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Annual variation of surface roughness obtained from wind profile measurements

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With 10 Figures

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Summary

Profile measurements of wind and temperature have been performed at the Agricultural University of Norway on a routine basis since 1997. 10-min. averages are stored in a database together with other relevant meteorological parameters. The database can be used to determine the seasonal variation of surface aerodynamic roughness, showing the growth of grass between cutting during the growing season, the effect of snowfall and the melting of snow etc. However, careful screening of the data must be conducted before reliable estimates can be made. The main objective of this study is to establish simple practical rules for filtering out unreliable datasets for the evaluation of the surface roughness parameter z_0, and to present its annual variation. The resulting values for the summer period agree well with values found in the literature for homogenous grass covered surfaces. In the transition periods during autumn and spring, and during wintertime in mild weather conditions, the surface is generally non-homogenous with a mixture of snow patches, ponds of melting water and shrubs of withered grass. The results show that the mechanical interaction between a non-homogeneous land surface and the boundary layer flow can be described by one roughness parameter, with a numeric value somewhere in between the ideal values for the different surface characteristics. Another use of the database is to investigate drainage flow and the relationship between drainage flow, prevailing wind direction and the mean vertical velocity of the air. Most micrometeorological studies of the fluxes of heat and water vapour in the surface layer, assume the mean vertical velocity to be zero, focusing on eddy fluxes and thereby excluding any transport in the mean flow. In certain situations, this may lead to serious errors. This work shows that convergence of horizontal flow leads to an upward movement of air, which is enhanced if the prevailing direction of the wind opposes the outflow of the cold drainage winds from the area.

1. Introduction

Wind is an important parameter for the estimation of fluxes from surface to atmosphere and the diffusion of scalars within the atmosphere. Flow over flat, uniform and homogeneous surfaces are well understood, but for land surfaces they represent the ideal rather than the actual situation.

When air passes over a rough surface, the mean flow and turbulence tend towards an equilibrium with the conditions of the surface, creating an internal boundary layer where roughly the lowest 10% may be considered fully adjusted, i.e. in complete equilibrium with the surface. This is the constant flux layer, where the fluxes are assumed to be independent of height.

Estimates of surface roughness parameters from wind profile measurements have been performed for decades for different types of surfaces (homogeneous, non-homogeneous, short vegetation, tall vegetation, cities etc.). A survey of estimates can be found in micrometeorological textbooks, i.e. Arya (1988) and Brutsaert (1982).

More recent findings are given in Bottema et al. (1998), Driese and Reiners (1997), Grimmond et al. (1998), Hiyama et al. (1996), Mathias et al. (1990) and Rooney (2001). However, few investigations define the surface as an active surface with characteristics that change during the measurement period.

At the Agricultural University of Norway (AUN), routine measurements of meteorological parameters relevant for agriculture have been performed since 1863 (air temperature and precipitation). The measurement program at the AUN agroclimatical field laboratory has been extended several times, and from 1997 annual profile data for air temperature and wind up to ten meters height are stored as 10-minutes averages in a database. This makes it possible to study the changes in surface-air exchange due to the annual variation of surface characteristics.

To extract relevant information from tens of thousands of datasets is a challenge. Datasets that do not satisfy the conditions of the method for obtaining the surface roughness, or contain systematic measurement errors, must be rejected. The filtered datasets must be statistically evaluated in order to eliminate other unreliable datasets. The remaining datasets can be used to evaluate the annual variation of the surface roughness parameter. For the present investigation, datasets for the year 1998 were used for this purpose.

With a distance of 300–500 meters to the nearest residential buildings in the relevant sectors (Fig. 3), the agroclimatical field laboratory with surroundings represents a relatively homogeneous area during summertime. Although the terrain slopes slightly towards southwest and the area representing the field laboratory can be considered as a shallow basin for collecting drainage flow from all sectors, excluded the southwestern, drainage flow is not a serious problem during summertime and never during daytime. In wintertime with snow-covered ground the situation is different. Large temperature gradients may develop during clear nights and the inversion is maintained for several days. The drainage flow converges at the agroclimatical field laboratory, and this imbalance leads to a net upward motion of air. Prevailing winds coming from the southwest tend to oppose the drainage out of the basin, thereby enhancing the vertical motion. Similar situations have been observed by Lee (1998) for diverging drainage flow, leading to downward motion of the air.

2. Theory

The theory describing the interaction between airflow and ground surface is well known and originates from the pioneering works of Monin and Obukhov. The surface roughness parameter z_0 is evaluated from the measured windprofiles by the expression

$$\left(\frac{u}{u_*}\right) = \frac{1}{k}\ln\left[\frac{z}{z_0} - \Psi_m\left(\frac{z}{L}\right)\right] \tag{1}$$

Here u is the velocity at height z, u_* is the shear velocity, k von Karmans constant and Ψ_m a stability function. The stability function can be evaluated directly from the M–O length L, knowing the flux of sensible heat, or indirectly through simultaneous measurements of air temperature profiles.

2.1 Divergence/convergence of horizontal flow

Flow over non-uniform surfaces will result in divergence or convergence of the horizontal flow.

Fig. 1. Agricultural University of Norway (AUN) and surroundings. The AUN agroclimatical field laboratory is encircled

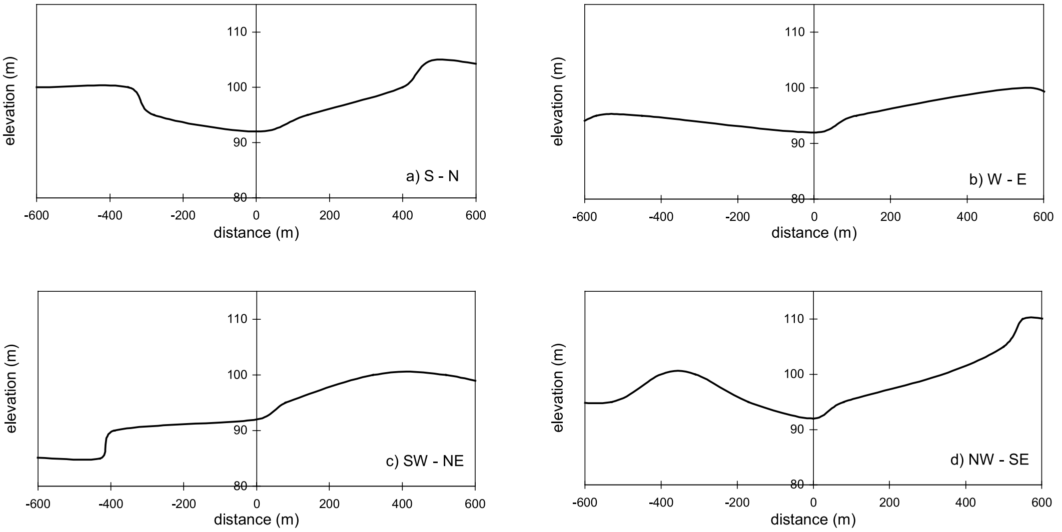

Fig. 2. Field topography

This is readily seen from the continuity equation for stationary flow of an incompressible fluid

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z} = 0 \tag{2}$$

A change in surface roughness will lead to a change in friction or surface stress, and the wind profile must adopt accordingly. With the x-axis in the direction of the mean wind ($\bar{v} = 0$), Eq. (2) reduces to

$$\frac{\partial \bar{u}}{\partial x} = -\frac{\partial \bar{w}}{\partial z} \approx -\frac{\bar{w}_r}{z_r} \tag{3}$$

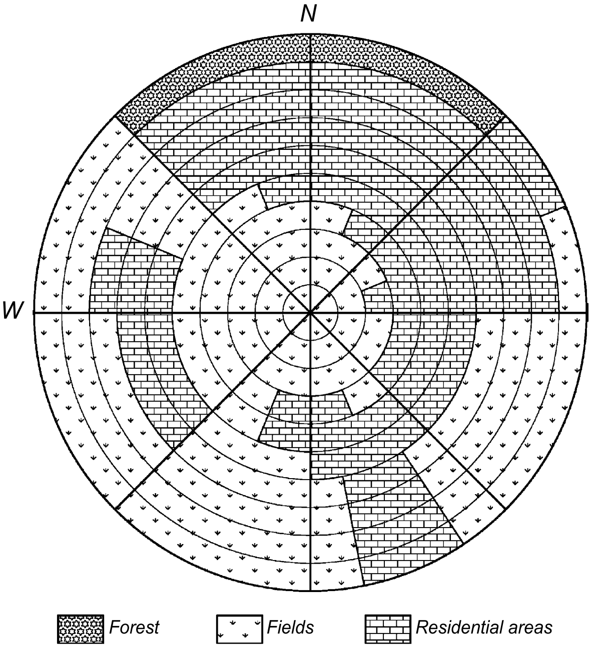

Fig. 3. Land use within 1 km radius of the agroclimatical field laboratory

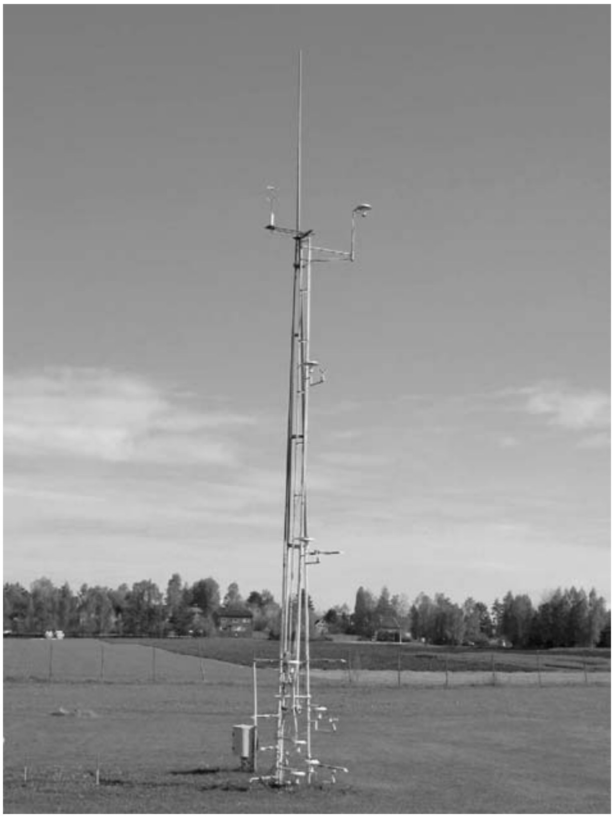

Fig. 4. Mast for profile measurements of temperature and wind

where $\bar{w}_r$ is the mean vertical velocity at the height of observation z_r.

Several mechanisms related to differences in surface temperature may result in a non-zero $\bar{w}$:

Convection is a well-known phenomenon that is easily observed but difficult to describe theoretically, particularly for natural surfaces with differences in both roughness and temperature. In general, ascending motion in a convective boundary layer is confined to relatively thin walls surrounding larger columns of slowly descending motion. For uniform surfaces, the probability of a wind sensor mounted on a tower to be influenced by descending motion is thus much higher than by ascending motion. The distribution of "hot" and "cold" areas on the surface will obscure this picture. In this study, the micrometeorological mast is mounted at the centre of a field surrounded by residential buildings and farmlands. During the summer time one would expect the surface temperature at the experimental site to be lower than that of the surroundings, leading to a predominance of descending air.

Drainage flow is another local phenomena that can lead to non-zero vertical velocity (Lee, 1998). Undulating terrain can lead to drainage flow even with slopes as small as $1.5 \cdot 10^{-3}$. A downward air motion must compensate the divergence along the slope due to gravitational acceleration, and flow convergence due to retardation must be compensated by air moving upwards. Observations of nocturnal slope flow are given in Horst and Doran (1986), and through analysis of the momentum balance of down slope gravity flows, Mahrt (1982) derived the following relation for the velocity of the drainage wind in advective-gravity flow:

$$\bar{u} = \left(\frac{g\Delta\theta}{\theta} L \sin\alpha \right)^{1/2} \tag{4}$$

where θ is the potential temperature outside the gravity flow, and $\Delta\theta$ is the average potential temperature depression in the flow. L is the down slope distance from the virtual source where $u = 0$, and α the slope angle. Equation (4) represents an idealized solution neglecting cross-slope advection and nonstationarity, assuming constant flow depth and slope angle. With values representative for the experimental site during wintertime ($\Delta\theta = 5$, $\theta = 260$, $L = 400\,\mathrm{m}$, $\alpha = 1.5°$), Eq. (4) yields a convergence/divergence rate of $3.5 \cdot 10^{-3}\,\mathrm{s}^{-1}$ and from Eq. (3) a mean vertical velocity at 10 m height of $0.04\,\mathrm{ms}^{-1}$. The agroclimatical field laboratory lies in the centre of a shallow basin with cold air inflow from the west–north–east–south-sectors, and outflow through the southwesterly sector. The two-dimensional analysis inherent in Eq. (4) is an oversimplification, and the slope angle is not

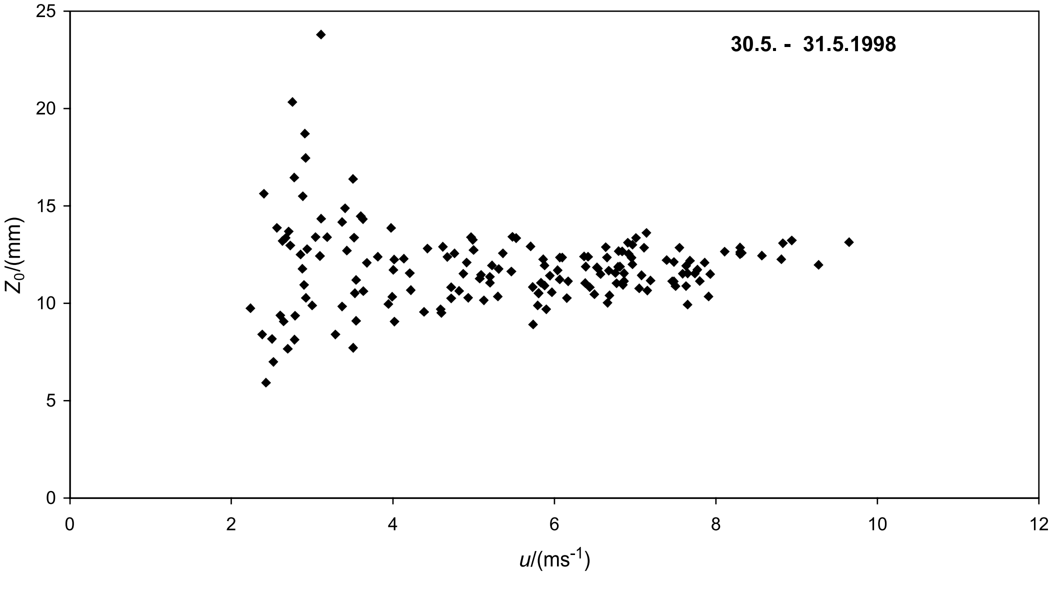

Fig. 5. Surface roughness obtained from 170 datasets for the period 30.5.98 to 31.5.98. The wind came from the south throughout the entire period. No corrections for stability have been performed, as evident from the large scatter in data seen for wind speeds below approximately $3.5\,\mathrm{ms}^{-1}$

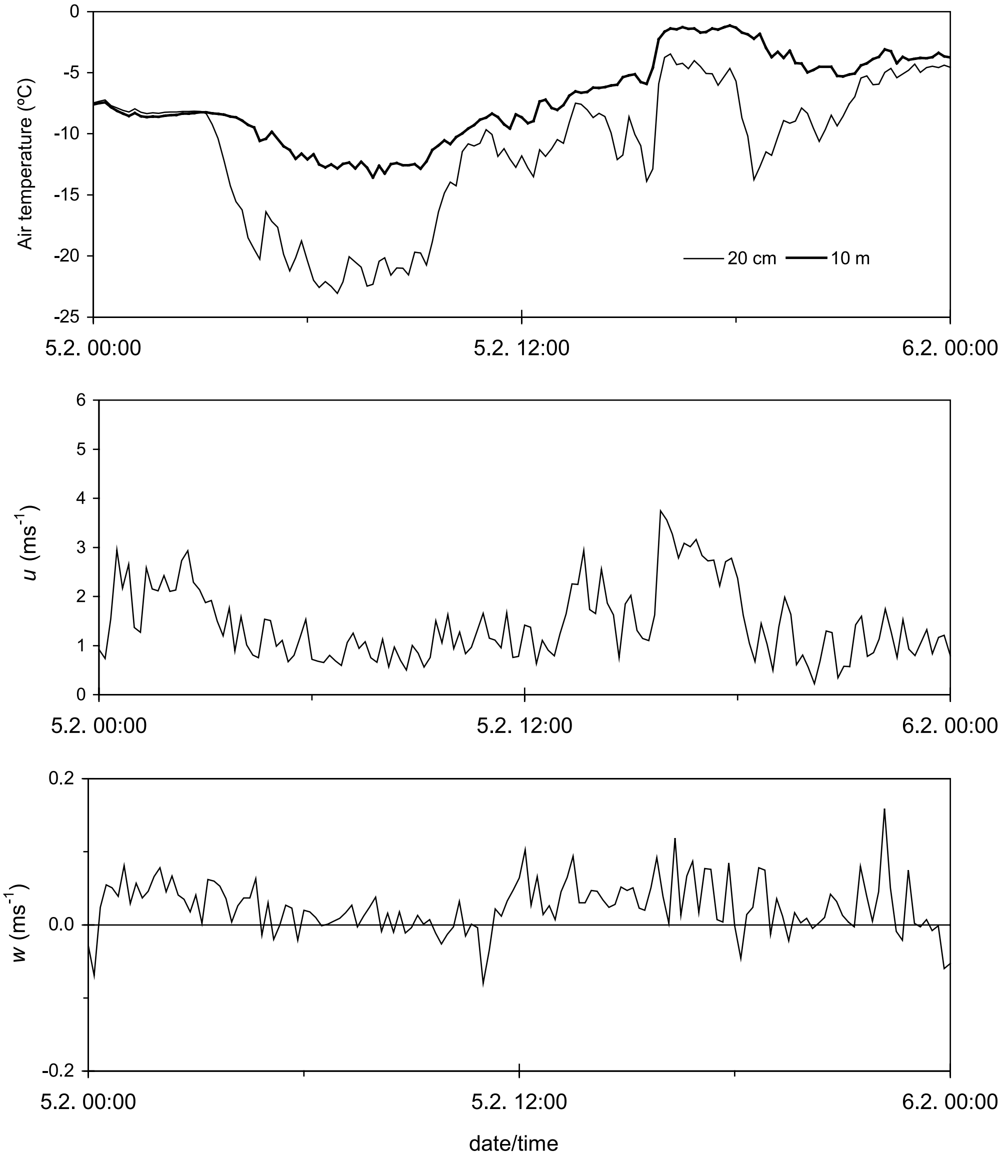

Fig. 6a. Top: Air temperature at 10 m and at 20 cm. A strong temperature inversion developed during the cold calm night of February 5th and disappeared more or less during daytime due to increasing wind and a change in weather conditions. Middle: Diurnal variation in horizontal wind speed. Bottom: Diurnal variation in vertical wind speed

constant throughout the flow. But the order of magnitude of the vertical velocity ($10^{-2}\,\mathrm{ms}^{-1}$) gives an indication of what to expect from observations during periods of cold air drainage.

3. Methods

3.1 Site description

The agroclimatical field laboratory is situated at the Agricultural University of Norway, approximately 30 km south of Oslo (10°47′ E, 59°40′ N). An aerial photo of the University and surroundings is shown in Fig. 1.

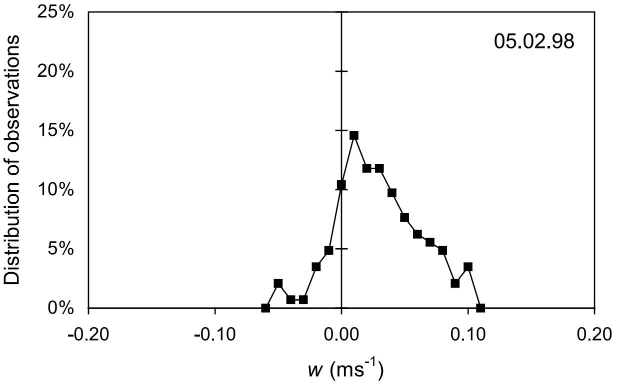

Fig. 6b. The frequency distribution of the vertical wind throughout February 5th is skewed towards positive values due to convergence of drainage flow

The area of the agroclimatical field laboratory is fairly flat covering about 12000 m^2 (Fig. 2), and surrounded by arable fields for grass and cereal production. Outside the fields are woodlands and low residential buildings (Fig. 3).

3.2 Instrumentation

Profiles of mean wind and temperature were measured on a 10 m tower at eight levels (Fig. 4). Except for the top level, all instruments were mounted on booms perpendicular to the mast, and directed towards the south, due to the predominance of southerly winds during summertime. For the lowest levels, some adjustments had to be done to avoid interference and shadowing effects between the different sensors. Inspection of the data showed no mast interference for winds coming from the southerly sectors (south-west through south-east). The data from the lower levels are erroneous for other wind directions due to the instrument box on the north side of the mast, wires and mechanical structures. The wind measurements were performed with cup

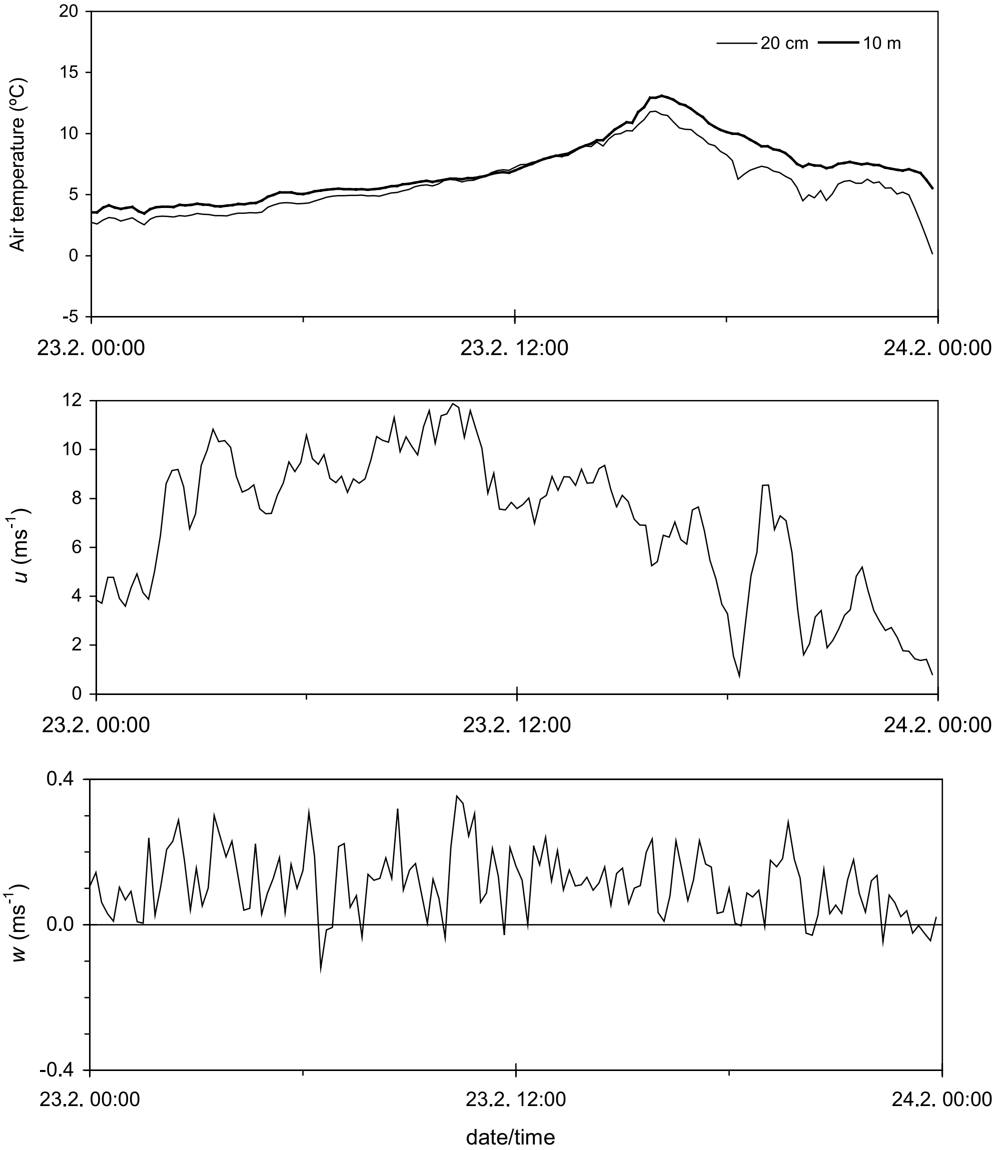

Fig. 7a. Top: Air temperature at 10 m and at 20 cm. Strong winds from southwest during the morning and midday hours of February 23rd lead to efficient mixing of the air. Middle: Diurnal variation in horizontal wind speed. The direction of the wind changed from south-southeast to southwest during the evening of February 22nd, with a marked rise in wind speed during the morning hours of February 23rd. Bottom: Diurnal variation in vertical wind speed

anemometers from Vector Instruments, Model A100R, which have a threshold value of $0.6\,\mathrm{ms}^{-1}$. At the top level, a Windmaster ultrasonic anemometer from Gill Instruments was used to measure mean horizontal and vertical wind velocity, as well as wind direction.

Grass height was measured manually. Air temperature was measured using ventilated and radiation protected platinum resistance elements. A data logger, 21 X, from Campbell Scientific logged the instruments every ten seconds, and mean values at 10-min intervals were recorded. A more detailed description of maintenance and control routines, validation of data etc. will be given in a following paper.

3.3 Data approval

Automatic check routines were performed according to direction (only southerly winds were allowed), and wind speed at the lowest and highest levels. Periods with fluctuating wind direction were rejected due to the possibility of a change in direction during the 10-minutes averaging period. Data sets where the wind speed at the lowest level was less than $1\,\mathrm{ms}^{-1}$ were rejected due to the threshold value of the anemometers. Stability corrections were first applied by evaluating the Richardson number and using the method outlined by Businger et al. (1971). However, measurement errors lead to large errors in Richardson number when the gradients are small. A better approach is to use only those datasets where the wind velocity at 10 m height is higher than a certain limiting value. Above this value, which depends on the radiative heating or cooling of the surface, conditions are near neutral and stability corrections are not needed. Tests performed for several days throughout the year show that a value between $3\,\mathrm{ms}^{-1}$ and $3.5\,\mathrm{ms}^{-1}$ is an appropriate choice, as illustrated by Fig. 5.

4. Results and discussion

4.1 Drainage winds

The air temperature and wind velocity during an inversion period and the subsequent dissipation of the inversion due to changes in the general weather conditions are shown in Fig. 6a–6b. The ground was snow-covered and a strong temperature inversion developed during the clear and calm night and early morning of February 5th. The inversion dissipated during the late morning hours when the wind direction changed from northwest to south, with an abrupt rise in air temperature and humidity. From noon the 6th throughout the 7th, strong winds led to efficient turbulent exchange of heat and momentum and a more or less neutral boundary layer. Figure 6d shows the frequency distribution of the mean vertical velocity during the inversion period (5.2 00:00 to 23:50). The distribution is skewed towards positive values with a mean velocity for the entire period equal to $\bar{w} = 0.03\,\mathrm{ms}^{-1}$.

The period February 20th to February 23rd represents another situation. There was no snow

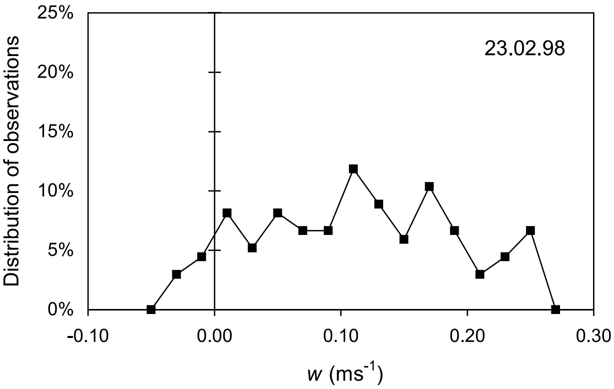

Fig. 7b. Frequency distribution of the vertical wind during February 23rd, when mesoscale wind blew in a direction opposite the drainage wind. Pile-up of drainage flow led to a relatively large updraft

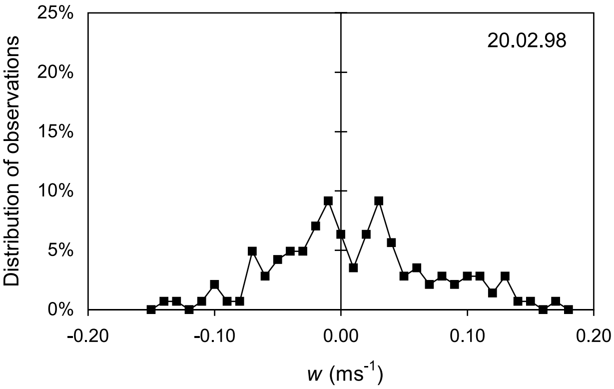

Fig. 7c. Frequency distribution of the vertical wind during February 20th, where little or no drainage flow could develop

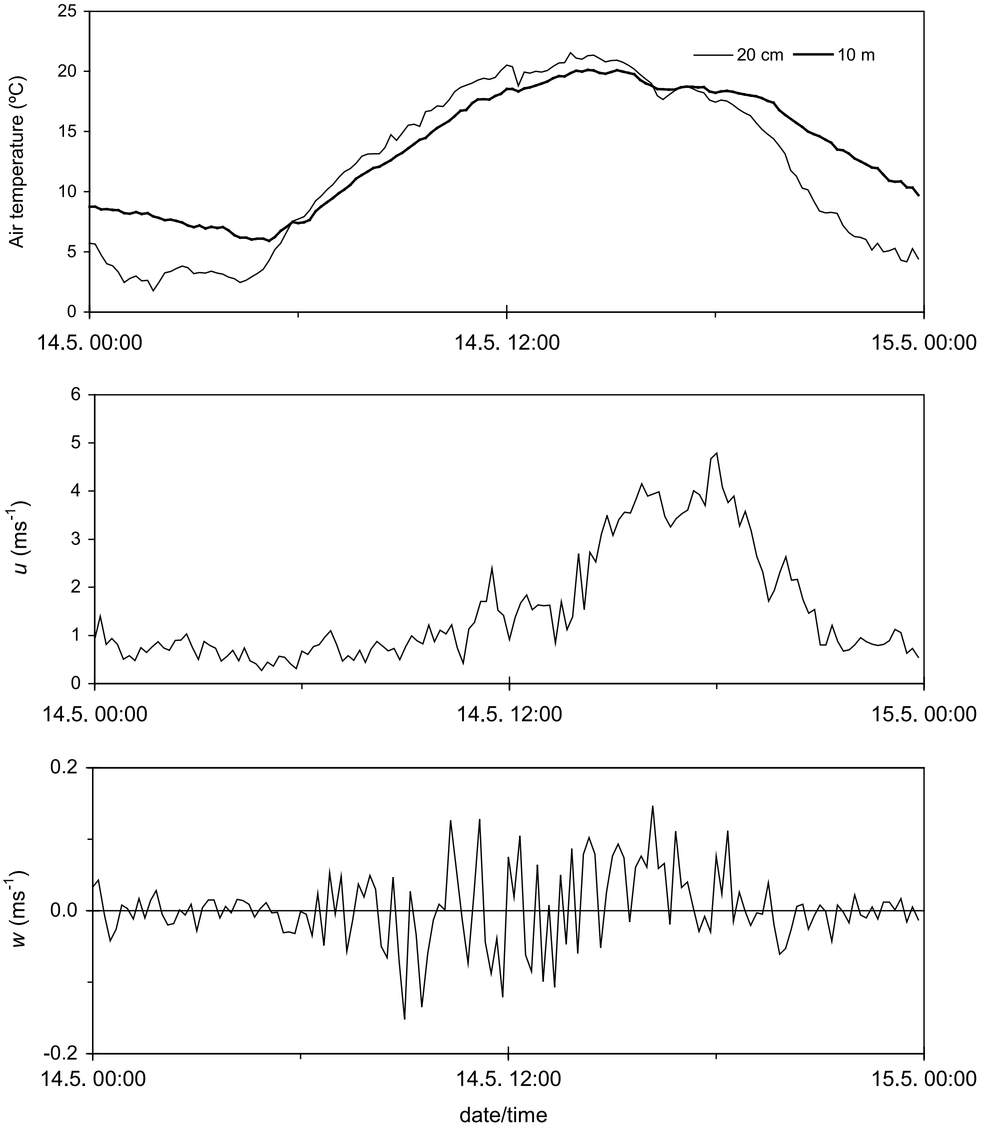

Fig. 8a. Top: Air temperature at 10 m and at 20 cm. A typical summer situation where inversion during the night changed to lapse during the morning hours, and back to inversion during the afternoon. Middle: The diurnal cycle of heating and cooling was responsible for a thermally driven wind system. Bottom: Diurnal variation in vertical wind

cover on the ground, and the mild southerly winds changed from south-southeast during the first half of the period to southwest during the second half (Fig. 7a–7c). The frequency distribution of vertical winds during February 20th was approximately symmetric around zero, whereas the distribution for February 23rd was predominantly skewed towards positive values with a mean value as high as $0.1\,\mathrm{ms}^{-1}$. This was probably due to updraft by topographic forcing for strong winds coming from southwest.

An example from early summer is given in Fig. 8a–8b. Calm winds during the night and morning hours of May 14th changed to moderate

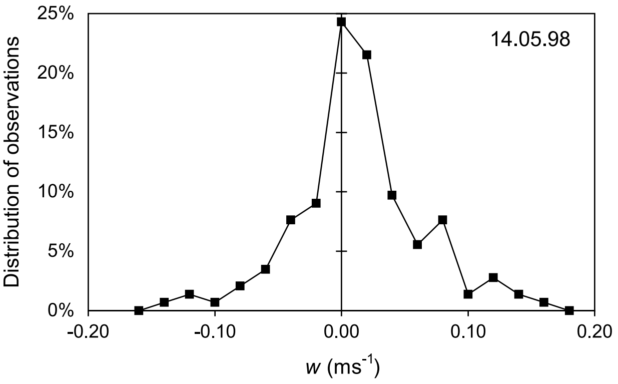

Fig. 8b. The frequency distribution of the vertical wind was approximately symmetric around zero

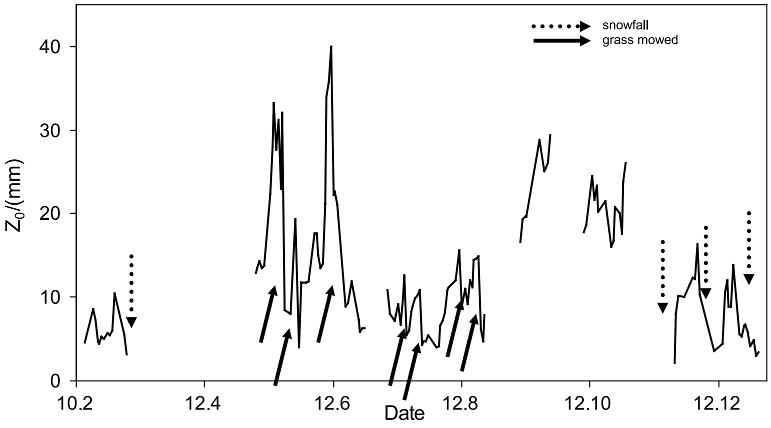

Fig. 9. The annual variation of surface roughness during 1998. The peaks and troughs reflect the different surface cover throughout the year

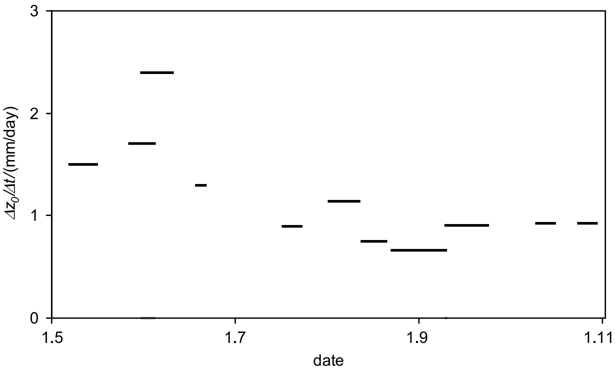

Fig. 10. Daily change in surface roughness during the growth period

winds during daytime. The inversion developed due to radiative cooling during the night, and turned to lapse during the morning hours due to solar heating of the surface. The frequency distribution of vertical velocity was approximately symmetric around zero showing no sign of drainage flow.

4.2 Surface roughness

The change in surface characteristics throughout the year is shown in Fig. 9. There was no snow cover during the period February 9th to March 4th. The surface was relatively dry and unfrozen and covered with dead grass. The roughness value z_0 as derived from the wind profiles was 6 mm. Ten cm snowfall on March 6th decreased the roughness to 3 mm. The last snowfall occurred on April 9th. The grass was mowed for the first time on May 20th. The growth of grass between mowing is illustrated in the figure. With a detailed inspection of the figure, most of the days when the lawn was mowed can be identified. The mean roughness value after mowing was 5.8 mm. Additional measurements of mean grass height during the growing season made it possible to study the relationship between height and roughness, giving the linear function $z_0 = (0.15 \pm 0.05)h$, where h is the mean grass height.

This is consistent with other findings. A snowfall during the morning of November 21st is seen ($z_0 = 2.1$ mm), as well as the following melting of snow. Approximately 2 cm of snow fell during December 10th to December 11th, resulting in a roughness value of 4.4 mm. Snowfall on December 27th changed to rain during the day, and the roughness changed from 1.8 mm (new snow) to 3.8 mm (melting snow) to 5.2 mm on December 28th after heavy rain resulting in a surface flooded with water.

A roughness value of 2–3 mm agrees well with values reported in the literature for natural snow surfaces (farmlands).

Figure 10 shows the change in roughness due to the growth of grass. The grass grew during May and the first half of June (10–15 mm/day). Growth almost ceased (2 mm/day) by the midst of October. It is to be noted that June, July and August were cold months with temperatures well below average, which explains the dip in the growth curve by the end of June.

5. Conclusions

The first part of this investigation relates to drainage flow where cold air drains into a shallow basin where the only outflow is in the direction of southwest. Drainage winds in converging flows were associated with vertical motion of the air in the upward direction. The observed mean vertical velocity was consistent with simple theoretical estimates. The vertical motion was enhanced when the direction of the prevailing wind was opposite the outflow direction from the basin. The frequency distribution of vertical wind in weather situations that did not encourage the formation of drainage flow was symmetrical around zero.

Neglecting the mean flow component of the vertical flux of a scalar quantity can lead to serious errors, as shown by Lee (Lee, 1998). As an example, neglecting the mean flow component during the strong inversion period of February 5th would lead to an energy imbalance in the order of $150\,\mathrm{Wm}^{-2}$.

As to surface roughness, it is interesting to follow the change in wind profile as a result of the annual changes in surface characteristics, and to actually observe the growth of grass from observed changes in roughness. Numerical values of the roughness parameter z_0 were consistent with results from other investigations: 2–3 mm for natural snow surfaces (farmlands), 6–14 mm for patchy surfaces of dead grass with ponds of melting water, and 15% of mean grass height during the growing season.

Acknowledgements

We would like to thank all persons who, trough many years have contributed to the maintenance and supervision of the agroclimatical field laboratory. Special thanks are given to research technician Signe Kroken and electronic engineer Tom Ringstad for their everlasting enthusiastic participation. C. M. Futsäther at the Agricultural University of Norway is greatly acknowledged for her evaluation of and valuable suggestions for the contents of this paper.

References

Arya SP (1988) Introduction to micrometeorology. Academic Press, 307 pp

Bottema H, Klaassen W, Hopwood WP (1998) Landscape roughness parameters for Sherwood forest-experimental results. Bound-Layer Meteorol 89: 285–316

Brutsaert WH (1982) Evaporation into the atmosphere. D. Reidel Publishing Company, 299 pp

Businger JA, Wyngaard JC, Izumi Y, Bradley EF (1971) Flux profile relationships in the atmospheric surface layer. J Atmos Sci 28: 181–189

Driese KL, Reiners WA (1997) Aerodynamic roughness parameters for semi-arid shrub communities of Wyoming, USA. Agric Forest Meteorol 88: 1–14

Grimmond CSB, King TS, Roth M, Oke TR (1998) Aerodynamic roughness of urban areas as derived from wind observations. Bound-Layer Meteorol 89: 1–24

Hiyama T, Sugita M, Kotoda K (1996) Regional roughness parameters and momentum fluxes over a complex area. J Appl Meteorol 35: 2179–2190

Horst TW, Doran JC (1986) Nocturnal drainage flow on simple slopes. Bound-Layer Meteorol 34: 263–286

Lee X (1998) On micrometeorological observations of surface-air exchange over tall vegetation. Agric Forest Meteorol 91: 39–49

Mahrt L (1982) Momentum balance of gravity flows. J Atmos Sci 39: 2701–2711

Mathias AD, Kustas WP, Gay LW, Cooper DI, Alves LM, Pinter PJ Jr (1990) Aerodynamic parameters for a sparsely roughened surface composed of small cotton plants and ridged soil. Remote Sens Environ 32: 143–153

Rooney GG (2001) Comparison of upwind land use and roughness length measured in the urban boundary layer. Bound-Layer Meteorol 100: 469–486

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