

The Dependence of Boundary-Layer Shear on Diurnal Variation of Stability

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ABSTRACT

Boundary-layer data from several different geographical locations are analyzed to document the behavior of boundary-layer shear above the surface. The influence of diurnal variation of stability is emphasized. The applicability of the power law for use in shear estimates is examined.

1. Introduction

Knowledge of low-level vertical shear of the mean horizontal wind in the boundary layer is important to aircraft operations, fatigue of large wind generator blades, estimation of wind power potential from surface observations and dispersal of atmospheric pollutants. Such shear has been studied in detail primarily in the atmospheric surface layer. Shears above the surface layer are generally smaller but in special circumstances may be as large as 0.1 or 0.2 s^{-1} . For example, under certain conditions, Kusano *et al.* (1969) found that very active fronts sometimes produce shears between 0.10 and 0.15 s^{-1} lasting for several hours. In thunderstorm outflows, Fujita and Byers (1977) reported shears of 0.12 s^{-1} extending up to 100 m. Various studies in WMO (1969) show that at most locations, the shear of the 5 or 10 min averaged wind above the surface layer is greater than 0.1 s^{-1} less than 1% of the time. Maximum shear values increase as the averaging time and depth of the layer of computation decrease (Rijkoort, 1969).

This paper considers the characteristics of boundary-layer shear over simple terrain. The influence of diurnal variation of stability on the evolution of shear is of primary interest.

2. Methods of shear computation

Care must be taken to define exactly what is meant by shear. Normally shear of the horizontal wind is defined as $\partial v/\partial z$, where v is the horizontal wind vector. Often, however, only the wind speed is known and shear is taken as $\partial v/\partial z$, where v is the wind speed. The speed shear will always be less than or equal to the magnitude of the vector shear especially at night when variation of wind direction with height may be large.

Shear calculations can be further subdivided according to the ordering of the following three calculations: differencing quantities at two heights, combining components to obtain a vector magnitude (scalar), and averaging. For example, one can compute the shear of each wind component, find the magnitude of the shear vector, and then average, giving

$$\overline{\left| \frac{\partial \mathbf{v}}{\partial z} \right|}.$$

We will refer to this quantity as the average total shear. If, on the other hand, only the wind speeds $|\mathbf{v}|$ are available, only two computations are left; one can either average and then compute the vertical difference

$$\frac{\partial \overline{|\mathbf{v}|}}{\partial z}$$

or first find the vertical gradient and then average to obtain

$$\overline{\left(\frac{\partial |\mathbf{v}|}{\partial z} \right)}.$$

These two approaches turn out to be equivalent and will be referred to as average speed shear. Another possible method is to compute the resultant wind vector at each level and then determine vertical differences to obtain the vertical shear.

Fig. 1 compares the average total and average speed shear using data from the 16 and 100 m levels of the Wangara experiment. As noted above, calculations based on speed only underestimate the average total shear, especially at night. Fig. 2 shows the frequency distribution of the shear components parallel and normal to the Wangara 50 m wind direc-

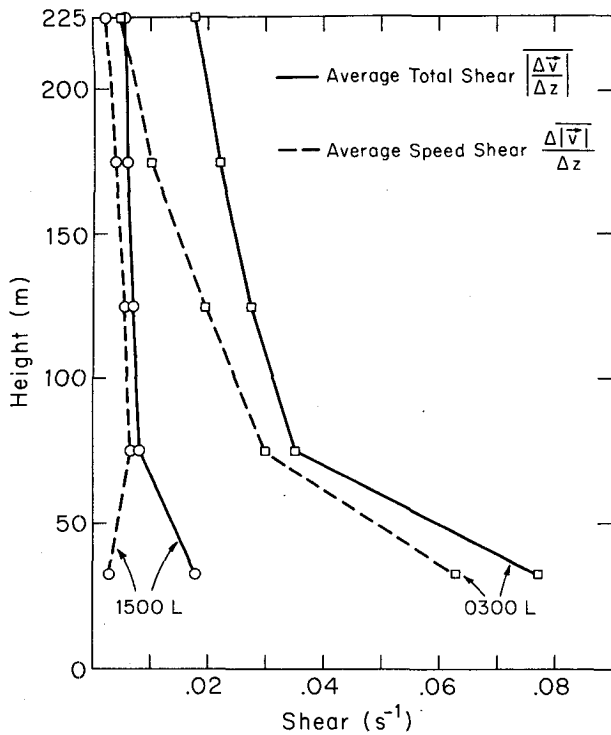


FIG. 1. Early morning and afternoon average total shear and average speed shear for Wangara.

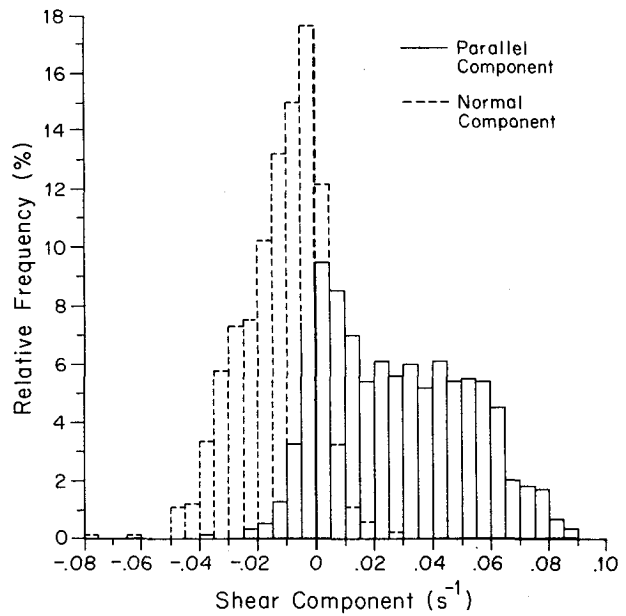


FIG. 2. Shear components at Wangara for the 16-100 m layer parallel and normal to the 50 m wind direction. Negative normal component shears indicate counterclockwise turning of the wind velocity vector with height.

tion which indicates that directional changes of wind may become an important factor. A general impression of the frequency distribution of shears for a variety of geographical locations is shown in Fig. 3. The largest shears normally occur with strong stratification which most frequently develops on clear nights.

3. Diurnal variation of boundary-layer shear

Vertical shear develops when turbulent mixing is too weak to eliminate velocity differences at different heights. Above the surface layer over land, the degree of mixing is often dominated by buoyancy effects. On days with significant surface heating, convective mixing minimizes shear development

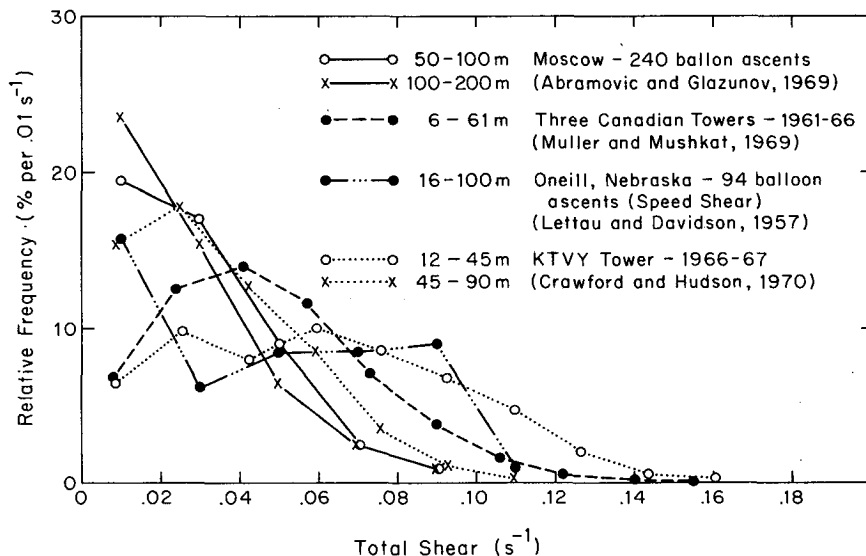


FIG. 3. Frequency of occurrence of total shear over the indicated layer.

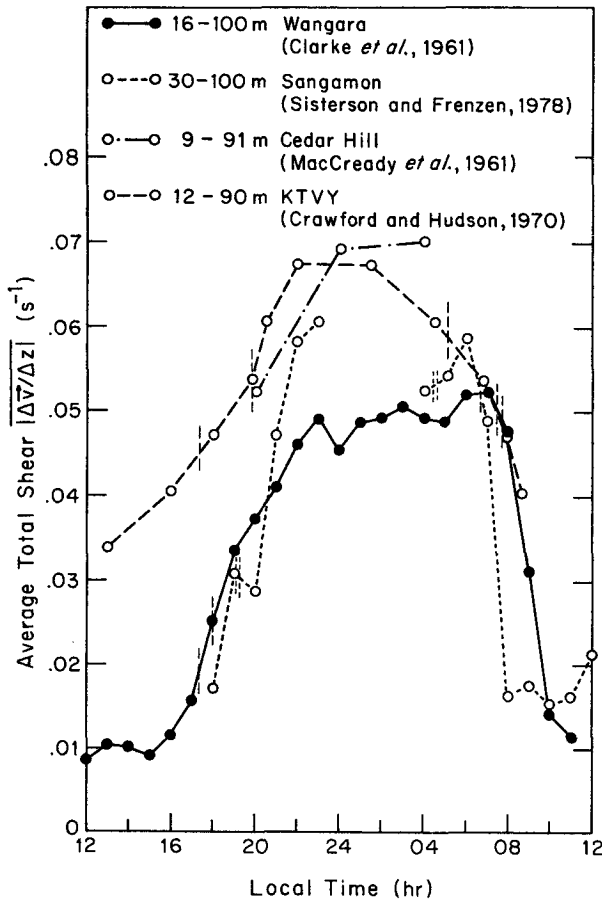


FIG. 4. Diurnal variation of average total shear over the indicated layer (vertical dashed lines indicate range of sunrise and sunset times occurring during observational period).

above the surface layer. During nights with strong surface cooling, mechanical mixing is inhibited by buoyancy effects and large velocity differences may develop. Diurnal variation of the stress and boundary-layer depth may induce significant nocturnal acceleration of low-level winds above the surface layer resulting in further enhancement of nocturnal shear. A low-level wind maximum frequently forms as low as one hundred meters above the ground, producing especially large shear below this level.

Fig. 4 shows that the diurnal variation of averaged total shear above the surface layer is significant at several different sites. We now attempt to document the sensitivity of shear above the surface layer to diurnal variations of stability. The usual stability parameters, u_* / fL and h/L (u_* is the surface friction velocity, L the Monin-Obukhov length, h the depth of the boundary layer and f the Coriolis parameter), are not easily calculated at night because of uncertainty in estimating surface fluxes which may be small and intermittent, and because of uncertainty in estimating the boundary-layer depth. Alternatively, we will compute a Richardson number of the form

$$Ri = \frac{gH(\theta_H - \theta_s)}{\theta U_H^2}$$

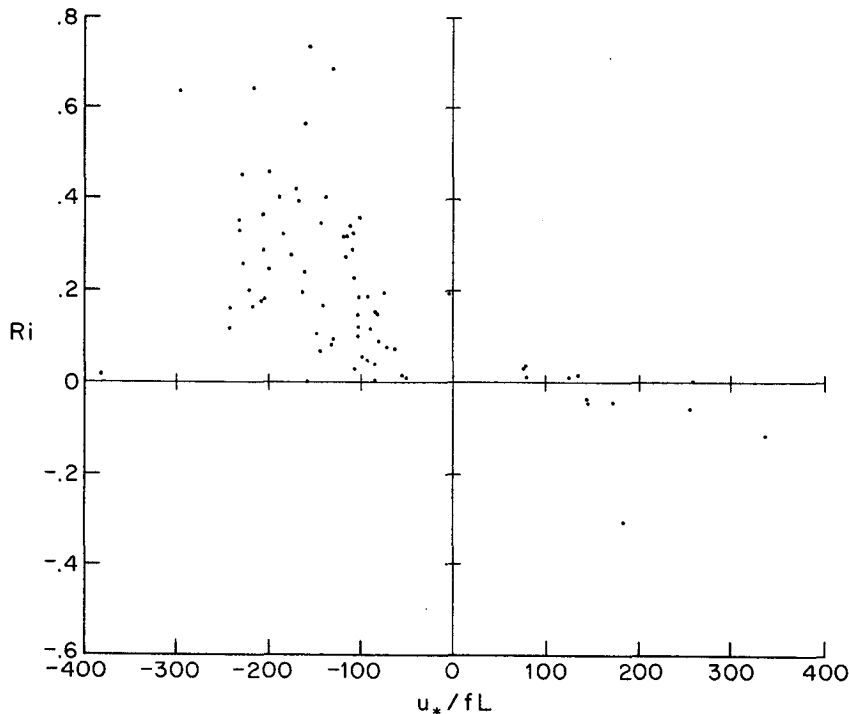


FIG. 5. Surface-100 m layer. Richardson number at Wangara versus u_* / fL of Melgarejo and Deardorff (1975).

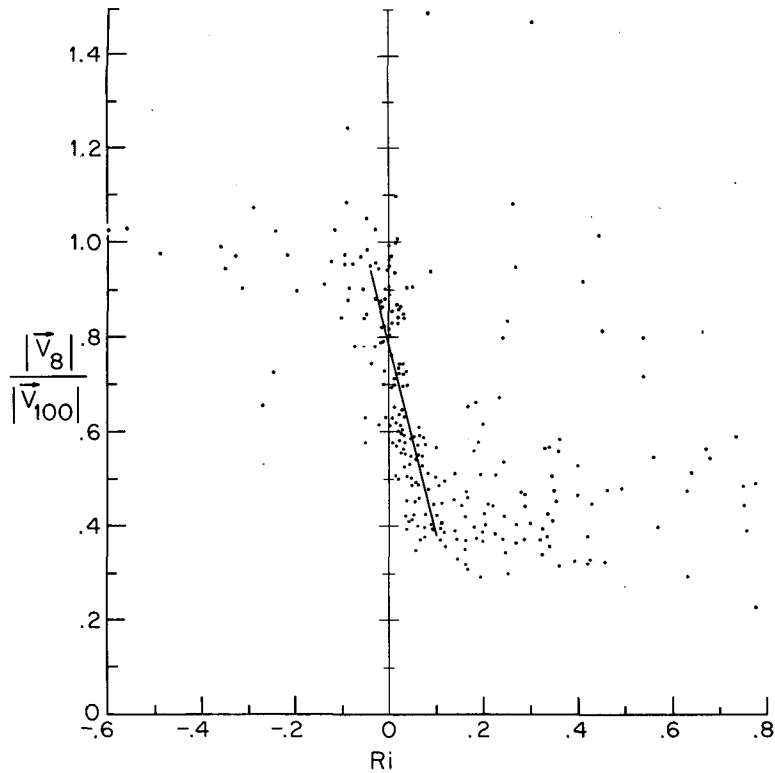


FIG. 6. Ratio of wind speeds at 8 and 100 m versus the surface-100 m layer Richardson number for Wangara. The straight line is a least-squares fit to points in the range $-0.04 \leq Ri \leq 0.10$.

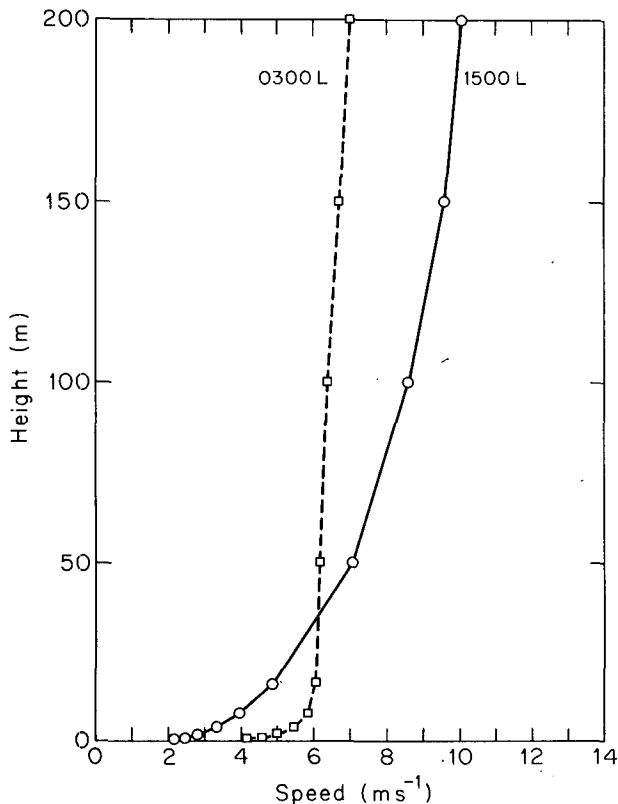


FIG. 7. Average wind speed for Wangara.

where H is the depth of the layer of significant shear, θ_H and U_H are the potential temperature and wind speed, respectively, at the top of this layer, θ_s the potential temperature at the surface and g the acceleration of gravity. For simplicity, H is chosen as 100 m for the data at Wangara (Fig. 5). In spite of uncertainties in values of surface fluxes and using constant H , Fig. 5 shows that there is sufficient correlation between Ri and u_*^2/fL that Ri can be used as a substitute stability parameter in the cases where surface fluxes are not available.

The ratio of winds at eight and 100 m, which can be used as an indicator of bulk shear, is quite sensitive to stability (Fig. 6). Most of the variation with stability occurs within the transition period between stable and unstable flow. For unstable flows, the ratio is near 1.0, indicating the nearly well-mixed nature of the layer. With very stable conditions, there is considerable variability possibly due partly to the intermittency of the turbulence. The increased shear above the surface layer under stable conditions is accompanied by decreased shear in the surface layer (Fig. 7). Since shear varies most rapidly with stability at near neutral values of stability, substantial variation of boundary-layer shear occurs even at maritime locations such as Risø, Denmark (Fig. 8).

Since low-level stability often varies diurnally (Fig. 9), we also expect significant diurnal variation

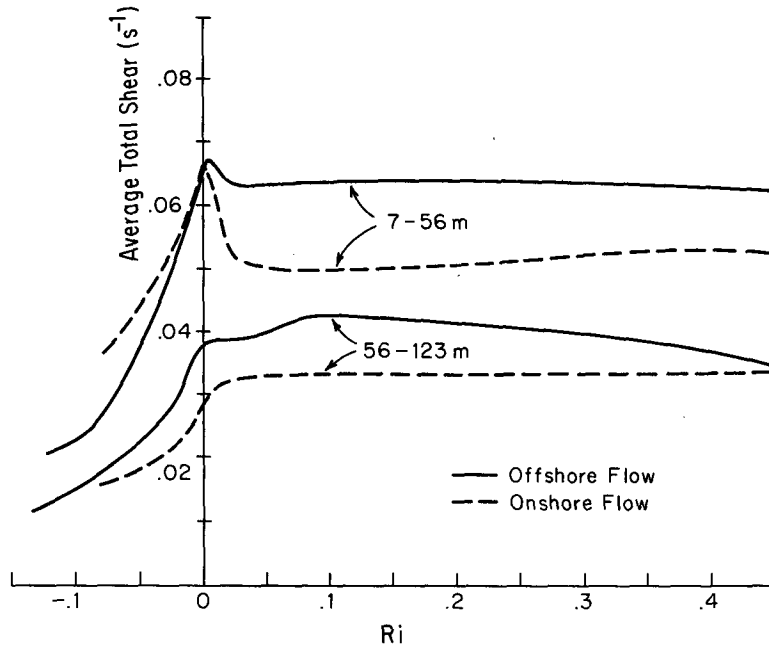


FIG. 8. Average total shear over the indicated layer versus Richardson number for Risø, Denmark (1958-62).

of boundary-layer shear. Such diurnal variation of shear for Wangara and the KTVY tower near Oklahoma City (Crawford and Hudson, 1970) is shown in Fig. 10. These cross sections indicate that while shear is larger at night at all levels above the surface layer, the greatest diurnal variation occurs around 50 m.

4. Power law

The usual and simplest approach for statistically representing shear is the power law which can be expressed in the form $\partial v/\partial z = p v/z$, where p normally increases with stability and surface roughness and decreases with height above ground (e.g., De-

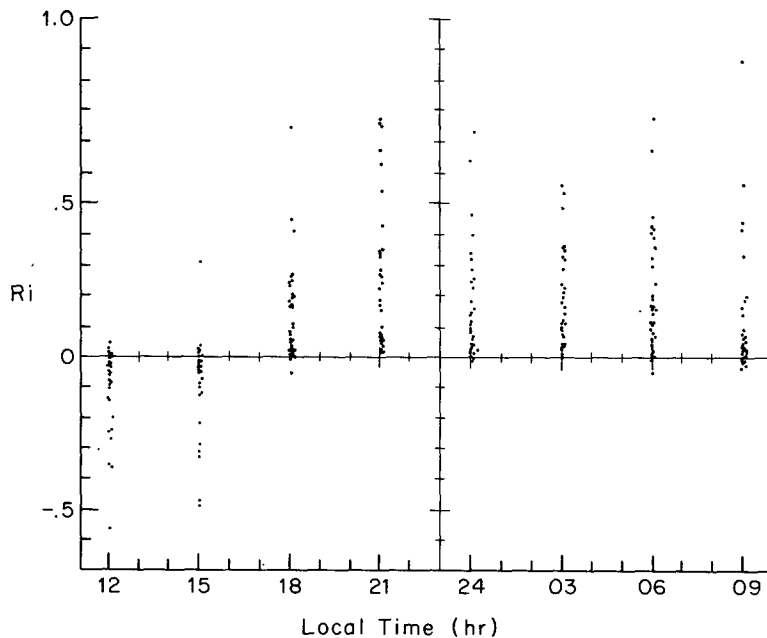


FIG. 9. Variation of the surface-100 m layer Richardson number with the time of day at Wangara.

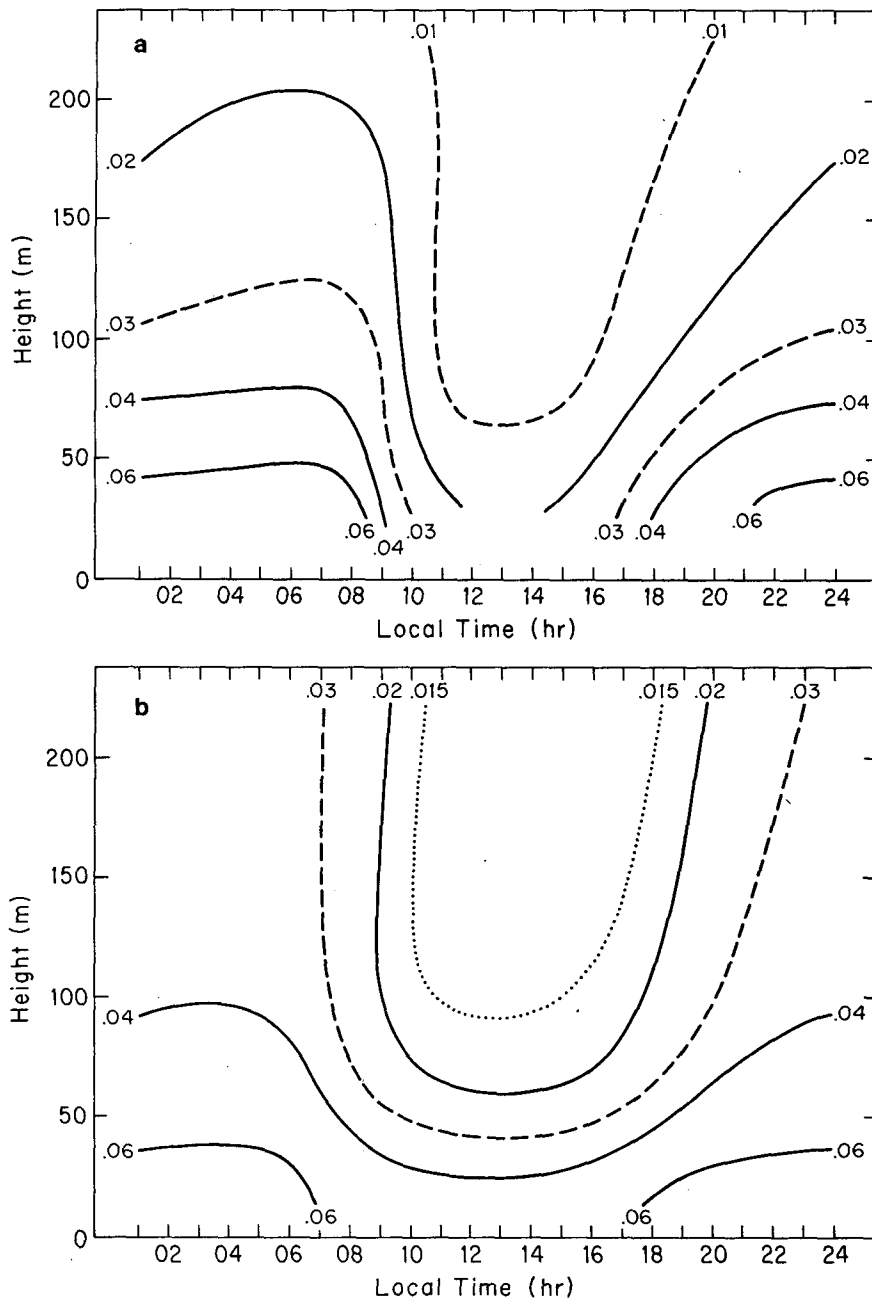


FIG. 10. (a) Average total shear for Wangara (s^{-1}); (b) As in Fig. 10a for KTVY.

Marraais, 1959; Smedman-Högström and Högström, 1978). Over very rough surfaces, the variation of p with stability may not be so marked (Smedman-Högström and Högström, 1978). With increasing positive Richardson number, the scatter of p becomes large (Fig. 11) as noted by Thuillier and Lappe (1964). This scatter probably again reflects some intermittency of turbulence and possibly increased baroclinity. Figs. 11 and 12 show that in the Wangara experiment, the mean value of p in the 8–100 m

layer is roughly 1/6 or 1/7 in agreement with Peterson and Hennessey (1978) and others. However, Fig. 12 indicates that this mean value actually occurs at a relative frequency *minimum*. This minimum is associated with a rapid variation of p with stability at near neutral or slightly stable values of stability. There is much less variation of p with stability outside this transition zone (see Fig. 6). Thus, the variation of p with stability for the Wangara data could be crudely parameterized by choosing a p value of

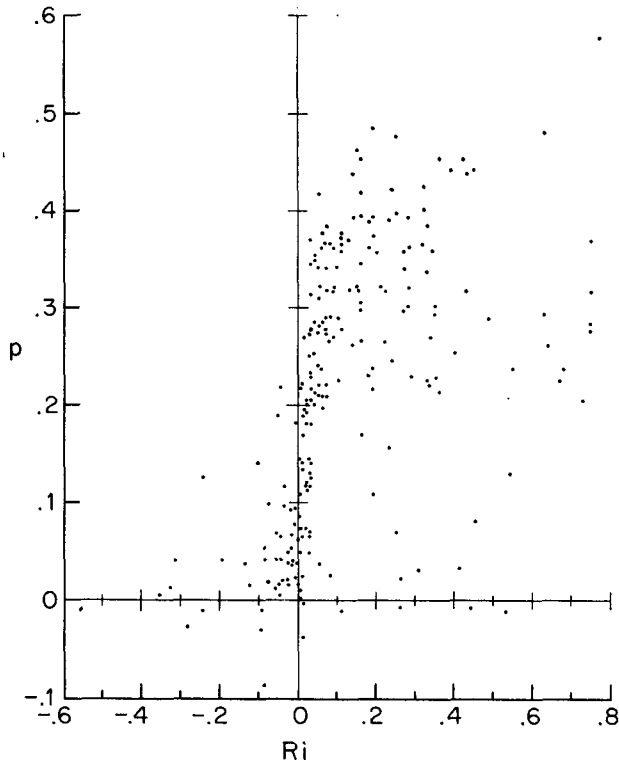


FIG. 11. Exponent p of the power law, fit to wind speeds at 8 and 100 m versus Ri at Wangara.

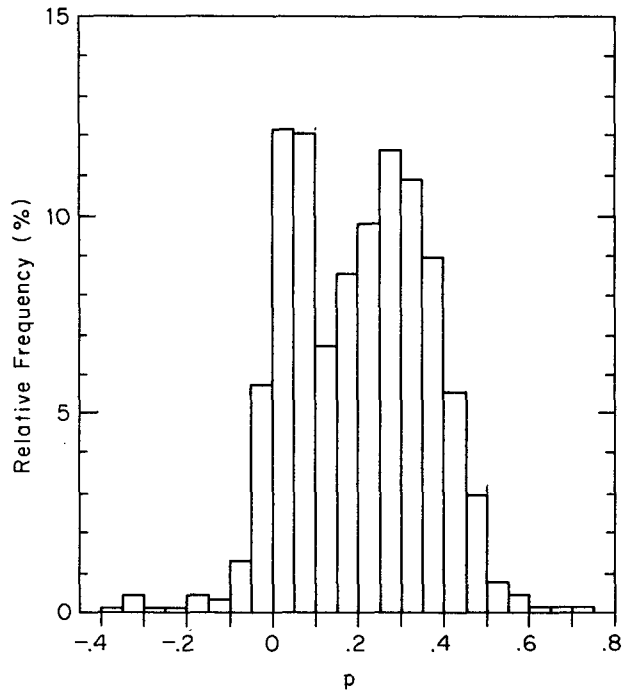


FIG. 12. Frequency of occurrence of p fit to wind speeds at 8 and 100 m for all hours for Wangara.

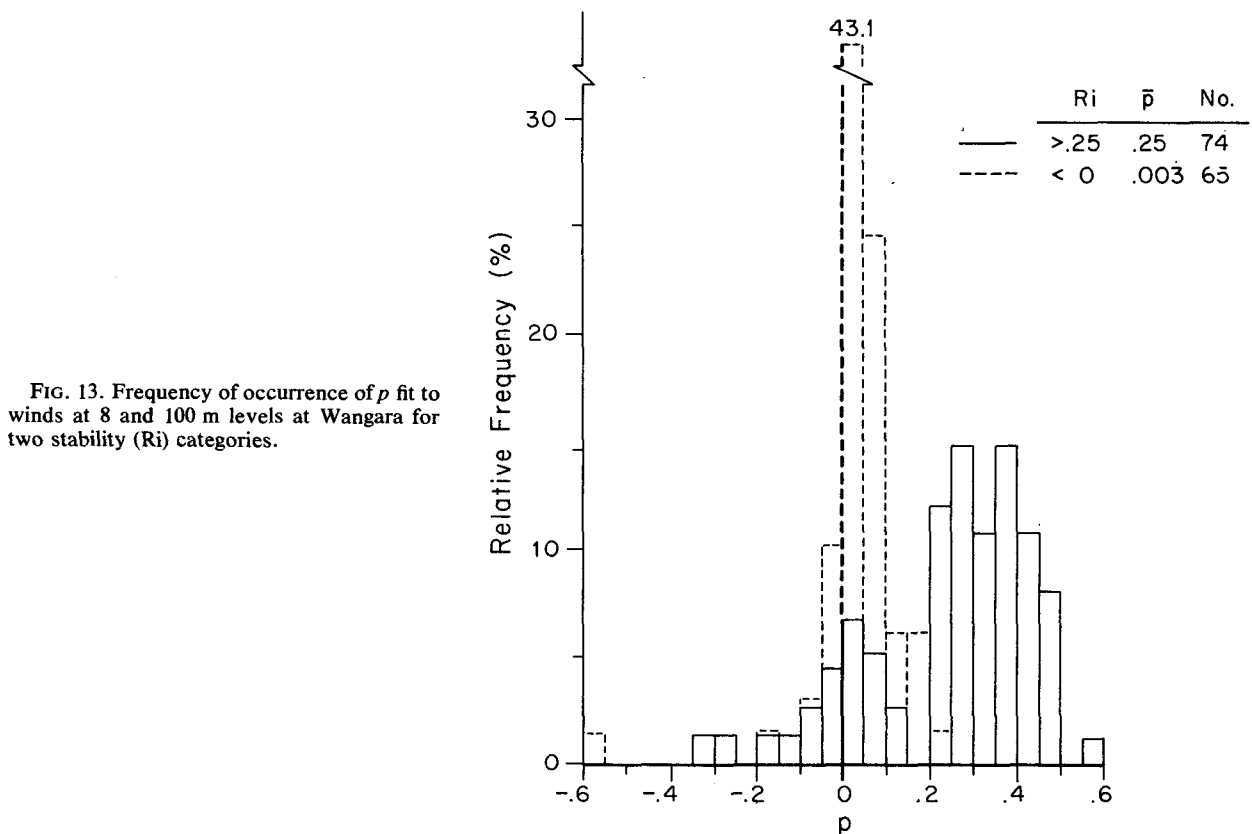


FIG. 13. Frequency of occurrence of p fit to winds at 8 and 100 m levels at Wangara for two stability (Ri) categories.

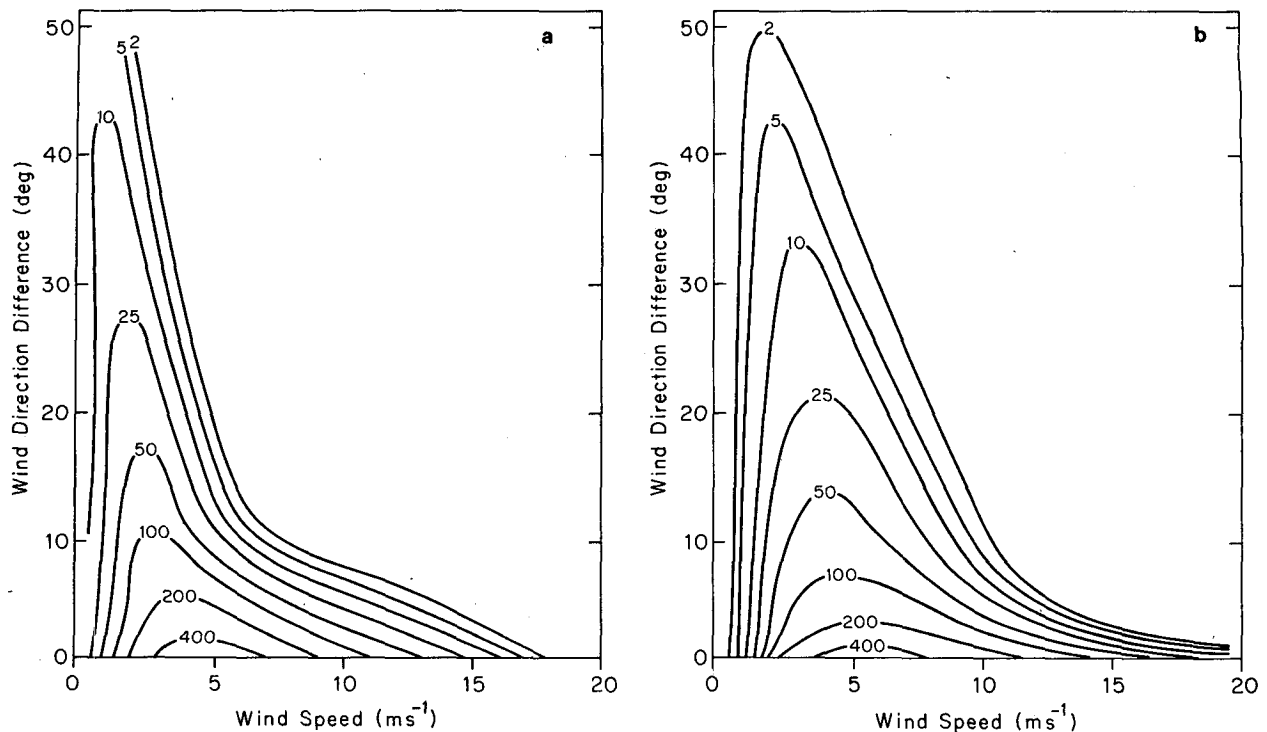


FIG. 14. (a) Frequency of occurrence of wind direction difference between 11 and 76 m, and the wind speed at 43 m for Risø; (b) frequency of occurrence of wind direction difference between 43 and 117 m, and the wind speed at 76 m for Risø.

~ 0.3 in stable conditions and 0.05 in unstable conditions. Fig. 13 divides p into two stability classes: $Ri < 0$ and $Ri > 0.25$. With very unstable conditions, the Monin-Obukhov length is much less than 8 m so that the flow becomes nearly well mixed in the entire layer and p approaches zero.

Failure to recognize variations of p with stability could lead to serious errors when using mean profiles to estimate nonlinear functions of wind speed such as wind loading or wind power. It would be better to categorize profiles according to stability and then average.

The value of p also normally decreases with height (DeMarrais, 1959). Based on Wangara data, the best fit of p for daytime cases ranged from ~ 0.1 near the surface to near 0 for levels above 16 m. At night the best fit of p decreases more slowly with height in the first few hundred meters but then becomes quite small near the boundary-layer top or at the level of the low-level wind maximum typically located 200 – 300 m above ground. The usual power law should not be used for extrapolation through a layer with a low-level wind maximum since negative shear and corresponding negative p correspond to infinite wind speed at the surface.

5. Directional shear

For certain applications, it is useful to estimate the probability of large directional shears. Direc-

tional shears are most likely to be greatest for weak mixing, that is, strong temperature stratification and weak wind speed. On the other hand, for many applications, directional shear becomes important only with significant speed. Fig. 14 shows the relationship between directional shear and wind speed at Risø for one year of 10 min average that include a variety of synoptic situations. The frequency of significant directional shear (say, greater than 20° between 11 and 76 m) drops off rather quickly as speeds exceed a few meters per second. However, search of a 10 -year period indicates that occasionally directional shears of 90° or more may occur over a depth of a few tens of meters with wind speeds > 5 $m\ s^{-1}$ in the upper part of the shear layer. Such occurrences at Risø were associated with a strong low-level inversion capping a shallow layer of cold air.

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