3.2 MODELLING OF THE AIRFLOW OVER CAPE GRIM

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This study is in response to a request from the Cape Grim project of the Global Atmospheric Change programme of DAR for an examination of the flow patterns around Cape Grim. The particular objective was to relate the flow past the intakes at heights of 10 m and 70 m above local ground level to heights of the corresponding air over the sea, when the flow is from directions 180° to 280°. Observations have shown that air at 10 m has systematic and significant differences from that at 70 m in CO₂ concentration and its isotopic mix (private communication, G.I. Pearman and R.J. Francey). These experiments were undertaken to investigate whether the local flow pattern could contribute to these differences.

The flow past Cape Grim is an example of 'bluff-body aerodynamics', and may be likened to the flow past a large building. Accordingly, one or more stagnation points (with zero fluid velocity) may be expected on the upstream face, with separated flow regions (bounded by lines where the fluid attaches to or leaves the surface) and vortical motions at low levels. The towing tank in the Geophysical Fluid Dynamics laboratory at DAR is an ideal facility for studying this type of flow. Other realistic possibilities would involve wind tunnel modelling, but this would involve a large wind tunnel and a much larger physical model than in the towing tank, and proportionately greater effort (typically, a factor of 10 in size, effort and cost). The principal reason for this difference is that the kinematic viscosity of air is approximately 10 times that for water. Wind tunnel studies do have some advantages, in that (i) different measurement techniques are available, and (ii) small-scale turbulence may be introduced into the upstream flow in a controlled way. However, these do not imply any significant advantages for the present study.

The Experiment

A scale model of Cape Grim (scale 1000:1, so that 1 cm in the model corresponds to 10 m in the real world) was constructed from a judicious and subjective blend of the limited topographic maps available, with information from photographs and people familiar with the landscape. This landscape is shown in Fig. 1.

![Figure 1. Views of Cape Grim looking approximately north and south respectively.](image)

Since the base of the tower at Cape Grim is at a height of 95 m, this corresponds to a height of the model of 9.5 cm. In the experiments, this model was placed on a flat tray (thickness 0.15 cm) with the leading part approximately 25 cm from the leading edge of the tray. The tray was then towed at uniform speed along the tank (length 4.0 m, width 1.5 m, in fresh water of depth 30 cm).

![Figure 2. Dye lines over a stream of 25 cm. The bottom of 1 cm (corresponding to are at intervals of 2 cm.](image)

![Figure 3. As for Fig. 2, but for receiving runs.](image)

The flow was visualised by raising dye from a rake upstream of the tower. As the flow runs the dye rake was placed in the tank. For the runs it was horizontal. In the experiments, the rake was horizontal, so that the height of the dye level was constant. Neutrally buoyant particles were added to the dye so that it could be observed by laser light with the assistance of the laser light system.

**Velocity profiles**

In the modelled situations, the boundary layer of air over the sea is assumed to be laminar. The velocity profile u(z) is found by assuming no fluctuations above the sea surface:

\[
u(z) = \frac{z}{k} \frac{u}{H}
\]
where $u_*$ is the friction velocity with the surface stress $\tau$ given by $\tau = \rho u_*^2$, $\rho$ is the density of air, $k = 0.4$, and $z_0$ is the roughness length, given approximately by the Charnock relation:

$$z_0 = \frac{u_*^2}{g}.$$

In the model, the flow is laminar and the fluid is initially at rest. The upstream flow profile that impinges on the model is therefore uniform except for a lower boundary layer that grows from the leading edge of the towed plate upon which the obstacle is placed. This is a Blasius boundary layer which has a thickness of approximately $3(\nu x U)^{0.5}$, where $U$ is the towing speed, $\nu$ is the kinematic viscosity of the fluid, and $x$ is the distance from the leading edge of the plate. If we take a value of $U = 10$ m s$^{-1}$ at a height of 10 m in the atmosphere and $\nu = 0.01$ cm$^2$ s$^{-1}$, $x = 25$ cm, $U = 5$ cm s$^{-1}$ in the laboratory, the comparison between the two profiles is as shown in Fig. 4.

The flow was visualised by releasing dye from a rake upstream, which gave streamers of dye that passed the orography. In some runs the dye rake was vertical, as shown in Fig. 2 and 3, but for most of the data-gathering runs it was horizontal. The heights of this horizontal rake were increased by 1 cm in succeeding runs, from ground level (i.e. 'sea-level') to above the maximum height of the model, so that the vertical resolution of the behaviour of the flow in the real world was 10 m. Neutrally buoyant polystyrene beads illuminated by laser light were also used in some cases.

**Velocity profiles**

In the modelled situation, the stratification over the sea is assumed to be neutral. The mean velocity profile $u(z)$ as a function of height $z$ above the sea surface is then

$$u(z) = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right).$$

![Figure 4. A comparison between the mean logarithmic velocity profile in the atmosphere over the ocean (for $U = 10$ m s$^{-1}$ at height 10 m), and the Blasius boundary-layer profile of the laboratory.](image)

Although the fit is not perfect, the laboratory profile is seen to be a reasonable approximation to the mean atmospheric one, with most of the shear in the bottom 10 m. The
weak shear in the upper part of the atmospheric profile is not seen to be important for present purposes, but it should be borne in mind that these observations relate specifically to the laboratory profiles.

The principal dynamical parameter governing the flow is the Reynolds number \( R = \frac{U H}{v} \), where \( U \) is the fluid (or wind) velocity and \( H \) is the height of the topography. In the atmosphere, for Cape Grim with \( U = 10 \text{ m s}^{-1}, R = 6 \times 10^7 \). It is not possible to have such large Reynolds numbers in the laboratory, but from the principle of 'large Reynolds number similarity', if \( R \gg 1000 \), the differences between the flow pattern in the laboratory and the atmosphere should be small and essentially independent of wind speed. With a towing speed of 5 cm s\(^{-1}\), we have a Reynolds number in the laboratory of approximately 5000, which is sufficiently large for our purposes.

The flow directions studied covered the range from 180° to 280°, the directions of interest for wind from the sea, with attention concentrated on the directions 180°, 200°, 220°, 240°, 260° and 280°.

**Flow Patterns and Results**
Flow visualisation by dye released upstream shows a variety of flow structures due to the complex shape of the Cape. These include: vortical circulation near the base of the cliff, due to stretching of the low-level vorticity in the upstream wind profile over the sea; elevated stagnation points on the cliff face; and a substantial semi-stagnant or rotating region within the steep-sided cove on the western side (hereafter denoted the 'western cove'). Details of the flow vary with the direction of the incident wind, and schematic representations of the flow from each of the main directions is shown in Fig. 5. These diagrams depict the vortical flow in the lowest 10-20 m, and the flow directions on the surface at heights above this. The complex vortical motion within the western cove, that exists for nearly all directions, is also shown. Although the general character is the same for each wind direction, there is significant variation as depicted in these sketches.
Residence times

Some attempt was made to estimate the residence times for low-level fluid at the base of the cliff and within the western cove, in situations where it subsequently passed the 10 m air intake. This involved flow from directions 260° and 280° in these experiments. With a towing speed of 5 cm s⁻¹, observations of a blob of dye showed that after entering the western cove it first emerged after an interval of 6 s and parts of it could still be seen passing the tower site (or close to it) after 12 s.

If the time scale in this experiment is $T_r = H/U$, with $U = 5$ cm s⁻¹ and $H = 9.7$ cm we have $T_r = 2$ s, so that the minimum residence time is greater than $3T_r$ and the maximum is greater than $6T_r$. For the full-scale situation with $H = 97$ m and taking $U = 10$ m s⁻¹, we have $T_r = 10$ s; the corresponding minimum residence time is then 30 s, the maximum is greater than 60 s.

Possible future extensions of this work

Whilst we are confident about the validity of the qualitative details of this experiment, for quantitative purposes it should be regarded as a preliminary study. The principal concern is the deviation of the upstream velocity profile in the laboratory from the mean logarithmic wind profile over the ocean, as described above. Accordingly, if accurate quantitative results are sought, a more detailed study could be undertaken which would (or could) include the following:

(i) The use of laboratory techniques to approximate the logarithmic wind profile.

(ii) More accurate measurements of residence times, as a function of mean wind direction with the logarithmic profile.

(iii) More detailed description of the surface flow patterns on the surface of the Cape, using surface tracers.

(iv) The use of laser illumination with tracers in the fluid to obtain sections of fluid velocity in the horizontal or vertical.

Table 1. Source height of sampled air arriving at the main Cape Grim intake from different wind directions.

<table>
<thead>
<tr>
<th>Wind direction (°)</th>
<th>Source height of sampled air</th>
<th>10 m inlet (m)</th>
<th>70 m inlet (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>20</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>30</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>30</td>
<td>125</td>
<td></td>
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<tr>
<td>240</td>
<td>20</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>10, 20, 30</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>10, 20</td>
<td>125</td>
<td></td>
</tr>
</tbody>
</table>

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Conclusions

1. The flow pattern around Cape Grim is complex, particularly at low levels where the vorticity in the upwind profile is significant, and causes elevated stagnation points.

2. The lower sampling point (10 m above local ground level) receives air that may come from a range of near-sea level heights, up to 30 m above mean sea level, and depend on the incident wind direction. In particular, for wind from 260° to 280°, the western cove causes air from a range of low-level upstream heights to surmount the cliff face and reach the vicinity of the 10 m air intake.

3. The residence times at the base of the cliff and within the western cove for fluid that passes the 10 m air intake have a minimum of $3T_r$, and a maximum of greater than $6T_r$, where $T_r = H/U$.

4. The upper sampling point (70 m above ground level) always ingests air from a height of approximately 125 m above mean sea level. This implies that air arriving at the lower intake may be significantly affected by effective contact with the ground and associated vegetation, whereas air entering the upper intake is not. It follows that conventional simple flux-gradient relations are not applicable in this situation.