Wind profiles and change of terrain roughness at Risø

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SUMMARY

The Risø 125 m tower is situated on a narrow peninsula, surrounded by bays of varying width. The resulting surface roughness changes are clearly reflected by 'kinks' in the measured wind profiles, whose characteristics depend on the wind direction. The height of the lowest kink for water-to-land trajectories is in good agreement with theory.

The roughness lengths computed for the immediate surrounding of the tower vary with wind direction in a manner consistent with terrain features. However, the roughness lengths of the water estimated from the profiles are unrealistically small.

The mean profiles obtained when the trajectory passes over relatively homogeneous terrain are represented quite well by wind profile expressions that are usually applied only in the surface layer.

1. INTRODUCTION

A 125 m meteorological tower is located near the tip of a narrow tongue of land occupied by the Research Establishment Risø of the Danish Atomic Energy Commission. The site provides an unusual opportunity for studying wind profiles behaviour over inhomogeneous terrain because of the varying patterns of land and water surfaces that occur (Fig. 1).

Figure 1. Map of Risø tower and surrounding area, with major sectors of wind direction indicated.
Anemometers are mounted at 7 levels on the tower, thermometers at 8 levels, and moisture equipment at 2 levels. Ten-minute average winds, centred on every hour and recorded over a period of ten years, are now available on magnetic tapes.

The Risø data are valuable for qualitatively comparing current ideas concerning the effect of roughness change on wind profiles with data obtained in an operational situation. Moreover, some of the measured data are relevant to the still controversial question of the shape of the wind profile over uniform terrain up to 100 m or so.

Still the site is far from ideal because the nearby land surfaces are not homogeneous and the tower is located on a low hill, 6-50 m above the water-level.

2. THE OBSERVATIONS

Wind speeds and directions are obtained from cup anemometers and vanes, built according to specifications by Risø personnel. Temperatures are sensed by platinum resistance thermometers, and humidity by lithium chloride humidiometers.

Wind speeds are measured at 7 heights above the base of the tower; 7 m, 23 m, 39 m, 56 m, 72 m, 96 m, and 123 m; temperatures at the same heights and at 2 m; wind directions at 7 m, 56 m, and 123 m; moisture at 2 m and 123 m.

The booms are directed towards the south-west, so that winds between north and east were not used in this study. The topmost anemometer was mounted directly above the tower. The mean profiles indicated significant differences between the behaviour of the anemometer at this top level, and those at the lower levels, probably due to the difference in aerodynamic environment. Therefore, the wind at 123 m was omitted in the detailed analysis.

The foundation of the tower is on a smooth hill at the height of 6-5 m above mean sea level. The tower is composed of 15 sections 8 m long, bolted together. In cross-section they present an equilateral triangle with sides of length 1.70 m; the three sides face north, south-west and south-east. The instruments are mounted on triangular booms extending from the south-west side of the tower and are positioned 2-35 m from the lattice work of the tower.

Air trajectories reaching the tower from various directions (excluding 005° – 005°) may be divided into 3 general classes.

Class A: Wind directions 85° – 125°; trajectory almost entirely over land, but with somewhat variable roughness as function of distance and direction.

Class B: Wind directions 125° – 245°; trajectory first over land, then over water, and then over land again, the stretch over water varying from 300 to 800 m in length.

Class C: Wind directions 265° – 005°; long water trajectory followed by about 300 m land trajectory.

3. REDUCTION OF THE OBSERVATIONS

Originally, all the data were separated according to wind direction into 11 groups as listed in Table 1. Observations were used only if at least two of the three measured wind directions fell within the range of wind directions specified for the particular group. If any wind direction, speed or temperature was missing at any hour, no observations for this hour were used. Also, observations were omitted if the wind speed at 7 m was less than 2.5 m s⁻¹.

For each wind direction group, the wind data were also classified according to the gradient Richardson number computed from differences between winds and temperatures at 7 m and 23 m. The Richardson numbers used in the categorization were computed from centred three-period averages of temperature and wind speed differences, because 10 min averages have large 'random' deviations.

Five Richardson number categories were defined for each wind direction group, separated by Richardson numbers −0.03, −0.005, +0.005 and +0.25.

The central category will be called the 'neutral' category.

For each wind direction group, and each Richardson number category, mean wind speeds were computed at all seven levels, as well as standard deviations of 10 min wind speed, minimum and maximum profiles and mean Richardson numbers.

4. PROPERTIES OF THE MEAN WIND PROFILES IN NEUTRAL AIR

For each wind direction group and Richardson number category, mean wind profiles were plotted on semilogarithmic paper. The number of individual profiles averaged in each mean profile varied from 42 to more than 2,600.
### TABLE 1. PROFILE CHARACTERISTICS IN NEUTRAL AIR

<table>
<thead>
<tr>
<th>Group</th>
<th>Direction, deg.</th>
<th>Number of profiles averaged</th>
<th>Distances in m to:</th>
<th>Roughness lengths, cm</th>
<th>Kink h</th>
<th>Heights, m h''</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>water</td>
<td>far shore</td>
<td>$z_0$</td>
<td>$z_0'$</td>
</tr>
<tr>
<td>1</td>
<td>85–105</td>
<td>49</td>
<td>—</td>
<td>—</td>
<td>7</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>105–125</td>
<td>51</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>125–145</td>
<td>77</td>
<td>300</td>
<td>600</td>
<td>5</td>
<td>small</td>
</tr>
<tr>
<td>4</td>
<td>145-165</td>
<td>42</td>
<td>100*</td>
<td>700*</td>
<td>6</td>
<td>imag.</td>
</tr>
<tr>
<td>5</td>
<td>165–195</td>
<td>53</td>
<td>100</td>
<td>900</td>
<td>10</td>
<td>0-3</td>
</tr>
<tr>
<td>6</td>
<td>195–215</td>
<td>77</td>
<td>200</td>
<td>600</td>
<td>2</td>
<td>0-01</td>
</tr>
<tr>
<td>7</td>
<td>215–245</td>
<td>255</td>
<td>300</td>
<td>700</td>
<td>12</td>
<td>small</td>
</tr>
<tr>
<td>8</td>
<td>245–275</td>
<td>505</td>
<td>300</td>
<td>2,500</td>
<td>30</td>
<td>small</td>
</tr>
<tr>
<td>9</td>
<td>275–305</td>
<td>458</td>
<td>300</td>
<td>6,500</td>
<td>22</td>
<td>small</td>
</tr>
<tr>
<td>10</td>
<td>305–335</td>
<td>185</td>
<td>280</td>
<td>5,500</td>
<td>28</td>
<td>small</td>
</tr>
<tr>
<td>11</td>
<td>335–605</td>
<td>68</td>
<td>280</td>
<td>4,500</td>
<td>5</td>
<td>small</td>
</tr>
</tbody>
</table>

* Also islands in the water
† Uncertain

<table>
<thead>
<tr>
<th>Group</th>
<th>Fetch over far shore in m</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>&gt; 20,000</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 20,000</td>
</tr>
<tr>
<td>5</td>
<td>20,000–1,000</td>
</tr>
<tr>
<td>6</td>
<td>1,000–700</td>
</tr>
<tr>
<td>7</td>
<td>700–0</td>
</tr>
</tbody>
</table>
In order to avoid confusion, the 55 individual mean profiles are not shown here, but mean profiles for the three principal trajectory classes will be shown and discussed later. However, many of the properties of the individual mean profiles are listed in Table 1.

A large fraction of the individual 10 min profiles exhibit 'kinks' that then appear in the group mean profiles as the features that would be expected from discussions of the effect of roughness change on wind profiles. As suggested first by Elliott (1958), when air under neutral conditions travels from homogeneously smooth to homogeneously rough terrain, the wind profile over the rough terrain essentially consists of two logarithmic parts with different slopes; the lower part of the wind profile is characteristic for wind flow over rough terrain, with large wind shears and roughness lengths, and the upper part reflects the flow over smooth terrain with smaller wind shears and roughness lengths. At the height of the intersection of the two logarithmic sections, \( h \), a 'kink' appears. The level of the kink, \( h \), effectively separates the lower part of the flow, which has been affected by the rough terrain, from the upper part of the flow, which has not yet been influenced by the rough terrain. All wind profiles with wind directions from 125° clockwise to 005° show such kinks.

Blom and Wartena (1969) have shown that for two successive changes of roughness the wind profiles can be divided into three sections; the lowest responds to the local roughness around the tower; the second is characteristic for the air flow over the water, and the highest has wind shears typical for the flow over land at considerable distances. Such conditions were observed for wind directions between 125° and 225°.

Table 1 shows that single kinks (\( h \)) are indeed found for water \( \rightarrow \) land trajectories, and double kinks for land \( \rightarrow \) water \( \rightarrow \) land trajectories. Typically, with fetches over land of 300 m, the lowest kink occurs at about 39 m; for significantly shorter fetch (group 5) \( h \) is smaller. In the cases with land \( \rightarrow \) water \( \rightarrow \) land trajectories, the upper kink occurs at 56–72 m when the distance of the far shore from the tower is of order of 600 m.

Table 1 also gives roughness lengths, \( z_0 \), \( z'_0 \) and \( z''_0 \), corresponding to the land near the tower, the water, and the far shore, respectively. These were determined by fitting lines to the separate sections of the profiles and noting the intercept with the ordinate axis. The rationale for this technique is that Elliott and other have shown that logarithmic profiles fit profiles quite well even when the stress varies with height and the air is not in equilibrium.

Still, these estimates must be regarded as relatively crude; first, the terrain around the tower is quite heterogeneous; and second, the effect of the elevation of the base of the tower above the water is not known. Previous experience suggests that a displacement length is not indicated, as long as heights are measured from the base of the tower.

The main conclusions which can be drawn from Table 1 are that; first, the roughness lengths \( z_0 \) of the land around the tower varies with wind direction in a manner qualitatively in agreement with what would be expected from the ground cover; second, the measured roughness lengths \( z'_0 \) are unrealistically small in most cases, and are not good estimates of the 'true' roughness of the water. A similar conclusion was also reached by Echos (1970) from profiles measured on shore shortly after leaving water. A possible cause of the discrepancy is that the profiles were assigned to the stability categories according to the conditions that prevailed over land; the stability over the fjord obviously may be quite different. It is planned to obtain wind profiles directly over water in order to compare \( z'_0 \) with the actual over-water roughness.

As shown in the Table, the height of the lower kink is typically 38 m, a value that can be compared with theoretical estimates. We will use Elliott’s theory, which is based on the assumption of logarithmic profile segments. There exist now theories and observations showing that this assumption is not quite correct (Peterson 1969); nevertheless, the interface heights \( h \) computed from Elliott’s theory agree well with observations and with estimates from more complex theories.

Elliott gives an approximate formula for \( h \) which should be valid under the conditions of the observations used here:

\[
h/z_0 = (0.75 + 0.03 \ln (z'_0/z_0)) (x/z_0)^{0.8}
\]

in which \( x \) is the distance from the tower to the point of terrain change. Fortunately, \( h \) is only slightly affected by the roughness of the water surface, \( z'_0 \), which is poorly known. We use here \( z'_0 = 0.01 \) cm, a typical value derived from over-water wind profiles (Brooks and Krügermeyer 1970). With this \( z'_0 \) and with \( z_0 = 20 \) cm, \( h \), the height of the interface, comes out as 36 m, in good agreement with the observed values.

The differences in the group mean profiles contained within each major class were not extreme, so that only mean wind profiles for the major classes are shown here. They illustrate well the differences between the classes, and are presented as Fig. 2.
The mean profile in Class A in neutral air does not depart significantly from the logarithmic law. Since the terrain in this sector is certainly not completely homogeneous, no quantitative conclusions can be drawn from this profile alone. However, it is one added piece of evidence that, contrary to earlier expectations, the logarithmic wind law fits profiles over homogeneous or nearly homogeneous terrain in neutral air up to at least 100 m without systematic deviation. This suggestion was first made by Thuillier and Lappe (1964) on the basis of observations near Dallas, Texas; and recent observations over generally homogeneous terrain at the 150 m tower at Cape Kennedy, Florida (unpublished) have confirmed this hypothesis.

The features of the profiles in Classes B and C have already been discussed in connection with Table 1.

5. THE PROFILES IN UNSTABLE AIR

Wind profiles in unstable air over homogeneous terrain in the surface layer are quite well understood, on the basis of Monin-Obukhov similarity theory. The normalized logarithmic wind shear, $\phi$, is given as a universal function of $z/L_0$ where $L_0$ is the Monin-Obukhov length, which depends on the vertical surface fluxes of heat and momentum and is usually assumed to be independent of height, at least up to 20 m or so.

There is now general agreement about the universal function in unstable air. An expression well fitting most carefully measured wind profile is

$$\phi = \left(1 - \gamma \frac{z}{L_0}\right)^{-1/4} \tag{2}$$

Here $\gamma$ is a constant, which has a value of about 16 (Paulson 1970). Frequently, heat and momentum flux are not measured, so that $L_0$ is not given. It is therefore, convenient to use the working hypothesis proposed independently by Businger, Dyer and Pandolfo that, in unstable air, $z/L_0 = \text{Ri}$. We will use this equation to determine $L_0$ by use of temperature and wind differences between 7 m and 23 m, so that:

$$L_0 = \frac{z}{\text{Ri}} \tag{3}$$

where $z$ will be taken as 13 m, the geometric mean height between 7 m and 23 m.

Eq. (2) has generally been applied in the surface layer. We shall test the hypothesis that this equation is valid for higher levels on the basis of wind directions class A, for which the neutral wind profile was essentially logarithmic. Since $du/dv$ (In $z$) varies only very little with height, we can
then assume that $\phi = 1$ for this profile, provided we use the surface friction velocity $u_*$ in the definition of $\phi$.

We consider the ratio of wind differences $\Delta u$ between the same levels in unstable and stable air:

$$\frac{\Delta u}{\Delta u_n} = \frac{u_{n*} \phi_n}{u_{n*} \phi_n} \quad (\phi_n = 1).$$  \hspace{1cm} (4)

Subscripts $n$ and $u$ denote neutral and unstable respectively. Such ratios should be relatively independent of terrain irregularities since the same terrain effects are present.

Since Eq. (2) is acceptable in the surface layer we may apply its integrated form (Paulson 1970)

$$u = \frac{u_*}{k} \left( \ln \frac{z}{z_o} - \phi \left( \frac{z}{L_o} \right) \right).$$  \hspace{1cm} (5)

to estimate the surface friction velocity

$$u_* = \frac{ku(z_1)}{\ln \frac{z_1}{z_o} - \phi \left( \frac{z_1}{L_o} \right)} \quad (z_1 = 7 \text{ m}) \hspace{1cm} (6)
$$

where

$$\phi \left( \frac{z}{L_o} \right) = \ln \left( \frac{2 \text{ Ri}}{1 - x} \right) - 2 \tan^{-1} x + \frac{\pi}{2} \quad \hspace{1cm} (7)$$

and $x = (1 - 16 \frac{z}{L_o})^{1/4}$. Insertion of Eq. (6) into Eq. (4) leads to

$$\phi_n = \frac{u_n(z_1)}{u_n(z_1) \Delta u_n} \left( 1 - \phi \left( \frac{z_1}{L_o} \right) \right). \hspace{1cm} (8)$$

Fig. 3 compares values of $\phi$ obtained from Eqs. (2) and (8). This Figure also shows estimates of $\phi_u$ obtained from wind profiles from the 150m tower at Cape Kennedy. At this site, hour-mean winds were available at 18 m, 30 m, 60 m, 90 m, 120 m and 150 m; the method of computation was analogous to that described above.

![Figure 3. Comparison between observed and computed normalized logarithmic wind shear in unstable air.](image)

Taken together, Eq. (2) fits the observations reasonably well, with no significant difference in behaviour between the points below or above 30 m. Of course, the scatter is considerable. Also, there appears to be a slight systematic error in the sense that Eq. (2) overestimates $\phi$ for large $z/[L_o]$. In fact, for this limit, $\phi$ appears to vary more nearly with $(z/[L])^{-1/2}$ than with $(z/[L])^{-1/4}$, in agreement with 'classical' free-convection theory.
Fig. 4 shows mean wind profiles in the three direction classes in slightly unstable air (average Ri = -0.016 in each sector). This number differs so little from zero that straight-line sections still fit the profiles well. As expected the heights of the kinks are not significantly different from those in neutral air.

If the wind profile satisfies Eq. (5) then observed values plotted as a function of ln z - ψ should picture straight-line profile segments whose intersections with the ordinate axis give the roughness lengths.

Thus u was plotted as function of ln z - ψ (Ri) for the profiles of Fig. 4 (indicated on the figure as ‘corrected’), and the geometric mean roughness lengths near the tower were 2.3 and 20 cm for classes A, B and C, respectively, in fair agreement with the corresponding roughness lengths in neutral air, 3, 7 and 23 cm (Fig. 2).

Fig. 5 shows the profiles in the most unstable Richardson number category, in which the average Richardson number was -0.195, -0.215 and -0.140 in classes A, B and C, respectively. As is to be expected, the plotted points show some curvature, concave to the left. As before, these profiles can be used to infer roughness lengths near the tower in the three classes. The values were 2, 3, and 20 cm in the three classes, exactly the same as in slightly unstable air. Altogether the roughness lengths are quite consistent, showing again that the effect of instability on wind profiles is handled satisfactorily by similarity theory.

There appears to be no very significant difference in the heights of the kinks in neutral and unstable air except that in unstable air the portions of the class B profiles produced over water and those over the far shore cannot be distinguished.

There is a slight indication on Fig. 5, as well as on graphs representing wind profiles from narrower sectors that the interface separating the flow types induced by the smooth and rough terrain is slightly steeper in unstable than in neutral air. Whereas the intersection of this interface with the tower typically occurs near 39 m, in neutral air, it appears to occur nearer 45 m in unstable air. However, this estimate must be viewed as being extremely uncertain.

The effect of a change of surface roughness should spread more rapidly in the vertical in unstable than in stable air. This was first shown by Miyake (unpublished Master’s Thesis, University of Washington), who suggested that the slope of the interface should be proportional to the ratio of the standard deviation of vertical velocity and the wind speed, σw/u. In unstable air, this slope can then be written:

\[
\frac{dh}{dx} = \frac{\phi_3(Ri)}{\ln z/z_0 - \psi(Ri)} \tag{9}
\]

where \(\phi_3(Ri)\) is the universal function representing the ratio \(\sigma_w/u^*\). The average Richardson number
between the ground and 40 m on the tower is about $-0.3$ for the profiles under discussion. For this Richardson number, $\psi^0$ exceeds its neutral value by 15 per cent or so (Haugen, Kaimal and Bradley 1971). This estimate, though uncertain, would suggest an increased interface height by about 15 per cent for the unstable over the neutral profiles. An additional increase should result from $\psi$ in the denominator of Eq. (9). We must conclude then that an increase of interface height with decreased Richardson number is likely, but has not been well demonstrated by wind profiles at Riso.

Figure 6. Mean wind profiles in moderately to slightly stable air ($\text{Ri} < 0.25$) for classes A, B and C.
6. Wind profiles in stable air

Fig. 6 shows average wind profiles for the three classes in stable air, but with Richardson numbers less than 0·25. Surface layer analysis has been reasonably successful in stable air if $\phi$ is assumed to be linear in $z/L$, and $L$ is taken constant with height. An abortive attempt was made to extend this type of analysis to higher altitudes, but presumably because it is unrealistic to assume that $L$ is independent of height from the surface to 100 m. Therefore, Fig. 6 will be discussed qualitatively only.

As is to be expected, the profiles are basically made of concave sections falling below a logarithmic law. Classes B and C generally indicate kinks between profile sections influenced by land and water at about 33 m, a little lower than those in neutrally stratified air. Near the top of the tower, the wind shear in class B is greater than that in class C due to effect of the land beyond the water; and the wind shear at low levels is greater for class C than for class B, because of the greater roughness near the tower for class C. Finally, class A has large shears all through the profile because all of it is influenced by land.

![Figure 7. Mean wind profiles in quite stable air for classes A, B and C.](image)

For completeness, Fig. 7 shows mean profiles for Richardson numbers above 0·25, when presumably, turbulence was weak or absent. Not much can be said about these profiles except that the curvature remains concave, and there appears to be little, if any, effect of surface roughness change on the profiles.

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