TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

A LABORATORY MODEL OF CONVECTION IN THE ATMOSPHERIC BOUNDARY LAYER

M.F. HIBBERD and B.L. SAWFORD

CSIRO, Division of Atmospheric Research
Private Bag No. 1, Mordialloc, Vic. 3195
AUSTRALIA

ABSTRACT

A laboratory model of dry penetrative convection in the atmosphere has been constructed to study various features of the turbulent dispersion of buoyant plumes in the planetary convective boundary layer. The model consists of a 3.2m x 1.6m x 0.8m deep glass-walled tank holding about 4000 litres of salty water and constructed to permit almost all-round flow visualization. In operation, the tank is initially filled with a stably-stratified aqueous salt solution to simulate the stably stratified atmosphere. The buoyancy flux needed to drive the convection is produced by supplying very salty water uniformly over the top of the tank through a porous membrane directly into the convectively mixed layer. The convection thus proceeds "upside-down" with the strong downdraughts of denser saltier water corresponding to thermal updraughts of lighter warm air in the atmosphere. This paper describes the modelling criteria used in the design of the tank and presents some results from the initial validation procedure.

INTRODUCTION

Laboratory models of geophysical flows continue to play an important role in improving our understanding of phenomena in the real world and helping to bridge the gap between the patchy measurements possible in the ever-changing atmosphere and the theoretical models of simple idealized situations. Field measurements of convective boundary layer turbulence, in particular, are complicated by the variability in important parameters such as the heat flux, wind speed and direction as well as by the need for very long averaging times to obtain accurate statistics.

The planetary convective boundary layer (CBL) is dominated by large energetic eddies with turnover times of about 15 minutes. The distribution of vertical velocities is skewed with narrow thermals of upward moving air surrounded by larger regions of slowly sinking air. Plume looping under these conditions produces some of the highest ground-level concentrations of emissions from tall stacks at many sites around Australia (and elsewhere in the world) including the Latrobe and Hunter Valleys, Mt. Isa and Kalgoorlie (Best, 1984, Carras and Williams, 1984; Manins, 1984).

Convective turbulence dominates the structure of the planetary boundary layer when there is a significant upward flux of sensible heat from the ground (50-400W/m^2) below a capping temperature inversion and the wind is sufficiently light that the surface layer in which mechanical turbulence is generated by wind shear is thin compared to the depth of the CBL. This last condition can be quantified as $z_i/-L > 10$, where z_i is the CBL depth and L the Monin-Obukhov length; a more useful form of this condition, obtained by making simple assumptions about the shape of the wind profile, is $U/w_* < 6$, where w_* is the convective velocity, defined below, and U the mean wind speed. This condition is often satisfied in the atmosphere for strong convection, where a typical value for w_* is 2m/s.

Laboratory experiments by Willis and Deardorff (1974, 1983, D&W 1985) with a heated water tank revolutionized thinking about, and understanding of, the convective boundary layer, including dispersion processes. However, this apparatus has now been closed down and dismantled although many useful and interesting dispersion experiments remain to be done. Building on their experience as well as that of other researchers, the current laboratory model was designed to overcome some of the limitations of the their model and develop a facility for obtaining high quality turbulence and dispersion data in strongly convective conditions. The model is intended to simulate the CBL resulting from a homogeneous surface heat flux in flat terrain with mixed layer depths from 500-3000m and characteristic convective velocities from 1-3m/s. The turbulence generated by wind shear is ignored but the mean advection is simulated by the simple transformation of towing the source through the tank.

DESIGN CRITERIA

In order to accurately model the convective boundary layer, various non-dimensional and dimensional quantities describing the flow need to be considered (see, e.g. Snyder, 1981); they include the Rayleigh and Reynolds numbers and the CBL scaling parameters z_i and w_*. Although an exact simulation of the atmosphere is not possible, it can be shown that the features important for plume dispersion are present in the model.

Saline Convection

As in many laboratory models of atmospheric flows, the fluid used in the convection tank is water. However, common salt (NaCl) rather than heat is used to produce the density stratification and buoyancies in this tank. The main advantage of using saline solutions is the freedom from the need to thermally insulate the apparatus and the longer time available to set up experiments due to the much slower molecular diffusion of salt than of heat in water; cf. Prandtl number of 7 and Schmidt number (ratio of momentum to salt diffusivity) of 750. Other advantages are the avoidance of strongly temperature-dependent quantities such as the coefficient of thermal expansion, and the ability to achieve somewhat higher Reynolds numbers and to better satisfy other scaling criteria.

Rayleigh Number

The Rayleigh number, representing the ratio of buoyancy forces to the combined effects of viscous forces and diffusion determines the stability and flow pattern in free convection. The critical value for the onset of turbulent flow between horizontal parallel plates depends on the Prandtl (or Schmidt) number and is equal to 10^8 for saline convection.

In the atmosphere ($Ra = 10^{20}$), the top plate is replaced by a stable stratification aloft, into which the CBL grows during the day by a process of penetration by stronger thermals and entrainment. For the saline model of penetrative convection a Rayleigh number of 10^{14} is achieved, which is well above the critical value for turbulent flow. Invoking the principle of high Rayleigh number similarity should ensure that the convection in the model accurately simulates that in the atmosphere.

Reynolds Number

Because a velocity does not enter the convection problem as an independent variable, the Reynolds number is not an independent dimensionless parameter. However, it can be defined in terms of the mixed layer depth and convective velocity as $Re = z_i w_* / \nu$ with a value of about 10^8 in the atmosphere. This is modelled in the tank by a Reynolds number of about 5000, which is high enough to obtain a reasonable range of scales, although the inertial subrange is rather short in common with most laboratory models.

Aspect Ratio

The aspect ratio is defined as the ratio of the width of the mixed layer to its depth; its value in the atmosphere is large. However, the laboratory model is restricted by the presence of sidewalls, which probably influence the convective eddies next to the walls and limit the number and motion of the eddies within the tank. A minimum aspect ratio to remove these edge effects could be expected to allow for at least four eddies across the width of the tank.

Fitzjarrald (1978) has shown that the horizontal scale of convection cells in the atmosphere in the limit of no wind shear is 1.5 times the depth of the mixed layer. Thus the tank was designed to have a minimum aspect ratio of 6.

Mixed Layer Depth

The depth of the CBL is one of two main quantities used to scale and compare results from the laboratory and field measurements. In the atmosphere it evolves during the day in response to the shape of the potential temperature gradient and the surface heat flux in the range from 500m to 3000m.

In the laboratory environment it is possible to make measurements with a resolution of O(1mm). If this is to correspond to a resolution in the atmosphere of O(10m) , which should be sufficient to resolve the important details of plumes emitted from stacks a few hundred metres tall, then the length scaling factor ε_l needs to be about 10^{-4}.

Using this factor for modelling a CBL depth of 2500m would require a depth of 25cm in the tank. Given the above aspect ratio requirement as well as considerations of space, and construction and running costs, the tank was designed to be 160cm wide.

Convective Velocity

The second mixed layer scaling parameter is the convective velocity, which is defined in terms of the surface buoyancy flux B_0 and the mixed layer depth as $w_* = (B_0 z_i)^{1/3}$. It is characteristic of CBL velocities with the standard deviation of both vertical and horizontal velocities equal to about $0.6w_*$ throughout much of the mixed layer. The cube-root dependence leads to a narrow range of values in the atmosphere between 1 and 3m/s. Typical buoyancy fluxes achievable in the saline convection tank lead to convective velocities of about 1 to 2cm/s giving a velocity scaling factor ε_v of about 0.01.

Plume Scaling

Correct modelling of buoyant plumes as well as the properties of the CBL introduces further parameters such as the buoyancy and momentum fluxes and the efflux Reynolds number. It can be shown that those parameters important under convective conditions are correctly modelled if the velocity and length scaling factors are chosen such that $\varepsilon_v^2 / \varepsilon_l = 1$. Any deviations from this relation require appropriate scaling of the relative density defect of the stack gas. From the values of the scaling factors given above, it can be seen that this condition is satisfied reasonably well in the current model.

The tank length is determined by the towing distance required for the dispersion experiments. Horizontal distances, x, are non-dimensionalised to $X = (x w_* / z_i U)$, which is equivalent to a non-dimensional travel time t/t_*, where $t = x/U$ is a travel time and $t_* = z_i / w_*$ is the timescale for dispersion in the CBL; complete mixing occurs after a few convective timescales. The above-mentioned space and cost limits led to a tank length of 320cm, which enables experiments to be undertaken up to $X_{max}.(U/w_*) = 10$.

THE CONVECTION TANK

Based on the above considerations, the model was constructed as a 3.2m × 1.6m × 0.8m deep glass-walled tank mounted on a frame 60cm above floor level, as shown in figure 1. The glass walls and floor permitted almost all-round visualization. In operation, the tank is initially filled with a 15cm deep constant density layer (being the initial mixed layer) and beneath that a 55cm deep linear density gradient is slowly added through low-disturbance nozzles at the bottom of the tank using a two-tank filling technique.

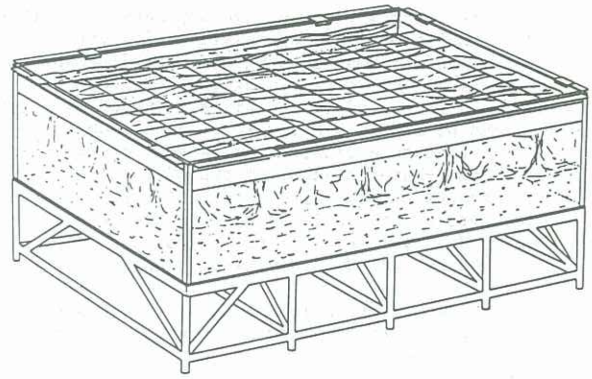

Figure 1. Sketch of convection tank

In order to minimize the quantities of salt used, the buoyancy flux is generated at the top of the convection tank by slowly drawing very salty water from the source tray through a porous membrane directly into the mixed layer. The flux is controlled by the density of the source solution and the rate at which fluid is drained from the bottom of the tank (which is similar to overall uplifting in the atmosphere). The convection thus proceeds "upside-down" with the strong downdraughts of denser saltier water corresponding to thermal updraughts of lighter warm air in the atmosphere. One complication of using this method for generating the buoyancy flux is that it requires a mass flux of salty water through the surface. This flux must be kept small in dispersion experiments so as not to significantly dilute the mixed layer.

RESULTS

The initial validation procedure was designed to check the filling and operation of the tank. Measurements were undertaken to: (i) check the reproducibility of the results; (ii) determine the size and spacing of the convection cells using tracer particles in the flow; (iii) check the evenness of the mixed layer depth across the width and length of the tank; and (iv) determine the mixed layer density and depth and hence calculate the total buoyancy flux and compare it with the surface flux calculated from the source density and the draining rate.

Run no.	N	B_0	z_i	w_*	t_*	$\left(\frac{dz_i}{dt}\right)\cdot 10^3$	$w_d\cdot\left(\frac{dz_i}{dt}\right)^{-1}$
	$[s^{-1}]$	$[cm^2/s^3]$	[cm]	[cm/s]	[s]	[cm/s]	[-]
1	0.85	0.10	28	1.41	20	5.5	0.18
2	0.85	1.6	20	3.17	6	13.0	0.06
		1.3	30	3.35	9	6.2	0.13
3	0.85	0.045	24	1.03	23	2.8	0.27
		0.055	33	1.22	27	3.1	0.32
4	0.82	0.05	29	1.13	26	2.6	0.23
5	0.84	0.06	25	1.14	22	3.4	0.15
6	1.18	0.11	20	1.30	15	4.2	0.18
		0.08	32	1.37	23	3.2	0.24
7	1.15	0.10	30	1.44	21	3.1	0.28

Table 1. Typical operating conditions

Table 1 summarizes the conditions used in these runs, where N is the Brunt-Väisälä frequency, B_0 the surface buoyancy flux, dz_i/dt the mixed layer growth rate, and w_d the effective draining velocity.

Figure 2 shows the growth of the mixed layer for all seven runs. The change in slope in run 3 is due to the drain being turned off at 3400s for about 400s and then on again with a 20% higher buoyancy flux. This response is indicative of the ability in the current facility to control the convection in the tank.

Ignoring entrainment from the stable layer (which was small in these runs), the growth rate of the mixed layer can be approximated by

$$\frac{dz_i}{dt} = \frac{B_0}{N^2 z_i}$$

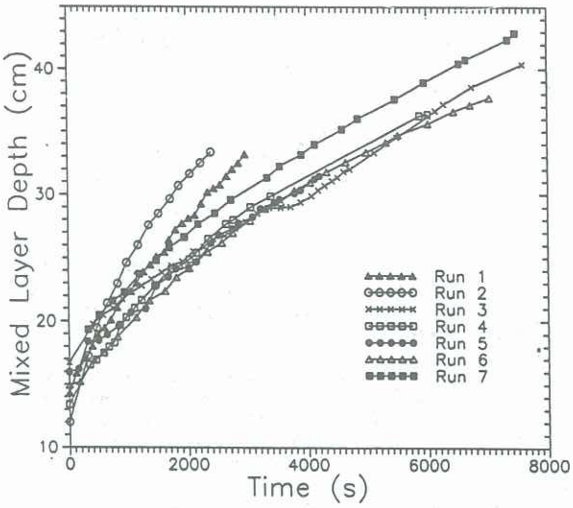

Figure 2. Growth rates of mixed layer

It can be seen that all the curves follow a $t^{1/2}$ dependence. Except for runs 1 and 2, the growth rates are all similar. Table 1 shows that the higher buoyancy fluxes of runs 6 and 7 are accompanied by the use of stiffer gradients in the stable layer (larger N) so that the growth rate according to the above formula remains approximately constant.

A vertically traversing conductivity probe and position-sensing potentiometer were connected to an x-y chart recorder to display density profiles, as shown in figure 3. The initially 16cm deep mixed

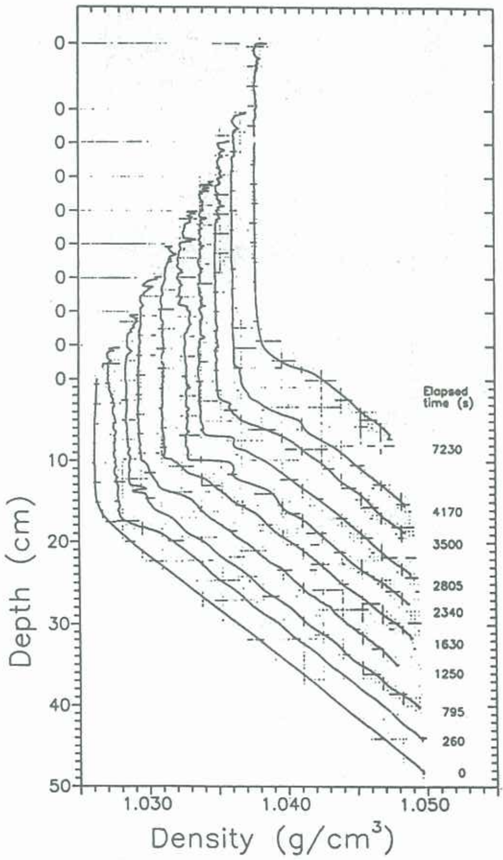

Figure 3. Typical density profiles during run 5; each profile offset vertically.

layer with a density of $1.026 g/cm^3$ grows to a depth of 37cm and a density of $1.038 g/cm^3$ by the end of the run (7230s). At time 0, the profile is seen to be smooth in both the initial mixed layer and the linear stable stratification but once convection commences the profile in the mixed layer becomes quite noisy, with particularly large fluctuations near the surface of the membrane. A few larger blips in the signal are due to beads lodging near the tip of the conductivity probe. The overshoot of the constant density region into the stable layer, which is characteistic of penetrative convection, is evident in all profiles, as is the presence of gravity waves in the stable layer.

Figure 4 shows some typical density traces recorded at various depths in the mixed layer at a distance of 30cm from one end wall. In each case the conductivity probe was stationary and the temporal variation of the density was recorded; the slight increase in density with time in all records is due to the continual growth of the mixed layer.

The density variance is seen to decrease rapidly from a maximum near the surface. All traces except the top one are positively skewed; this is indicative of the "thermals" of (negatively) buoyant fluid moving through an otherwise well-mixed layer. The lower traces display quite distinct "top hat" structures indicating that the "thermals" penetrate at least to the middle of the mixed layer and last for about one convective timescale (25-30 seconds). The more symmetrical trace at $z/z_i=0.004$ is characteristic

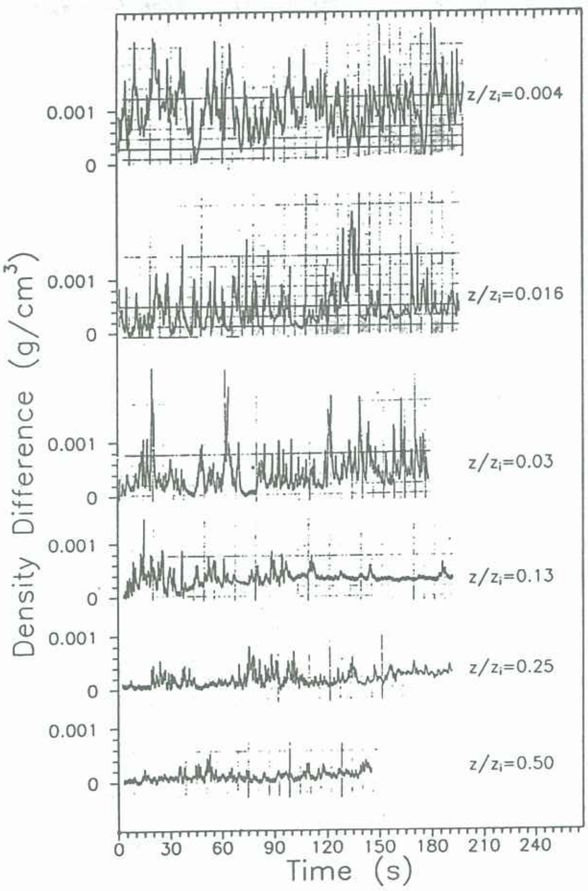

Figure 4. Density records at indicated depths

of the structure of the free convection layer near the surface in the absence of any well organized thermals.

Flow visualization of small neutrally buoyant polystyrene beads in the flow illuminated with a narrow sheet of light was used to reveal the positions of the "thermals". Their typical spacing was 2 to 3 times the depth of the mixed layer and they were observed to originate at varying positions across the membrane during the course of a run. Video recordings of the bead positions are being analyzed with a particle tracking program to obtain quantitative results on the distribution of up- and downdraughts as well as the velocity fluctuations.

CONCLUSIONS

A convection tank has been constructed to model the dispersion of buoyant plumes in the planetary convective boundary layer. The preliminary results obtained so far have shown that the buoyancy flux can be easily controlled to vary the model conditions and that there is good run to run repeatability. The tank appears to accurately simulate many important features of the CBL. Further measurements are being made to obtain velocity statistics and to fully characterize its operation before proceeding with plume dispersion studies.

ACKNOWLEDGEMENTS

The financial support of the State Electricity Commission of Victoria in the form of a Research Fellowship to one of us (MFH) is gratefully acknowledged. We also thank G.O. Scott for his indispensable help in the design, construction and operation of the experimental facility.

REFERENCES

BEST, P.R. (1984) The Callide air quality study, *Proc. 8th Internat. Clean Air Conf,* Vol 2, 485-506.

CARRAS, J.N. and D.J. WILLIAMS (1984) Measurements of plume-dispersion coefficients during convective conditions at various sites widespread around Australia. *Proc. 8th Internat. Clean Air Conf.,* Vol 2, 507-516.

DEARDORFF, J.W. and G.E. WILLIS (1985) Further results from a laboratory model of the convective planetary boundary layer. *Boundary-Layer Meteorol.,* 32, 205-236.

FITZJARRALD, D.E. (1978) Horizontal scales of motion in atmospheric free convection observed during the GATE experiment. *J. Appl. Meteorol.,* 17, 213-221.

MANINS, P.C. (1984) Chimney plume penetration of the sea-breeze inversion. *Atmos. Environ.,* 18, 2339-2344.

SNYDER, W.H. (1981) Guideline for fluid modelling of atmospheric diffusion, U.S. Environmental Protection Agency, Report 600/8-81-009.

WILLIS, G.E. and J.W. DEARDORFF (1974) A laboratory model of the unstable planetary boundary layer. *J. Atmos. Sci.,* 31, 1297-1307.

WILLIS, G.E. and J.W. DEARDORFF (1983) On plume rise within a convective boundary layer. *Atmos. Environ.,* 17, 2435-2447.