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AIR FLOW OVER CAPE GRIM – A LABORATORY MODELLING STUDY FOR OPTIMUM OBSERVATION SITES

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1. Introduction

This study is in response to a request from the Cape Grim Baseline Air Pollution Station to examine characteristics of the flow past the observational site at Cape Grim. The specific objective was to carry out a laboratory experimental study to identify the minimum height above the ground that instruments could be placed, in order that air passing them would not have had prior contact with the local ground. This height was required for a range of wind directions from 180° to 315°, at two specific locations, namely the Telstra tower, and another site designated site B, closer to the cliff face (see Figure 1). In other words, for these wind directions air received by the instruments at these locations above these heights would be from the Southern Ocean to the west, without contamination by local sources on land in Tasmania.

The study was carried out in the Geophysical Fluid Dynamics laboratory at CSIRO Atmospheric Research, Aspendale. A similar study for Cape Grim, with slightly different objectives, was carried out several years ago, and is described in Baines and Murray [1994]. The techniques and equipment used here are generally the same. However, in the present study the model was larger, and considerable effort was made to make it as accurate a representation of the real topography of the Cape as possible.

The problem in question is an example of bluff-body aerodynamics, in which the pattern of flow past the obstacle is largely determined by the obstacle shape. Water is used as the working fluid in place of air, which is possible because air is effectively incompressible (like water) at wind speeds much less than the speed of sound, which is the case at Cape Grim.

2. The Experiment

Constructing an accurate model of a three-dimensional shape as large and complex as the Cape Grim terrain is not an easy task. For the purposes of this study, it was felt that the model used for the previous study was too small. Since this would be a wholly new model, considerable effort was made to get an accurate description of the topography by making a fresh assessment of it. The authors had access to incomplete contour maps dating from the construction of the station in the 1980s, a range of photographs taken at various times, and opinions from various personnel who had worked at CGBAPS. To substantiate this information and fill gaps in it, we visited the site for two days in March 2001, when we took a large number of additional photographs, from all angles and elevations, and made additional measurements of heights and distances. From this information, a model of the terrain was made in plasticene with the scale 10 m (actual) = 12.5 mm (model). This was checked with all available data, including contour maps and photographs, and was consistent with them when viewed from all angles. This process is still somewhat subjective, but we are confident that it is as accurate as one can reasonably attain by this process.

As there was a request for more than one model, this initial model was not used in the experiments, but was instead used to make a latex rubber mould which could then be used to create others using fibre glass. The model actually used in the experiments is shown in Figure 1.

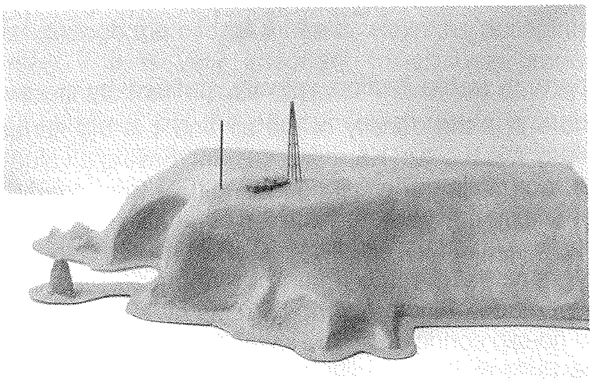

Figure 1. The model of Cape Grim used in the experiments, viewed from a southerly aspect. The vertical pole (scaled height 58 m) near the cliff face denotes the location of site 'B'. The heights above sea level of these sites are 89 m (Telstra tower) and 94 m (site B).

The experiments were carried out in an open tank of length 4 m, width 1.5 m and depth 0.4 m. This tank was filled to a depth of 0.38 m, which was effectively the maximum depth. The model was placed on a flat tray (thickness 1.5 mm) that could be towed along the tank by wires connected to an external motor. In all runs this tray was towed at a uniform speed of 43.2 mm per second, giving a towing time of about 90 seconds. This time is sufficiently long for the flow over the Cape to reach an approximately steady state, and the observations of this steady state were used to generate the conclusions of this study. Runs were carried out with a variety of different orientations of the obstacle, representing wind directions from 180° to 315°.

The question of dynamical similitude of experiments of this nature was discussed in Baines and Murray [1994]. We assume that the air flowing over the region is effectively potentially isothermal to heights greater than twice the topographic height. Over this range of depths, there are two main considerations. Firstly, the effect of viscous and frictional forces is primarily confined to drag and vorticity production at the solid and air-sea boundaries. These effects are characterised by the Reynolds number

$$\mathrm{Re} = UH/\nu \qquad (1)$$

where U is the undisturbed wind (in reality) or towing speed (in the tank), H is the topographic height, and ν is the kinematic viscosity of the fluid. In the atmosphere, the value of Re is very large for Cape Grim (6×10^7). Such values are not realisable in the laboratory, and instead we appeal to the principle of large Reynolds number similarity. This principle states that the flows in two situations that are dynamically similar, except that the Reynolds numbers differ, should be independent of the Reynolds number provided that its value is large (>> 100) in each case. For these experiments $Re = 5400$, so that the laboratory and atmosphere meet this criterion.

The other main factor concerns the nature of the upstream wind profile $U(z)$, where z is the height above the sea. In the atmosphere, this is well known to have the logarithmic form [e.g. Garratt 1992]

$$U(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \qquad (2)$$

where u_* is the friction velocity, defined by $\tau = \rho u_*^2$, where ρ is the density of the air and τ is the surface stress. k is the von Kármán constant, having a value of 0.4, and z_0 is the roughness length of the underlying surface. In the laboratory, on the other hand, the fluid is initially stationary, implying a uniform velocity with height as seen in the frame of reference of the Cape Grim model. Since this model rests on a moving tray, the no-slip condition on the lower boundary implies that this uniform flow is disturbed by a Blasius boundary layer that grows in thickness from the leading edge of this tray. The thickness δ of this layer (to the height at which the velocity reaches $0.95U$) is approximately [Jones and Watson 1963]

$$\delta = 3(\nu x/U)^{1/2}$$

where x is the downstream distance from this leading edge. This provides some similarity to the atmospheric profile at low levels. Above this level there are differences between the logarithmic and the uniform profiles, as shown in Baines and Murray [1994], but these are not large, and are assumed to be insignificant in promoting differences between the modelled and actual flows around as large and bluff an obstacle as Cape Grim.

A third factor concerns the finite depth of the tank. This has the effect of reducing the vertical displacements of the streamlines, but from theoretical considerations of potential flow [e.g. Batchelor 1967] the effect should be small for the flow close to the obstacle, which is the focus here. Moreover, the overlying stratification higher in the atmosphere (which varies from day to day and hence is effectively unknown) will tend to have the same effect.

As a result of these considerations we believe, as in Baines and Murray [1994], that this experiment provides a sufficiently realistic simulation of the air flow over the upstream face and summit of Cape Grim to provide useful data for the purposes required.

Seven different wind directions were studied (see Table 1), and these were realised by varying the orientation of the obstacle. For some runs, small nearly neutrally buoyant beads were suspended in the fluid as tracers, and were made visible by illuminating a vertical cross section of the flow with an oscillating laser beam. This technique gave an overall picture of the character of the flow in a vertical plane. However, for most data-gathering runs, the flow was visualised by releasing dye from a vertical rake that was situated upstream on the moving tray. This rake had five outlets with scaled heights of 10, 30, 55, 85 and 110 metres above sea level. Since we are interested in two sites at Cape Grim (the Telstra tower, and site B), the position of this rake was adjusted between runs until the released dye passed over the site in question, and data from this run were then used to obtain results. In principle, this implies two productive runs for each wind direction (i.e. one for each site). The dye was forced through the rake by a peristaltic pump. This resulted in a somewhat lumpy dye trace. This is readily allowed for in interpreting photographs of the experiments, where the flow is mostly smooth and laminar, and the lumpiness is due to the nature of the source of dye rather than the fluid motion. Where turbulence and mixing occur due to topographic effects, the dye in the affected fluid becomes elongated and diffuse, and this is readily discerned in the photographs shown in the next section. The dye traces were recorded on videotape using a camera situated to best observe the dye lines, and record their character. A photograph of the experimental set-up is shown in Figure 2.

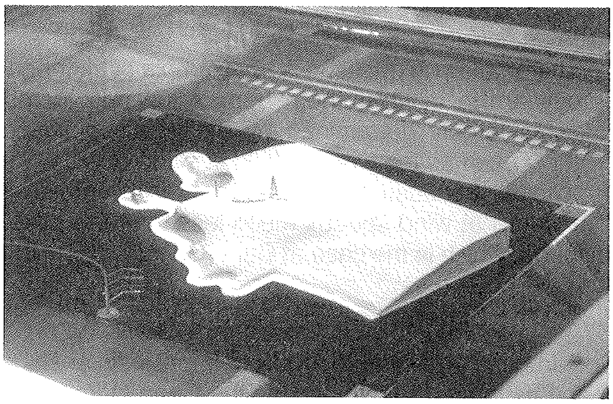

Figure 2. Photograph of part of the towing tank and experimental set-up. The model is situated on the towing tray (dark in colour) near the 'upstream' end of the tank, prior to a towing run. The tray is towed from top right to bottom left, and the rake that releases dye is visible upstream of the model.

3. Results

The main results are summarised in Table 1, which gives the minimum height above the ground at each of the two sites for instruments to be free of air that has had direct contact with the local terrain. These heights were inferred from observing the videotapes of the runs in which the dye traces passed over the site under study (i.e. the tower, or site B). Prudence would dictate that a margin for error of 5 metres should be added to these figures, for use in practice.

Table 1. The minimum height above ground for which the flow is not affected by turbulence generated by the topography, for a range of wind directions for each site.

Wind Direction from (°)	*Compass Point*	*Minimum height above ground for non-turbulent flow* (m) *Telstra Tower Site*	*Site B near Cliff Top*
θ			
180°	S	25	15
203°	SSW	25	15
225°	SW	30	10
248°	WSW	30	25
270°	W	45	35
293°	WNW	> 70	35
315°	NW	> 70	40

Representative photographs for each wind direction, and for each site, are provided in Figures 3 and 4. In these pictures, the uppermost dye line emanates from the outlet at (scaled) height 110 m, the next down from the 85 m outlet, and so on. Dye from the lowest two outlets is generally not visible in these pictures because it has been deflected laterally at lower levels.

Videos of these flows, taken from cameras showing plan views and vertical sections, may be viewed at CSIRO Atmospheric Research.

One question examined in this study was the possible presence of a 'separation bubble' at the cliff top. In flow over steep obstacles, particularly with sharp corners, the flow may separate from the surface at the corner and then subsequently re-attach (e.g. Baines [1995], Figures 6.22 and 6.23). If they occur, such flow patterns tend to be turbulent and highly variable. However, no evidence of a 'separation bubble' at the cliff top near site B was seen in any of the videos and photographs, probably because the topographic nose is well rounded, and not too abrupt.

In the flow from direction 225° (south-west), the incoming flow is relatively undisturbed, except that when approaching the Telstra tower the low-level flow encounters the buildings of the Baseline Station. Accordingly, the lower region of the tower is affected by the wake of the Station, making the minimum usable height there higher than for 203°, for example. The entries in Table 1 show that the minimum usable height increases as the wind direction tends northerly. This is mainly because the flow near the observation point becomes progressively more affected by bursts of air from the large 'gulch' on the northwest side of the station. As described by Baines and Murray [1994], low level air in this 'gulch' circulates and slowly rises to rejoin and mix with the prevailing wind at the top. This is an unsteady process, and as indicated in Figures 3f and 3g, these bursts may pass the tower in the form of eddies that extend over the whole 70 metres of it. Site B at the cliff top is less affected by this process for the directions studied, and usable heights for these directions at site B were discerned from our observations. Most runs were carried out with steady wind conditions. However, a small number of runs were also carried out in which the wind speed was varied, being reduced from a 'large' value to small values and even zero, before being increased again. As expected, these variations had little or no effect on the pattern of motion of the fluid in the irrotational (non-vortical) region away from the boundary and mixing region. Here, the flow pattern was unchanged, with fluid speeds varying in proportion to the towing speed. The only significant effect of the speed variation was that, at near-zero speeds, the mixing region tended to expand upward slightly, above the ground. However, this disturbance was small, and is effectively covered by the values given in Table 1, provided that the time of near-zero velocity is very short. Hence these results are also valid for varying winds provided that it does not approach zero, and in particular does not become negative. In the latter case, vortical motions caused by the topographic features may be expected to carry boundary-mixed fluid to heights in excess of the values given in Table 1. If the criterion for acceptable air intake is based on a time average (of an hour, say), it is possible that some wind from the north and east, with consequent ground contamination, may enter the intakes even though the overall mean is within the acceptable sector. If it is very important to exclude ground-contaminated air, this air could be monitored on a continuous basis, but the effort involved would probably render this practice impractical. A reasonable alternative may be to compile statistics of the reliability of the wind source for given mean wind speed within the acceptable sector, and then select a minimum mean wind speed for each sector as the simplest reasonable practical criterion.

4. Conclusions

The main results of this study are contained in Table 1. This gives heights at the two sites (Telstra tower, Site B near the cliff top) above which instruments may be placed to receive air that has not been contaminated by contact with the local ground, for winds from a range of specified directions. These winds may vary in speed and direction, provided they do not become too small, or vary outside the acceptable sector. A principle conclusion is that Site B is to be preferred over the Telstra Tower, since (i) the minimum required heights are lower, and (ii) the site is less susceptible to contamination from wind that strays outside the acceptable sector. This applies particularly to the effects of bursts from the northwest 'gulch'.

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