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STUDIES OF THE WIND VARIATION WITH HEIGHT IN ROUGH TERRAIN

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SUMMARY

The change of wind direction and wind speed with height in the surface layer and in the atmospheric boundary layer has been studied employing meteorological data from two sites in Norway with nonhomogeneous rough terrain.

Using wind data from a 36 m meteorological tower at a coastal site in western Norway the exponent of the power law wind profile has been evaluated as a function of upwind roughness length. Because of the diverse topographical features of the area the exponent were found strongly dependent on wind direction.

Wind direction changes in the lowest 1000 m of the atmosphere have been studied in the valley-fjord area of nedre Telemark, where up- and downvalley channeling and the diurnal oscillations dominate the local wind pattern. A study of the relationship between surface and geostrophic winds showed that in only 50% of the cases 0-60° veering (Ekman spiral) occured in the atmosphere.

Attempts to give a general description of the wind veering or to derive the relationship between geostrophic and surface winds have been impeded by the complexity of local and mesoscale circulations during the periods investigated.

CONTENT

1 INTRODUCTION

This investigation of the variations of wind with height in rough terrain has been based upon meteorological data from two sites in Norway. Part of the results of the study has been reported to the Scandinavian project Mesoscale Atmospheric Dispersion Modeling, organized by the Scandinavian Council for Applied Research (NORDFORSK).

One of the goals of the work was to establish empirical relationships between surface wind and winds at higher altutudes. This particular objective was not achieved, mainly because the complexities of the local and mesoscale circulations during the periods of investigations thwarthed the description of general relationships.

Consequently, this technical note presents data analysis specific to the study sites, but defers any definitive statements and final conclusions on general relationships until additional detailed data become available. Such information is expected to come from further work by the Norwegian Institute for Air Research (NILU) on wind profiles and wind fields in complex terrains in connection with studies on dispersion of air pollutants.

2 SITE DESCRIPTION

For the study of wind variation with height meteorological data from two sites, described below, were used.

2.1 Test site Kårstø

Wind profile measurements were carried out on a 36 m meteorological tower at Kårstø in Rogaland of western Norway (see map Figure 1). The site was characterized by substantial change in surface roughness in the different directions from the tower. This feature has been utilized to establish a power law wind profile as a function of roughness lenght. To the south of the site flat pasture grounds slope gently towards the waters of Boknafjord. A valley runs northwards from the site, flanked by two wooded hills which begin to rise about 500 m from the tower, one to the northwest (120 masl) the other to the northeast (220 masl). The nearest housing and scattered clumps of trees are at a distance of about 200 m from the tower.

2.2 Test area Nedre Telemark

To study the wind profiles above the planetary boundary layer, and the relationship between local wind patterns and geostrophic wind, data from the Nedre Telemark area has been used. The area consist of a mixture of forests farming districts, scattered housing, suburban and urban areas and a few industrial sites. A 4-5 km wide river valley and the about 8 km long and 2 km wide Frierfjord from an essentially north south oriented channel for local winds in the area. The rather flat valley-fjord system is surrounded by 100-200 m high hillsides bached by higher mountains. The location of the test sites is shown in Figure 2.

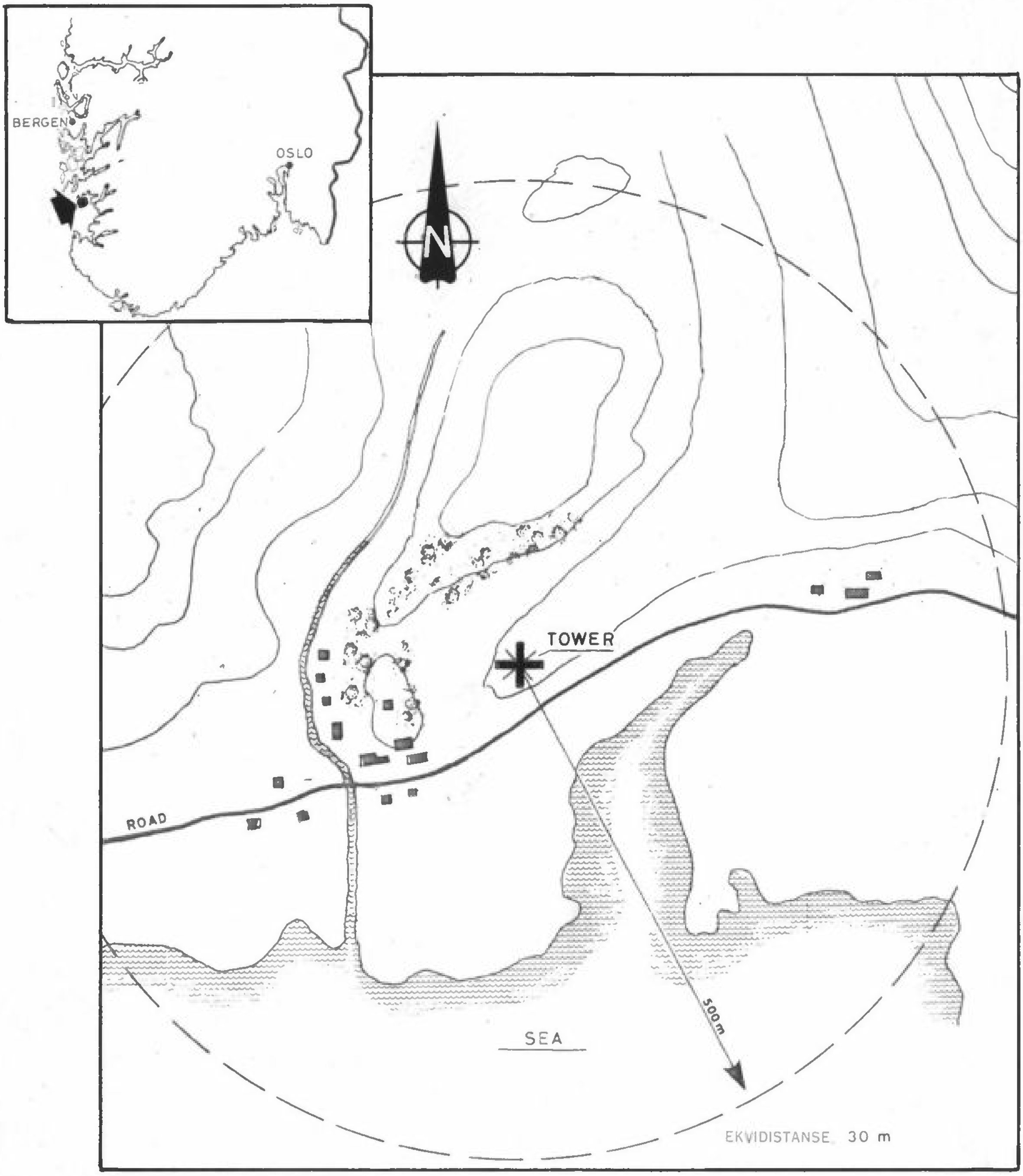

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Figure 1: Map of the Kårstö area.
The 36 m meteorological tower is indicated by a cross.

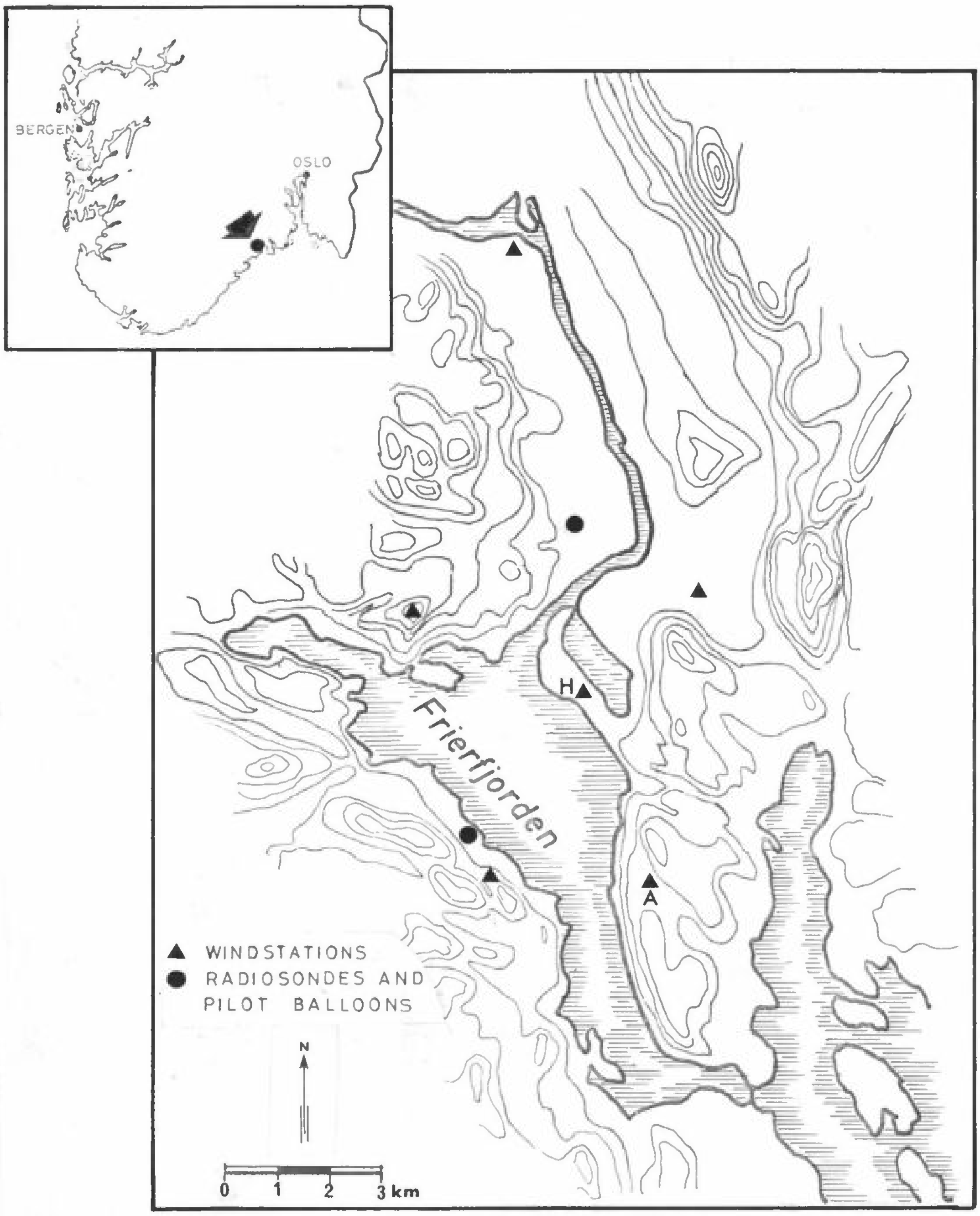


Figure 2: Topographical map of the test area Nedre Telemark.
The two stations referred to in the text are:

A : Ås
H : Heröya

3 TYPE OF INSTRUMENTS USED

The 36 m tower at Kårstø was equipped with cup anemometers and windvanes at the 36 m and 10 m levels, temperature sensors at 36 and 10 m levels, temperature difference sensors between 36 and 10 m, "turbulence" - monitoring system with sensors at 10 m level. The system is completely digitized and computes and logs on magnetic tape mean wind direction amplitude of wind direction fluctuations, standard deviation of the wind direction, mean wind speed, standard deviation of the wind speed and peak value of wind speed (gusts). The monitor usually operates unattended for about 2 months. (A detailed description of the turbulence monitoring system will be presented at a WMO-conference (13)).

The wind data in Nedre Telemark were collected with a conventional system. Surface winds were measured at the top of 10 m high towers and continously recorded (Woelfle instrument manufactured by Lambrecht). One hour average values of wind speed and wind directions were subsequently calculated and stored on magnetic tapes. Vertical wind profiles were obtained by tracking pilot balloons with a theodolite and a range finder. Vertical temperature profiles were determined from radio sonde soundings (Väisälä's low altitude radio sones) and air plane measurements. The geostrophic wind was estimated from the pressure distributions on ground level synoptic maps.

4 DATA SELECTION

The data from the automatic weather station at Kårstø for the winter period 1. Dec. 1975 - 28. Feb. 1976 were selected for this study.

In Nedre Telemark wind profile measurements were taken during the summer 1975. Most of the pilot balloon data originated from studies of the land/sea breeze circulations in the fjord-valley area, and were, therefore, strongly influenced by local and mesoscale circulations.

To establish the relationship between surface and geostrophic winds, data taken at 1300 hrs (local time) every day during the 1. March 1975 - 29. February 1976 period were selected.

5 THE MEAN VELOCITY PROFILE IN THE SURFACE BOUNDARY LAYER

Many functional relationships for the variation of the mean velocity with height have been suggested in the literature. A power law representation of the form $\bar{u}_1/\bar{u}_2 = (z_1/z_2)^{1/4}$ was proposed by Archibald in 1885 (1). ($\bar{u}_1$ and $\bar{u}_2$ is the average wind speed at heights z_1 and z_2, respectively). Sverdrup (2) some 50 years later pointed out that for most meteorological conditions the power law profile : $\bar{u}_1/\bar{u}_2 = (z_1/z_2)^P$ is applicable where p is indicative of the amount of turbulence present.

The power law seem to fit most data in the lower 100 m of the atmosphere, where wind profiles are needed for estimating the behaviour of plumes emitted from high stacks. In the lower 30-50 m of the boundary layer, however, the log-law profiles, as presented by Sutton (3), Blackadar (4) and many others, seems to be more appropriate.

The value of the exponent p at Kårstø has been evaluated from wind speed measurements at 36 and 10 m levels as a function of the wind direction.

The computed values of p as shown in figure 3a, vary between 0.09 - 0.44. There is also a certain connection between the value of p and the mean amplitudes of the horizontal wind-direction fluctuation ($\Sigma\phi/N$). This indicates the variation of mechanically induced turbulence, as most of these data were collected during near neutral stratification.

$\frac{\Sigma\phi}{N}$

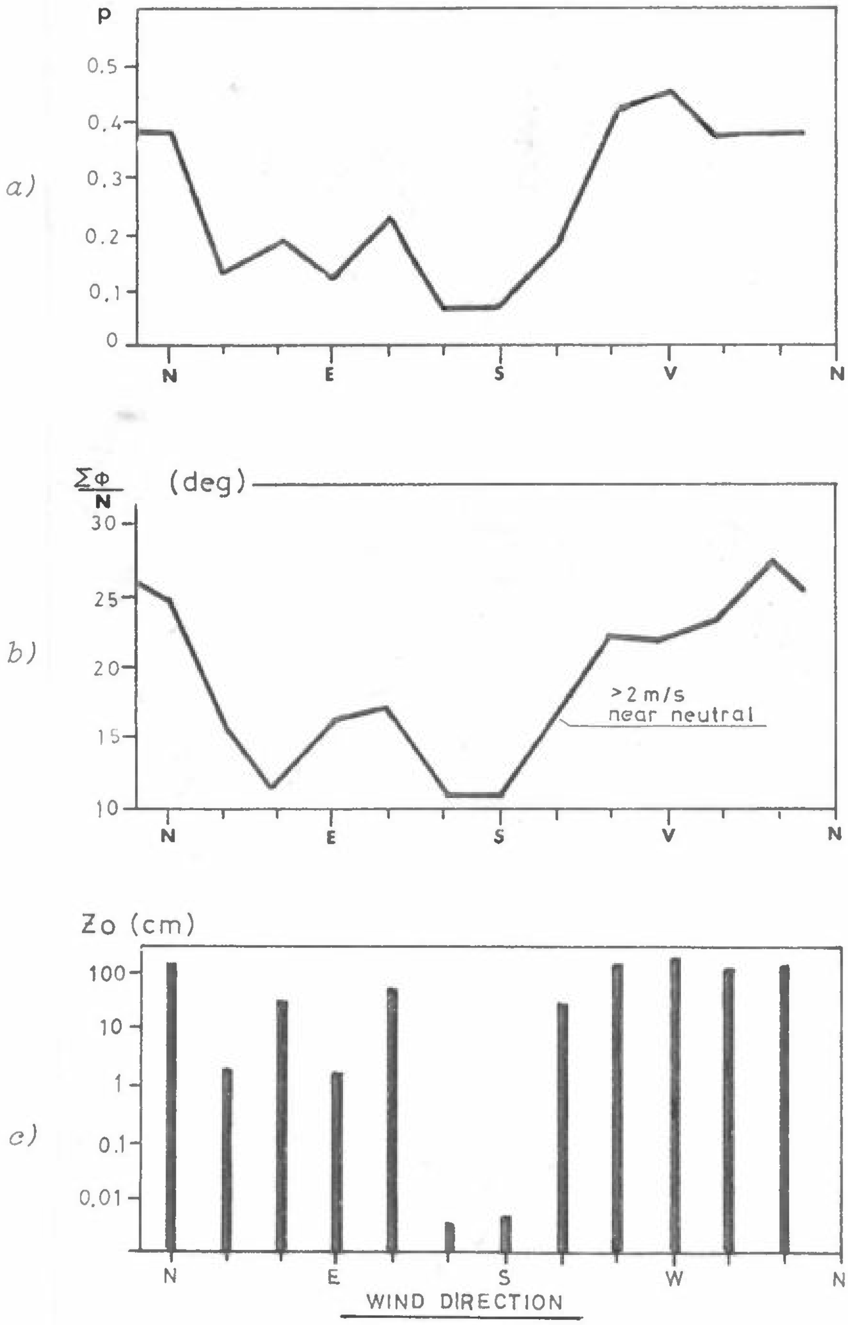


Figure 3: Wind direction depending of various parameters at Kårstø. The following parameters are shown as a function of wind direction:

a) the power law wind profile exponent p

b) the mean amplitude of the horizontal wind direction fluctuation

c) the estimated roughness length.

Depending on the wind-direction at the Kårstø site, the upwind surface roughness varies greatly from smooth water surface (south of the tower) to woody hillsides (to the north-west). The magnitude of the roughness length as a function of wind direction is derived from the log-law wind profile:

$$\bar{u}(z) = \frac{u_*}{k} \ \ln \left[(z+z_o)/z_o\right]$$

where u_* is the friction velocity, z_o is the roughness length and k is the von Karman's constant.

This equation however, only gives a first estimate of the roughness length which is also a function of fetch and atmospheric thermal stratification. The average thermal stratification for all wind direction corresponded to near neutral or slightly stable conditions during the selected period. The average wind speed at the 10 m level varied between 2.4 and 7.9 m/s.

The computed values of the roughness length (z_o) as a function of wind direction are shown in Figure 3c. The roughness length range from a low of <0.01 cm south of the tower to about 200 cm for the wooded hillsides towards the west and north-west.

These results were then used to plot the value of p as a function of the roughness length z_o (Figure 4). As can be seen that the Kårstø data fit quite well data given by Davenport (5).

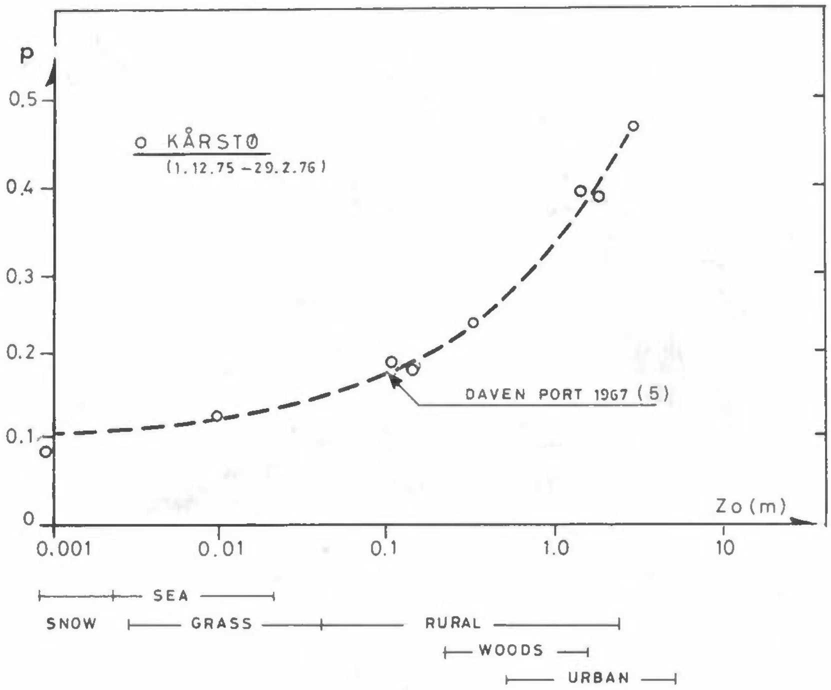


Figure 4: The power law wind profile index p *as a function of estimated roughness length at Kårstø (indicated by circles).*

6 WIND PROFILES IN THE ATMOSPHERIC BOUNDARY LAYER

6.1 Variation in wind direction with height

The analysis of wind direction variation in the lower 1000 m of the atmosphere is based on data collected from pilot balloon observations mainly during periods when the diurnal oscillation of the wind about the geostrophic wind was present. The data therefore, more than anything else demonstrates the complexity of the wind fields in a terrain like Nedre Telemark during the summer season.

Figures 5-8 show the wind direction changes with altitude for 4 classes of upper level wind directions. Some of the profiles clearly reveal a veeing of the wind. This, however, is strongly dependent upon the upper wind direction in relation to the direction of the valley axis and the time of the day.

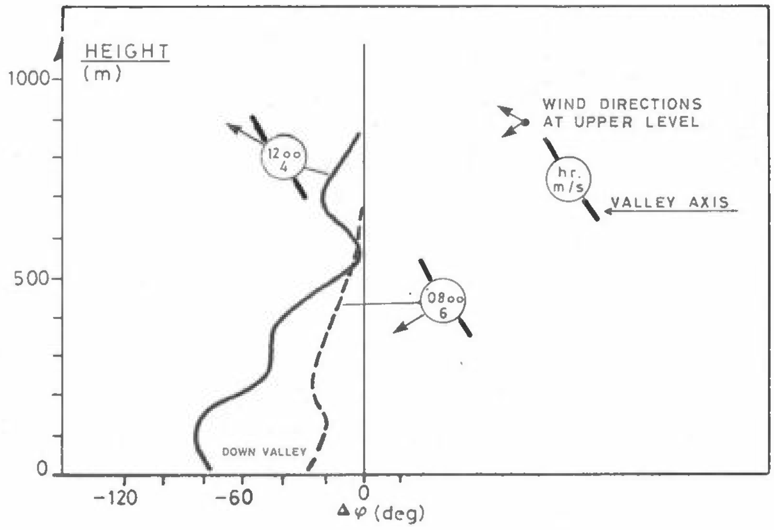


Figure 5: The variation of the angle between upper level wind direction and wind direction at different levels (Δϕ) as a function of height. Upper wind from around east.

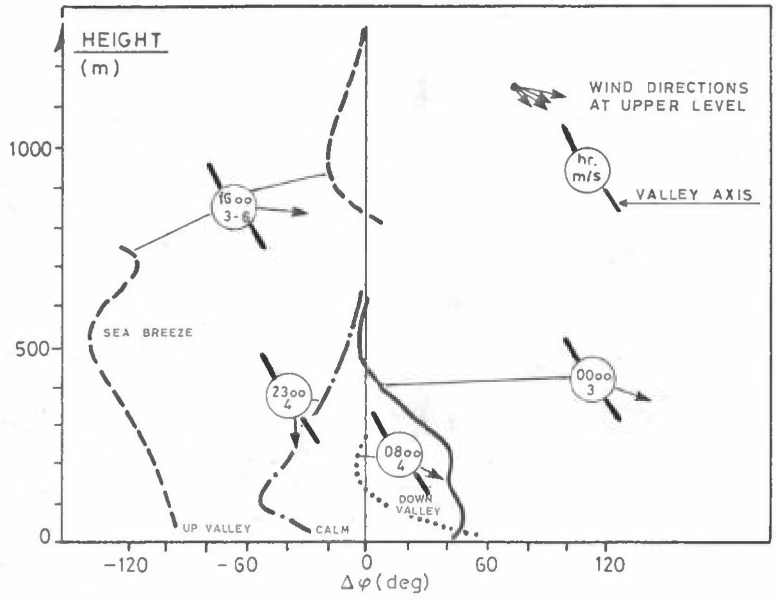


Figure 6: Same as Figure 5. Upper wind from west and north-west.

Figure 5 shows that with upper winds from easterly directions (ESE) and (ENE). Down valley ground level winds predominated even at noon time.

With upper winds from W and NW, the wind at ground level is more dependent upon time of the day, as shown in Figure 6. During night-time there is a down valley flow in these cases even if this results in backing of the wind in the lowest 300 m.

Geostrophic winds from the west have shown to favour the production of land/sea breeze circulations in the area (6). Also in the afternoon case (1600 hrs), shown in Figure 6, there is about 120 degrees difference in direction between the upper wind and the sea breeze, the latter having a vertical dimension of about 500 m.

Upper winds from S and SW (Figure 7) caused a wind veering, the resulting surface wind direction usually upvalley. During the transition periods between the on set of land or seabreeze, with nearly calm condition prevailing at ground level, the interpretation of the wind direction change is not as obvious. During daytime even winds from WSW resulted in an upvalley ground level flow as shown in Figure 8.

6.2 Variation in wind speed with height

To demonstrate the variation of wind speed with height in the fjord-valley area of Nedre Telemark, a test period without pronounced diurnal oscillations has been selected (7).

Figure 9 shows 3 profiles of wind direction variation and wind speed as a function of height for upper winds from around north. During the night and in the morning hours the wind was veering. In contrast in the afternoon the wind was backing, probably due to the influence of the onshore component of the local wind.

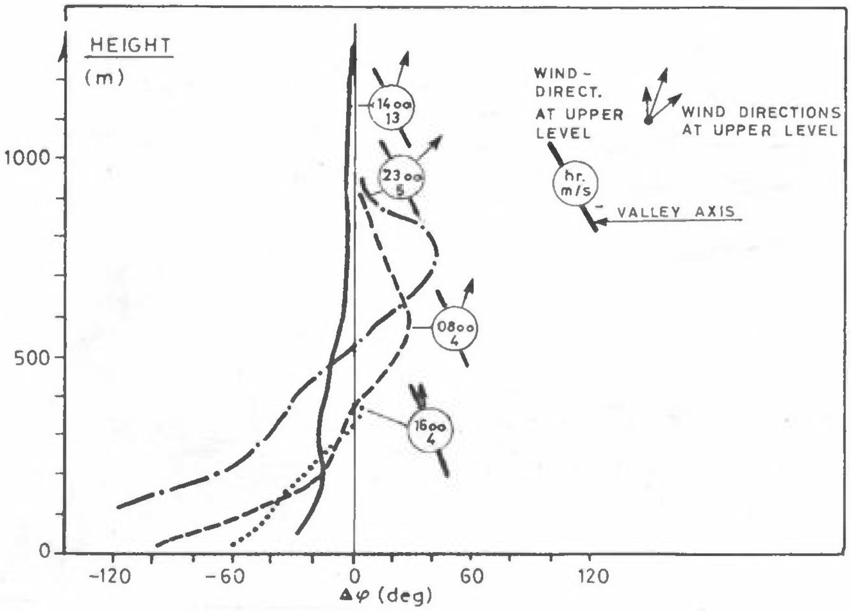


Figure 7: Same as Fig. 5. Upper winds from south and south-west.

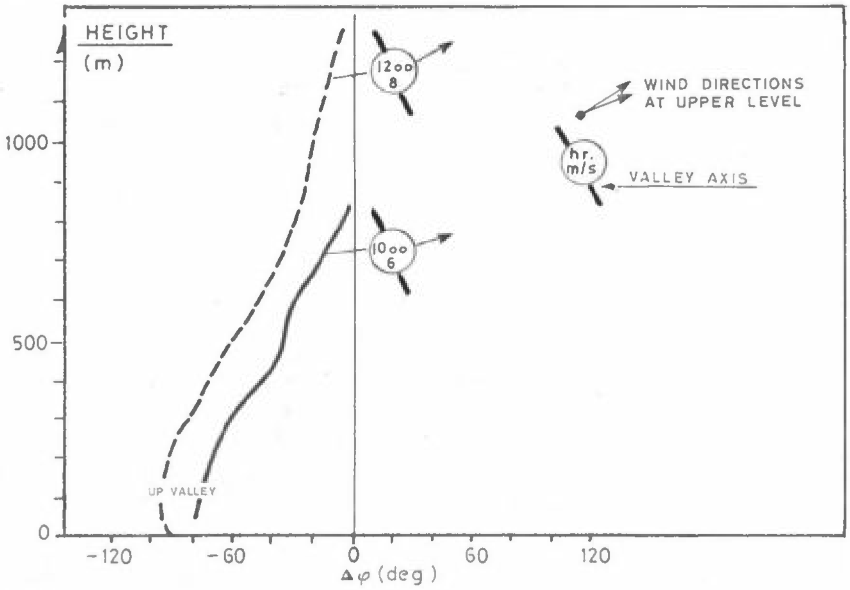


Figure 8: Same as Fig. 5. Upper winds from west-south-west.

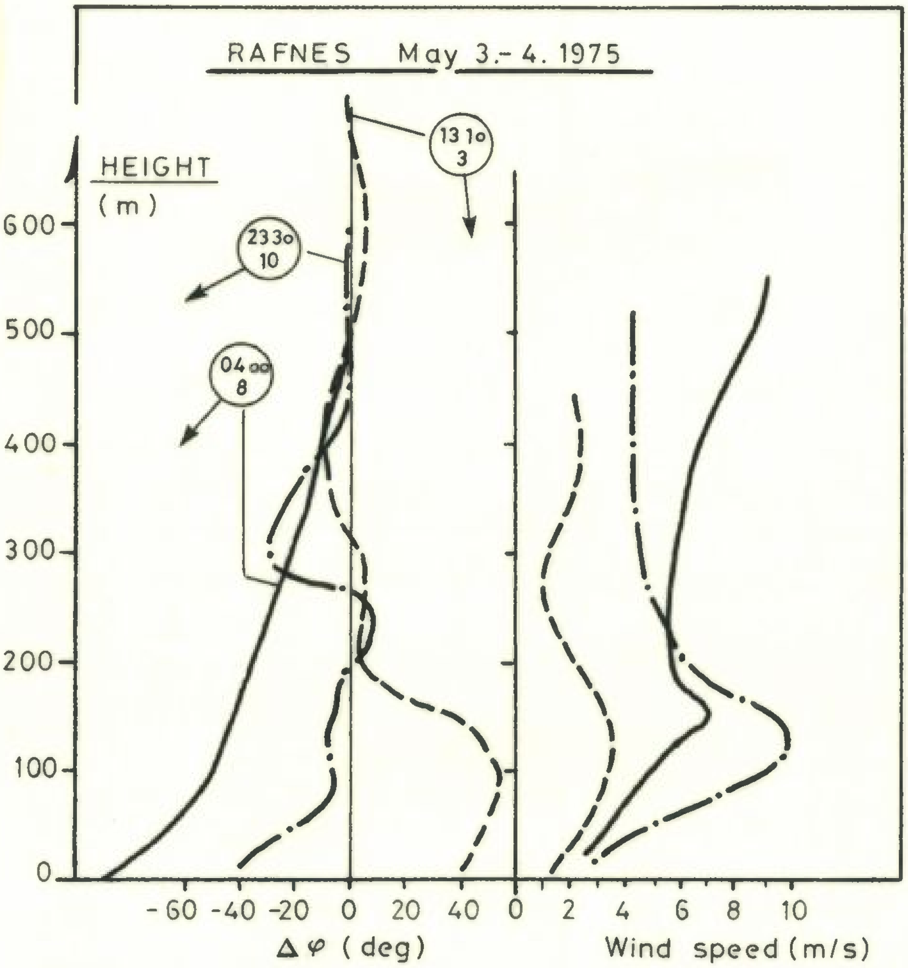


Figure 9: *The angle difference between upper wind direction and the wind direction at different levels (Δϕ), and the wind speed as a function of height above the ground.*

The vertical temperature profiles indicate a ground based inversion in the lowest 100 m during the night and a near dry adiabatic lapse rate around noon. The wind speed profiles show a maximum wind speed at the 100-150 m level. This is a typical and frequently observed feature of the wind speed profiles in this area, which seems to be related to the height of the hills surrounding the valley (6). This "valley jet" has also been reported by other investigators (8) (9).

7 RELATIONSHIP BETWEEN GEOSTROPHIC AND SURFACE WINDS

The relationship between geostrophic wind and winds measured at 10 m levels in the Nedre Telemark area has been analyzed from data collected at 1300 hrs local time during the 1 Mar. 1975 - 29 Feb. 1976 period. The main purpose was to ascertain, whether it is possible to estimate from geostrophic wind observations the surface layer winds in the area. It was also clear from the observations that it was not a question of estimating one wind direction and wind speed for the area, but rather a wind field (10). The wind fields seem to be influenced in addition to geostrophic wind by topographical channeling, heat flux variations (net radiation), and friction (roughness length). This functional dependency has not been established for the area, and the following presentation of data is intended to demonstrate some of the complexities involved in such a task.

Figure 10 compares the annual frequency distribution of wind directions at one station (Ås) with the annual frequency distribution of the geostrophic wind directions. As can be seen the most frequent geostrophic winds are from westerly, with a shift toward south-west during the summer season. The local winds at Ås have on an annual basis two distinct maxima: winds from NNW (which is mainly the wind direction during winter time and wind from around SSE (prevelent during summer time).

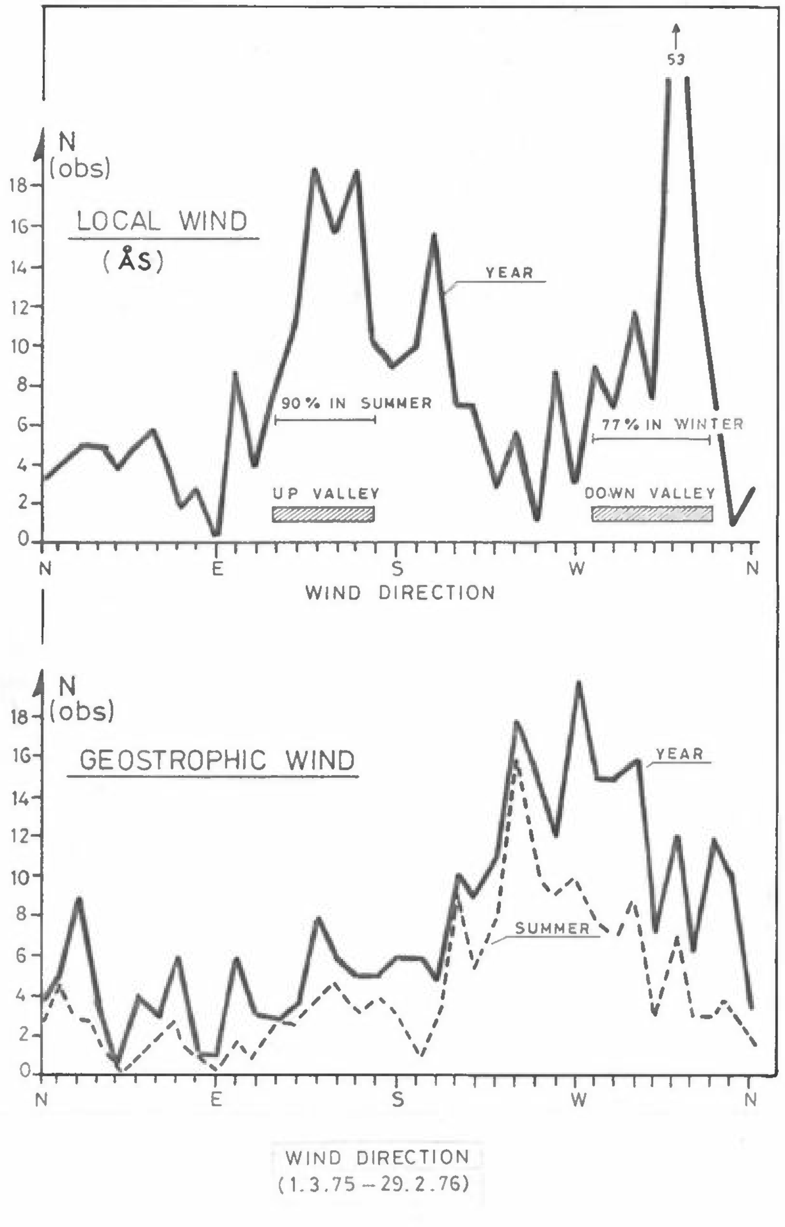


Figure 10: *Annual average frequency distribution of wind directions at Ås and for the geostrophic wind. (Based on data collected at 1300 hrs during the period 1.3.75 - 29.2.76.*

In the summer there is about 90° difference between the most common up valley ground level wind and the most frequent geostrophic wind, with the local wind direction to the left of the geostrophic wind. During winter the channeled down valley wind blows about 70° to the right of the most frequent geostrophic wind directions.

More details on the geostrophic wind directions, producing up valley and down valley winds, are presented in the Figures 11-13.

On an annual basis up-valley winds (defined as wind from 120° - 180° directions) occur when the grostrophic wind direction is from between SSE and W (150°- 270°) (Figure 11a). Downvalley winds (between 280° - 340°) occur most often (about 70% of the cases) with geostrophic wind directions from between W and N. (Figure 11b). There seems to be a closer connection between downvalley flow and the associated geostrophic wind direction, than between upvalley wind and the corresponding geostrophic wind directions. This is partly due to the fact that all the data utilized where gathered around noontime, when the sea breeze and valley wind combine to produce general up valley flow (especially during the summer season) for a wide variety of geostrophic winds. The geostrophic winds has been divided into two classes of speed: $\leq$ 7 m/s, and > 7 m/s. The higher wind speed cases gave only a slight improvement in the relationship between surface wind and geostrophic winds (see also Figure 14).

To minimize the effect of mesoscale wind circulations (mountain/valley wind, and land/sea breeze) the geostrophic wind/local wind relationship has been presented in Figure 12 for local upvalley flow in winter time and down valley flow during the summer. All the cases producing upvalley wind during the winter season occured when the geostrophic wind was blowing to the right (30-120°) of the surface wind. The geostrophic

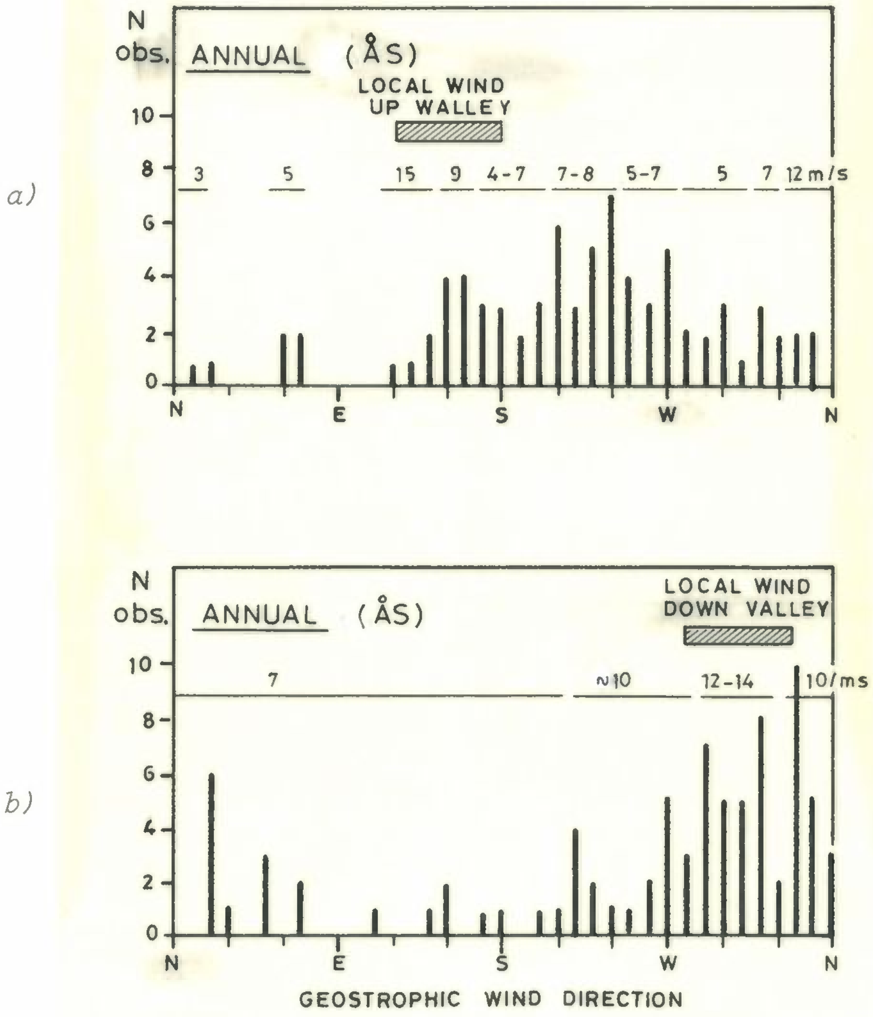


Figure 11: *The annual distribution of geostrophic wind directions producing:*

a) local up valley wind

b) local down valley wind

at Ås in Nedre Telemark.

(The average wind speeds for different directions are indicated.)

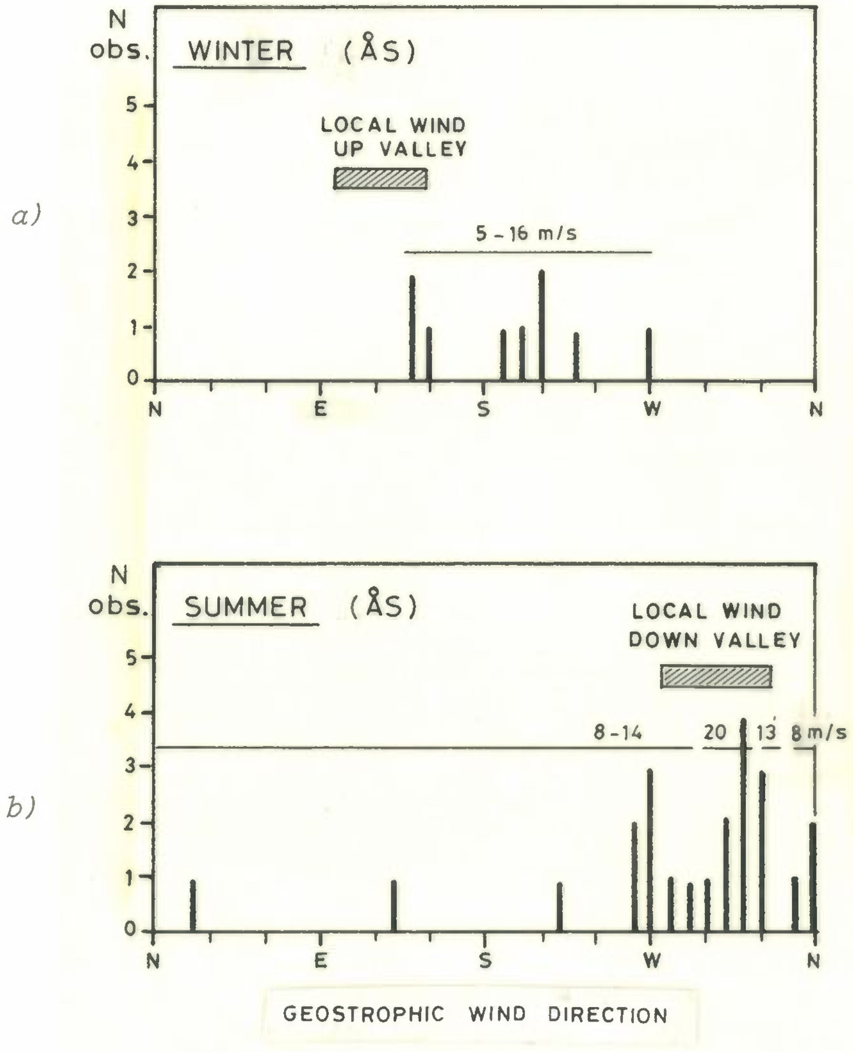


Figure 12: The distribution of geostrophic wind directions causing:

a) local up valley wind at Ås during the winter.

b) local down valley wind at Ås during the summer.

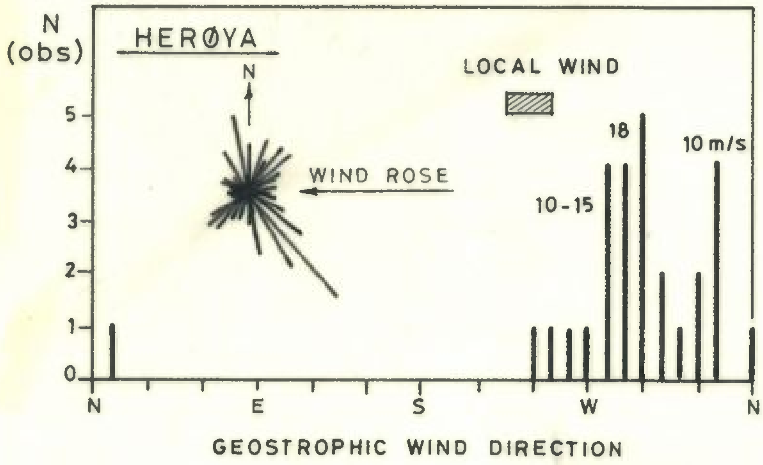


Figure 13: The distribution of geostrophic wind directions causing wind from WSW (230°-250°) at Herøya.

wind directions causing down valley flow at noon during the summer season in all but 3 cases hair about the same direction as the down valley flow. The geostrophic wind speeds required to produce downvalley flow in the summer are usually higher than the speed associated with upvalley flow during the winter time. This appears to be due to the fact that there is a certain diurnal wind oscillation on the mesoscale even in winter time, with a predominant upvalley flow at noon.

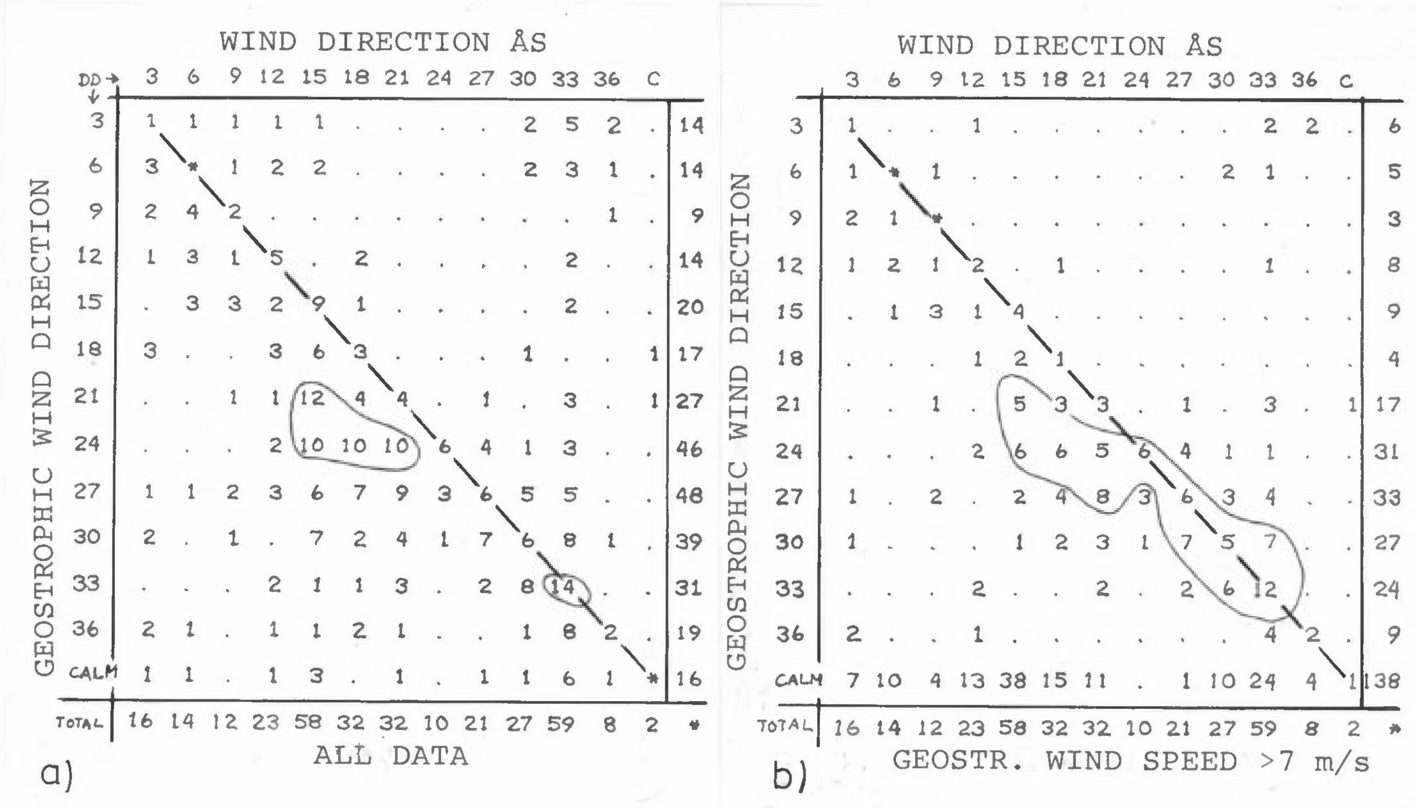
From the wind frequency distribution at the station Herøya (wind rose inserted in Figure 13) the upvalley-downvalley channeling of the winds is obvious. There is also an appreciable frequency (≈11%) of wind from WSW (230° - 250°), blowing across the more open part of Frierfjord (see map Figure 2). These local wind directions at Herøya are all associated with wind veering (1-130°) (Ekman spiral).

Figure 14 a summerizes the local wind/geostrophic wind dependency, showing the frequency distribution of wind directions at Ås versus the geostrophic wind.

For all data (Figure 14a) the surface winds have turned 0-60° to the left of the geostrophic wind (veering) in about 50% of the cases.

For geostrophic wind speeds of more than 7 m/s, the local wind veers 0-60° in about 65% of the cases. Consideration of only the high wind speed cases does not result in a significant improvement in the relationship.

An earlier investigation (11) of the relationship between geostrophic wind (pressure-gradients) and surface winds in nedre Telemark has shown that the pressure gradients explain less than 50% of the variance in the local wind components.



a)

WIND DIRECTION ÅS

GEOSTROPHIC WIND DIRECTION

DD→ ↓	3	6	9	12	15	18	21	24	27	30	33	36	C	
3	1	1	1	1	1	.	.	.	.	2	5	2	.	14
6	3	*	1	2	2	.	.	.	.	2	3	1	.	14
9	2	4	2	.	.	.	.	.	.	.	.	1	.	9
12	1	3	1	5	.	2	.	.	.	.	2	.	.	14
15	.	3	3	2	9	1	.	.	.	.	2	.	.	20
18	3	.	.	3	6	3	.	.	.	1	.	.	1	17
21	.	.	1	1	12	4	4	.	1	.	3	.	1	27
24	.	.	.	2	10	10	10	6	4	1	3	.	.	46
27	1	1	2	3	6	7	9	3	6	5	5	.	.	48
30	2	.	1	.	7	2	4	1	7	6	8	1	.	39
33	.	.	.	2	1	1	3	.	2	8	14	.	.	31
36	2	1	.	1	1	2	1	.	.	1	8	2	.	19
CALM	1	1	.	1	3	.	1	.	1	1	6	1	*	16
TOTAL	16	14	12	23	58	32	32	10	21	27	59	8	2	*

ALL DATA

b)

WIND DIRECTION ÅS

GEOSTROPHIC WIND DIRECTION

	3	6	9	12	15	18	21	24	27	30	33	36	C	
3	1	.	.	1	.	.	.	.	.	.	2	2	.	6
6	1	*	1	.	.	.	.	.	.	2	1	.	.	5
9	2	1	*	.	.	.	.	.	.	.	.	.	.	3
12	1	2	1	2	.	1	.	.	.	.	1	.	.	8
15	.	1	3	1	4	.	.	.	.	.	.	.	.	9
18	.	.	.	1	2	1	.	.	.	.	.	.	.	4
21	.	.	1	.	5	3	3	.	1	.	3	.	1	17
24	.	.	.	2	6	6	5	6	4	1	1	.	.	31
27	1	.	2	.	2	4	8	3	6	3	4	.	.	33
30	1	.	.	.	1	2	3	1	7	5	7	.	.	27
33	.	.	.	2	.	.	2	.	2	6	12	.	.	24
36	2	.	.	1	.	.	.	.	.	.	4	2	.	9
CALM	7	10	4	13	38	15	11	.	1	10	24	4	1	138
TOTAL	16	14	12	23	58	32	32	10	21	27	59	8	2	*

GEOSTR. WIND SPEED >7 m/s

Figure 14: Joint frequency distributions of wind directions at Ås and the geostrophic wind, based on data taken at 1300 hrs during one year; 1.3.75-29.2.76. The number of simultaneous observations of wind directions are indicated in 12 x 12 30°-sectors. Identical observations are accumulated along the diagonal indicated.

8 DISCUSSIONS

The wind variations with height has been examined by means of data from several sites located in areas with rough terrain. Some of the data have been collected during specific and restrictive situations (land/sea-breeze studies) and are not appropriate for establishing general relationships.
A qualitative description of the relationship between surface and geostrophic winds has been presented based upon data collected at 1300 hrs (local time) every day through out one year.

To further elucidate the relationship between surface and geostrophic winds, data are needed for more than one hour during each day. A more complete and detailed data set should enable establishing a functional depency of diurnal variations of the local winds on geostrophic wind, cloud cover and time of the year.

9 CONCLUSIONS

The following conclusions can be drawn from the limited results of this study:

- the value of the exponent of the power law wind profile in the surface boundary layer is a function of wind-direction at the sampling site, and, depending upon the roughness of the upwind area in the different directions, varies between 0.09 and 0.46.
- the values of the exponent found are in agreement with data of other investigators (12).
- the changes in wind direction with height in the atmospheric boundary layer is a function of upper wind direction and radiation balance (time of day, cloud cover).
- for most upper wind directions wind veering can be seen, but generally upvalley or down valley channeling governs the local wind patterns.

- the dominant up- and downvalley winds and a westerly geostrophic wind are the two prominant features of the relationship between surface and geostrophic winds (Figure 14).

- in about 50% of all cases examined the surface winds veers through 0-60° from the geostrophic wind direction (Ekman-spiral).

- the ratio between geostrophic and surface wind speed varies between 1.5 and 4.5 for upvalley wind, and between 2.7 and 10.0 for downvalley flows.

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