Some comparisons between observed wind profiles at Risø and theoretical predictions for flow over inhomogeneous terrain

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SUMMARY

Velocity profiles observed in near neutral conditions at the Risø 125 m tower are presented. The upwind terrain contains, depending on wind direction, either one or two distinct changes in surface roughness.

Comparisons are made between the observed profiles and those predicted using models based on mixing-length theory, and, in the case of a single roughness change, the turbulent energy equation. Comparisons with the mixing-length model are moderately good but some features of the observed profiles are missing from the theoretical predictions. The particular turbulent energy equation model used appears to give slightly less accurate predictions than the mixing-length model.

1. Introduction

In a recent paper Panofsky and Petersen (1972) present data obtained from the 125 m meteorological tower at AEK Risø. Here we consider those cases with essentially neutral stability in more detail and make some comparisons between data and theoretical results obtained from numerical models of two-dimensional flow above inhomogeneous terrain. The basic model is a development of that described by Taylor (1969, 1972b) with an implicit finite difference scheme and modifications to deal with several changes in surface roughness. It uses boundary-layer and mixing-length hypotheses. For some cases with a single roughness change a model using the turbulent energy equation based on Peterson's (1969) work has also been used.

Some of the Risø velocity profiles (groups 3 to 7 in Panofsky and Petersen's notation) are representative of flow which has passed over two abrupt changes in surface roughness upwind of the tower, as shown schematically in Fig. 1(a), while others (groups 9 to 11) are

Figure 1. General flow configurations.

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representative of flow above a single roughness change as depicted in Fig. 1(b). In both cases we have to assume that the upwind flow is in equilibrium with the underlying surface and has an appropriate logarithmic velocity profile. For input to the models significant parameters are the distances from the tower to the water and to the far shore and the roughness lengths of the land and water surfaces upwind of the tower. For the land surfaces we use the values of roughness length \( z_0 \) given by Panofsky and Petersen which were obtained from the upper and lower portions of the observed velocity profiles. In most cases we take a value of 0.01 cm for the roughness length of the water surface as a reasonable estimate. Attempts to obtain a value from the observed profiles at the tower were somewhat unsatisfactory and led to very low values, e.g. 3 \( \times 10^{-8} \) cm for group 9.

The upstream friction velocity, \( u_0 \), required for comparing the computed and observed profiles was obtained by assuming that the wind speed at 96 m on the mast was above the region affected by the changes in surface conditions. This appears to work satisfactorily except in one case (group 5) where the distance to the far shore is 900 m. Here a slight adjustment was made and a reasonable match obtained. The values of land roughness lengths and other parameters used are given in Table 1.

### Table 1. Details of cases considered

<table>
<thead>
<tr>
<th>Group</th>
<th>Two changes in roughness</th>
<th>Single change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of profiles averaged</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Distance (in metres) from tower to:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) water</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>(b) far shore</td>
<td>600</td>
<td>700</td>
</tr>
<tr>
<td>Roughness lengths (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_0 )</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>( z_0'' )</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Upstream friction velocity ( u_0 )</td>
<td>0.69</td>
<td>0.65</td>
</tr>
<tr>
<td>(ms(^{-1}))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) with \( z_0'' = 0.91 \) cm
(2) with \( z_0'' = 0.0001 \) cm

2. Cases with two changes in roughness

We use the mixing-length model to predict numerically the velocity profile development in the transition regions. We have been unable to obtain results using a model based on Peterson's (1969) hypotheses in these cases. With our finite difference scheme the model appears to be inherently unstable just downstream of a change from a rough to a relatively smooth surface. Blom and Warten (1969) have considered cases with two changes in surface roughness using the mixing-length hypothesis by making assumptions about the self-preserving character of the flow. Such assumptions are rather hard to justify beyond the second change in surface roughness and no comparisons have been made with their model.

In Fig. 2 we give some results of the computations together with the observed profiles at the tower for groups 3 to 7. Computed profiles shown are,

(a) the upstream profile (at the far shore),
(b) the intermediate profile at the near shore, and
(c) the profile at the tower.
Figure 2 (a) to (d). Caption on next page.
For groups 5 and 6 agreement between the model's profiles and the observations is good, but it should be noted that the profiles were forced to match at 96 m and the roughness lengths have been derived from the observed profiles. In groups 3, 4 and 7 there is a major discrepancy at heights of about 40 m where the observed profiles exhibit a pronounced 'shoulder' which is absent or smoothed in the computed profiles. The same feature is present to a lesser extent in groups 5 and 6. It may be noted that even in these cases the transitions or 'kinks' in the computed profiles, although considerably smoothed, occur at roughly the correct heights.

We have considered several possible explanations for the discrepancy at the 'shoulder'. Three relate to the model in which boundary-layer approximations are made, the mixing-length hypothesis is used and the roughness length of the water surface is assumed constant. Plate (1971, p. 144) discounts the boundary-layer approximation as a major source of error and observations by Rigby (1969) in channel flow with a roughness change support this view. It is, however, conceivable that the neglect of dynamic pressure effects in the model could be partially responsible for the discrepancies. A second weakness of the model lies in its use of a mixing-length hypothesis. An alternative to this would be to use a model incorporating the turbulent energy equation. Peterson's (1969) model, for a single roughness change, gives a more 'angular' velocity profile but it is unlikely that it would produce the extreme irregularity observed in groups 3 and 7. The Peterson model, which we will apply to cases with a single change in roughness, also has a tendency to predict shallower internal boundary-layers than a mixing-length model. An alternative model incorporating the turbulent energy equation is described by Taylor (1972b). The velocity profile resulting from this model is quite close to those predicted by the simpler mixing-length theory used here.

The assumptions that $z_0' = 0.01$ cm is a possible source of error for two reasons. First, it may be an inaccurate value, and second, variations in sea surface roughness with distance from the far shore may be significant. The latter problem is considered by Taylor...
(1972a) for flow above an idealized sea surface obeying the Charnock (1955) - Ellison (1956) formula, $gz_o'/u_*^2 = \text{const}$. In the cases discussed here it would appear possible from those results that $z_o'$ could vary roughly from 0·0001 cm near the far shore to 0·01 cm at the near shore. Inclusion of this effect could give a better match between theoretical and observed profiles but would be unlikely to account completely for the discrepancies.

A fourth possible explanation is that the 'shoulder' is there at least partly as a result of orographic effects associated with the step up from the water surface at the near shoreline. This feature is often present in observational studies of roughness change flows and so far no models have been developed which include it. We are reasonably confident that the 'shoulder' is not due to instrument error.

In Fig. 3 we present the shear stress profiles at the tower as predicted by the model and in Fig. 4 are shown the surface friction velocities upwind of the tower. In both cases these are scaled with respect to $u_0$ which varies from one group to another. We see from Fig. 3 that different fetches give distinctly different shear stress profiles.

![Figure 3. Shear stress profiles at the tower after two changes in roughness.](image)

3. Single roughness change cases

In cases with a single roughness change initial computations with the sea surface roughness $z_o' = 0·01$ cm appeared to give a poor representation of the upper portion of the observed profile and so a value of $z_o' = 0·0001$ cm was also used for comparison purposes. In addition computations were made using a model incorporating the turbulent energy
equation and related assumptions used by Peterson (1969). Further details of this model and
intercomparisons between it and several similar models are given in Taylor (1972b).

The computed and observed profiles are shown in Fig. 5; the governing parameters
are in Table 1. Different values of $z_0'$ give different upstream friction velocities and hence
different observed velocities on a plot of $U/u_0$.

For groups 9 and 10 the mixing-length computations match the data quite well with
either value of $z_0'$ except for the velocity measurement at 39 m where, as in some of the
cases with two roughness changes the observed velocity is higher than the theoretically
predicted one. This may suggest the possibility of an instrument error in that particular
anemometer or could be due to an orographic effect as discussed in Section 2. For group 11
the comparison is somewhat less satisfactory, as is the quality of the data. This is possibly
due to the presence of buildings upwind of the tower.

In all cases the Peterson model predicts a shallower region of flow modification than
was observed. Although the observations are somewhat sparse in the 6 to 30 m height range
there seems to be no indication of the pronounced inflection predicted by the Peterson
theory. There does, however, appear to be some inflection in the observed profiles at
heights around 30 m in contrast to the predictions of the mixing-length model where
$\partial U/\partial (\ln z)$ decreases monotonically with height.

4. Conclusions

The wind profiles observed at Riso provide an interesting opportunity for preliminary
comparisons with theoretical predictions of flow over quite complex terrain. These indicate
that we are able to match the velocity profiles moderately well but some features remain
unexplained. In particular many of the velocity profile data presented here appear to have
sharp 'kinks' at the edges of the internal boundary layers even though they are averages
over large numbers of observations. We believe that failure to match this feature, which is
Figure 5 (a) to (c). Velocity profiles at the tower with a single roughness change.
of course more pronounced when $U$ is plotted against $\ln z$ than $z$, is quite possibly a result of neglecting dynamic pressure effects in the models used here.

It would, of course, have been most helpful if data on turbulent intensities and/or shear stresses and also additional velocity measurements between ground level and 30 m were available. It is hoped that some attempts will be made to obtain such data in the future and that they will enable a more critical appraisal of the predictions of the theoretical models.

References


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