as tuned mass spectrometers or flame ionisation detectors through which a continuous air sample can be drawn. Although numerous attempts have been made to model CBL flows in wind tunnels prior to the commencement of this work (Rey et al. 1979, Ogawa et al. 1981, Poreh and Cermak 1984), the results have generally been only moderately successful with a significant lack of horizontal homogeneity as well as model scales and wind speeds which restrict the simulation of real world buoyant plumes.

ASPECT RATIO.

The aspect ratio of a CBL is defined as the ratio of the width of the mixed layer to its depth, z_i. In atmospheric CBL's the aspect ratio is generally very large (order 100 or greater), but a laboratory model is bound by solid side walls which can effect the flow field in the region near the walls. Additionally, in models where surface heating is used to drive the convection, the walls can be a source of heat loss with the fluid close to the walls being cooled. The combination of these effects can enhance the development of horizontal rolls within the model flow, distorting the turbulence field by limiting the number and motion of the large eddies. The experiments of

Willis and Deardorff (1974), performed with an aspect ratio of 2, show much weaker horizontal velocity variance and stronger vertical velocity variance than has been measured in the field. In the modelling of dispersion within the CBL the aspect ratio also becomes significant in that it needs to be large enough to ensure the dispersion measurements are not corrupted by the reflection of the plume from the walls of the test facility. Poreh et al. (1991) suggested an aspect ratio of at least 3 and preferably 5 for wind tunnel models, based on a flow visualisation study. Meroney and Melbourne (1992) suggested the aspect ratio should be greater than 4 for wind tunnel modelling. Based on an average horizontal scale for convective eddies in the atmosphere of $1.5z_i$, Hibberd and Sawford (1994) suggested a minimum aspect ratio of 4.5 for water tank experiments, ie 3 cells across the tank with the centre one presumably unaffected by the walls. They did indicate that larger values would be desirable and selected an aspect ratio of 6, corresponding to 4 cells across the tank, for their experiments.

EXPERIMENTAL MEASUREMENTS

Experiments were performed in various configurations of the 1*MW* Environmental Wind Tunnel at Monash University over a 6 year period.

Initial Experiments

The first set of experiments, undertaken in the initial 5*m* by 10*m* by 25*m* ground floor working section of the tunnel, utilised the section roof as the inversion layer, with rod heating elements providing the surface heating (see Melbourne et al. 1994). Thus for these experiments z_i = 5*m* and the aspect ratio was 2. Non penetrative convection was generated due to the solid capping of the section roof. Three component sonic anemometer velocity measurements were performed in the flow for both an unheated configuration and a surface heated configuration. Mean velocity profiles shown in Figure 1 indicated that with the application of surface heat significant horizontal rolls developed with significant counter flowing lateral velocity components obvious at the top and bottom of the section. The variance of the vertical velocity component was also considerably reduced on that obtained in full scale and other laboratory measurements. Other results such as the heat flux profile and temperature variance profile exhibited similar variations from the accepted standard for a horizontally homogeneous CBL. Vertical profiles for this model configuration were only possible in one location.

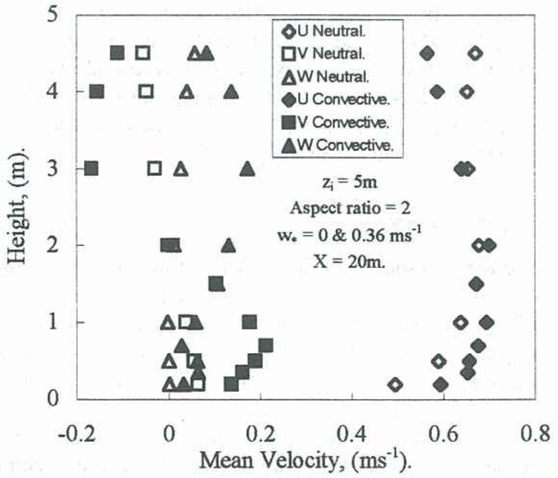

Figure 1 : Mean velocity components obtained in the initial experiments in the 5*m* by 10*m* by 25*m* long ground floor section of the wind tunnel using the section roof as the inversion layer.

Redeveloped Tunnel Experiments

With the redevelopment of the 1*MW* wind tunnel and the construction of the new upper level Environmental Working Section (EWS), development of the wind tunnel model CBL flows was able to recommence in mid 1996. The results presented in the remainder of this paper were obtained within the 4*m* high by 12*m* wide and 45*m* long EWS. The EWS was equipped with a 30*m* long region of floor or surface heating elements, and a bank of heating elements suspended from the roof close to the inlet end of the section, to enable the development of a stably stratified inversion layer above the model CBL. The roof of the EWS was insulated from slightly upwind of the stable layer heating elements, for the full length of the working section over which the CBL models were developed. Insulation was also added to the walls of the section during the course of the developmental experiments to minimise the heat loss through the tunnel walls. The results presented here were all obtained with the wall insulation installed.

The move from the lower to the upper (EWS) working section resulted in an immediate aspect ratio increase from 2 to 3 for the configuration utilising the section roof as the inversion layer. The results of velocity profiles obtained at 3 locations across the EWS at a distance 10*m* downwind from the start of the surface heating elements are presented in Figure 2a. Sampling times of 5 minutes or greater were used for the measurements in the EWS. Again very significant vertical and lateral velocity components are evident, indicating the development of horizontal rolls and the lack of horizontal homogeneity. In fact the vertical velocity components at one location approach the magnitude of the longitudinal velocity components in the centre of the mixed layer region of the flow. A plume released at this location would be quickly advected to the top of the CBL.

For Figure 2b the stable layer heating elements were used to develop a model inversion layer above the model CBL. This produced an inversion height of about 2.7*m* at the measurement location and an aspect ratio of 4.5. The model surface heating and fan speed remained unchanged. This resulted in a significant reduction in the magnitude of the very high vertical velocity components evident in Figure 2a, but significant lateral and vertical velocity components were still evident. Significant variations in the vertical velocity variance and other turbulence parameters were also measured within these flow fields.

As it was apparent that reducing the inversion height within the model had the effect of reducing the strength of the developed horizontal rolls, further attempts were made to minimise their significance by further increasing the depth of the model inversion layer. This

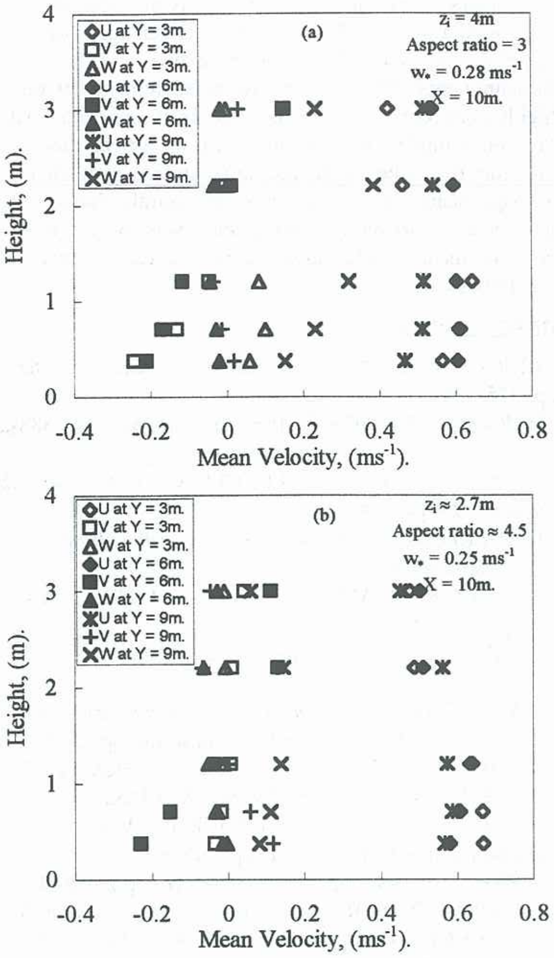

Figure 2 : Mean velocity components obtained in the upper level EWS of the redeveloped wind tunnel with the roof acting as the capping inversion layer (a) and using the stable layer heating elements to produce a stably stratified model inversion layer above the model CBL with an inversion height of approximately 2.7*m* (b).

was achieved by increasing the heat input to the stable layer heating elements and operating the tunnel at a slightly lower speed. A selection of results from some of these tests are presented in Figure 3 and 4 for model inversion heights of about 2.2*m* and 1.8*m* respectively, corresponding to aspect ratios of 5.5 and 6.5. The mean streamwise velocity profiles at the 3 locations across the tunnel for the $z_i = 2.2m$ configuration (Figure 3) indicate that the flow in the inversion layer is essentially stagnant, with the fans unable to advect it along the tunnel due to the very high temperature gradients within this region of the model. Also evident is the development of 2 horizontal rolls with significant vertical velocities in the centre of the tunnel. Lateral velocity components, changing sign at the centre height of the mixed layer of the CBL, are evident at the other two measurement locations. This resulted in significant variations in both the mean longitudinal velocity profiles and temperature profiles across the flow field. While the mean longitudinal velocity components close to the surface were equivalent, the significant up draughts in the centre of the tunnel have resulted in much higher longitudinal velocity components in the top half of the mixed layer and into the inversion layer in this region of the flow. The mean air temperature close to the surface was found to be significantly higher in the tunnel centre than at the measurement locations either side. In the upper levels of the mixed layer and the lower regions of the inversion layer the air temperature in the centre of the tunnel was found to be lower, indicating a significant lack of horizontal homogeneity within the flow field.
The turbulence parameters within this flow field also demonstrated a lack of horizontal homogeneity, with significantly greater fluctuations evident at the centre measurement location (Y=6*m*). Profiles of the turbulent heat flux also showed a significant lack of horizontal homogeneity, with significantly greater heat flux measured at the centre location with very significant updraughts. The magnitude of the mean lateral and vertical velocity components was of the order of the standard deviation of the vertical velocity component in the centre of the mixed layer region of the flow indicating the significants of the rolls on the overall flow structure. with the flow being completely dominated by the horizontal rolls or spirals.

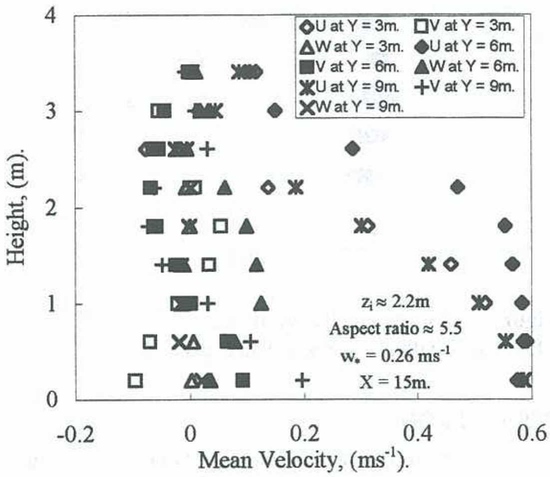

Figure 3 : Mean velocity components for a wind tunnel CBL model with $z_i = 2.2m$ and an aspect ratio of 5.5.

The final set of results presented is for the same heating configuration as the results of Figure 3, but with the wind tunnel fans operating at a lower wind speed. The results for this flow configuration are presented in Figure 4. The reduction in wind speed within the working section resulted in the development of an even deeper stably stratified inversion layer above the mixed layer region of the flow, in which reverse flows are even evident due to the inability of the fans to advect this region of the flow along the tunnel. The model inversion height was approximately 1.8*m* at the measurement location. It is immediately evident there has been a dramatic reduction in the magnitude of the mean lateral and vertical velocity components at all the measurement locations. The mean longitudinal velocity components were also more consistent at the various measurement heights throughout the profiles, as were the mean temperature profiles. The flow for this model configuration, with an aspect ratio of just above 6, was significantly more horizontally homogeneous than the previous flow configurations with aspect ratios below 6. The normalised vertical velocity and heat flux profiles for this model configuration also demonstrated significantly more consistency across the flow field. Although the turbulence parameter results were not as uniform as those of the mean velocity and temperature measurements, the variation was only of a magnitude generally expected and obtained in such large scale, high intensity turbulent flows due to their stochastic nature. It is however very obvious that the development of horizontal rolls or spirals within the flow field is not dominating the structure of the flow. The standard deviation of the velocity components was significantly greater than the mean lateral or vertical velocity components measured within the flow.

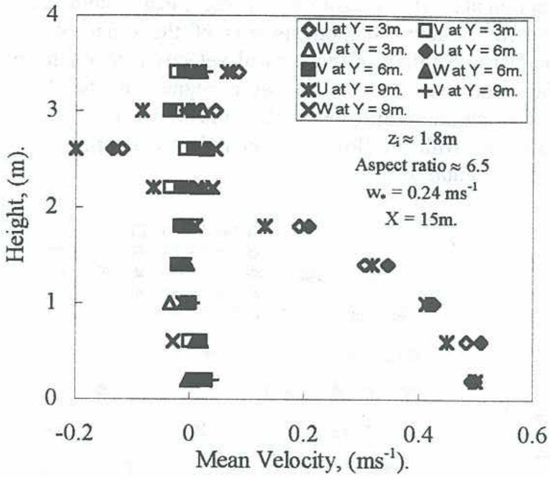

Figure 4 : Mean velocity components for a wind tunnel CBL model with $z_i = 1.8m$ and an aspect ratio of 6.5.

CONCLUSION

Velocity and turbulence statistics obtained from wind tunnel models of the atmospheric CBL over a range of model aspect ratios have been presented. It was shown that for the results with aspect ratios of less than 6, the application of the surface heating to the flow resulted in the development of significant mean lateral and vertical velocity components within the mixed layer region of the flow, indicating the establishment of significant horizontal rolls or spirals in the streamwise direction. The turbulence parameters were found to vary significantly depending upon the location of the measurements within these large scale structures, with the flow showing significant horizontal inhomogeneity. A set of measurements was also presented for a model configuration with an aspect ratio just above 6. In these results the mean lateral and vertical velocity components measured within the mixed layer region of the flow were essentially zero, within the limits and accuracy of the instrumentation and the general stochastic nature of such large scale high intensity turbulent flows, particularly at these extremely low wind speeds. Although the turbulence parameters in this model configuration did show variation between the various measurement locations, the magnitude of the differences was substantially less than obtained for the equivalent parameters in the model configurations in which strong horizontal rolls developed, and were generally of the order of the stochastic variation expected with such measurements. With regard to measurements within highly convective flows, it is possible to conclude that this latter model configuration, with an aspect ratio of the order 6, can be considered horizontally homogeneous as significant horizontal rolls or spirals have not developed. Horizontal homogeneity was observed in both the mean and turbulent statistics measured within this flow field.

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