12A.2

RELATION BETWEEN THE TURBULENT INTENSITY ON THE CREST OF A RIDGE AND WIND DIRECTION RELATIVE TO THE RIDGE LINE – PART 2: WIND TUNNEL EXPERIMENTS

Hitoshi Kono, Chinatsu Kameshima, Shoko Yahanda and Tomokazu Aoki
University of Hyogo, School of Human Sciences and Environment,

1. INTRODUCTION

Many studies have focused attention on the airflow and turbulence for a 2-D ridge or a circular hill. These include wind tunnel experiments of Pearse et al.(1981), Pearse (1982), Arya and Gadiyaram (1986), Teunissen et al. (1987), Finnigan et al. (1990), Gong and Ibbertson (1989), Ishihara et al.(1999); and field experiments of Bradley(1980), Mason and King (1985), Mason (1986), Taylor and Teunissen (1987) and Salmon et al.(1988). A review on boundary-layer flow over hills was written by Taylor et al. (1987).

On the crest of a 2-D ridge, the wind speed is larger than upstream at the same height above the ground as a result of the stream convergence occurring when wind blows perpendicular to the ridge line. Therefore, on the crest of a ridge, wind speed is larger when the prevailing wind blows perpendicular to the ridge line as compared to that blowing parallel to it (Wegley et al. 1982). However, the relation between the turbulence intensity on the crest and the prevailing wind direction to the ridge line has not been studied.

This study is a part of a series of studies carried out to investigate the relation between the turbulence on the crest of ridges and the wind direction/ridge orientation angle.
In the first study (Part 1), we have analyzed the turbulence at the crest of mountains, which were measured in the field (Kameshima et al., 2008). In the present study, we investigate the wind over a reduced model of the eastern ridge of Mt. Hyonosen in a wind tunnel. The data obtained using the reduced model are compared with the field measurement data that have been discussed in the first study.

* *Corresponding author address*: Hitoshi Kono, University of Hyogo, School of Human Sciences and Environment, kono@shse.u-hyogo.ac.jp

2. WIND TUNNEL AND REDUCED SCALE MODEL

The study was performed on the eastern ridge of Mt. Hyonosen. The area map is shown in Figure 1. The eastern ridge is surrounded by mountains and has a height of approximately 500 m from the bottom of the valleys. The vertical cross sections along lines (a) and (b) at the measurement site are shown in Figure 1. The altitude of the reduced model is in the range of 700 to 794 m, which is indicated in red (Figure 1). The model ridge covers the upper 17% of the total slope length of the eastern ridge (north-south direction). Figure 2 shows the detailed contour map of the crest of the ridge. The altitude of the ridge is in the range of 650 to 794 m. The vertical cross sections along the lines AA′ and BB′ are shown in Figure 2. The distances from the top of the model ridge to the base are 350 m ($12H_m$) along the normal to the ridge and 1000 m ($33H_m$) along the ridge, where H_m (=30 m) is the height at which a 3-cup anemometer is mounted. The experiments were carried out in the atmospheric boundary-layer wind tunnel of our laboratory. The length, width and height of the working section are 3 m × 0.3 m × 0.3 m.

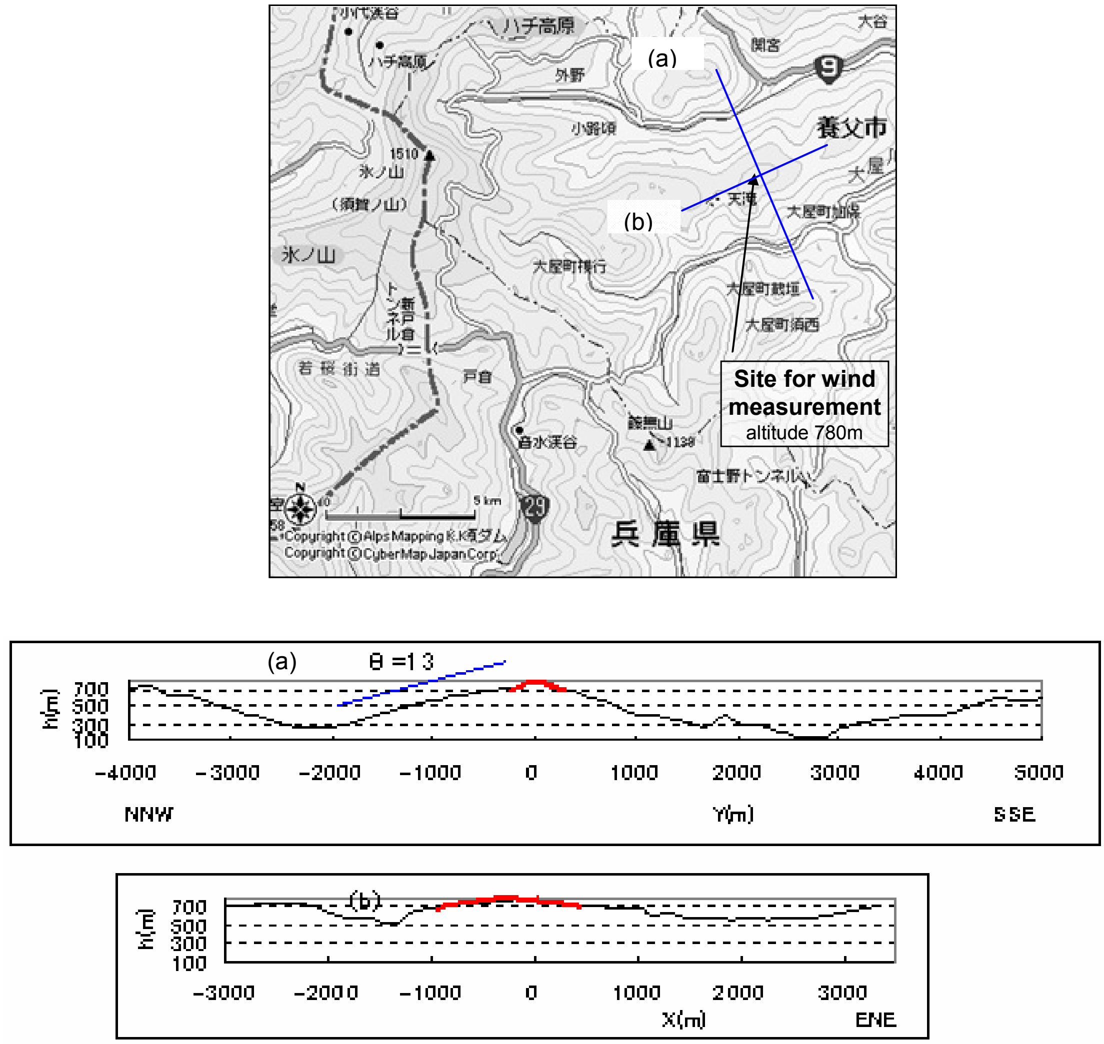

Fig. 1. The area map of the eastern ridge of Mt. Hyonosen and the surrounding terrain. Vertical cross section along the line (a) and the line (b).

The details of the wind tunnel are shown in Figure 3.

The wind speed was measured using a U-type hot-wire anemometer (0251R-T5, IHW-100, Kanomax) placed normal to the wall of the wind tunnel (Figure 3) and an X-type hot-wire anemometer (0252R-T5, IHW-100, Kanomax) place to the upstream with a L-type stem. There were some differences in the measurements carried out using the U- and X-type anemometers. The σ_u of the data obtained by using the U-type anemometer was 10%–14% smaller for z = 10–40 mm than that obtained by using the X-type anemometer.

The sampling interval and the sampling time of the measurement performed by using the U-type hot-wire anemometer were 2 ms (500 Hz) and 20.5 s, respectively.

The sampling interval and the sampling time of the data collected by using the X-type anemometer were 1 ms (1 kHz) and 10.2 s, respectively.

A neutral boundary layer was simulated in the wind tunnel. The boundary layer of the approach flow was generated by covering the entire floor with towels. The thickness of the towel was 5 mm and the nap length was 2 mm.

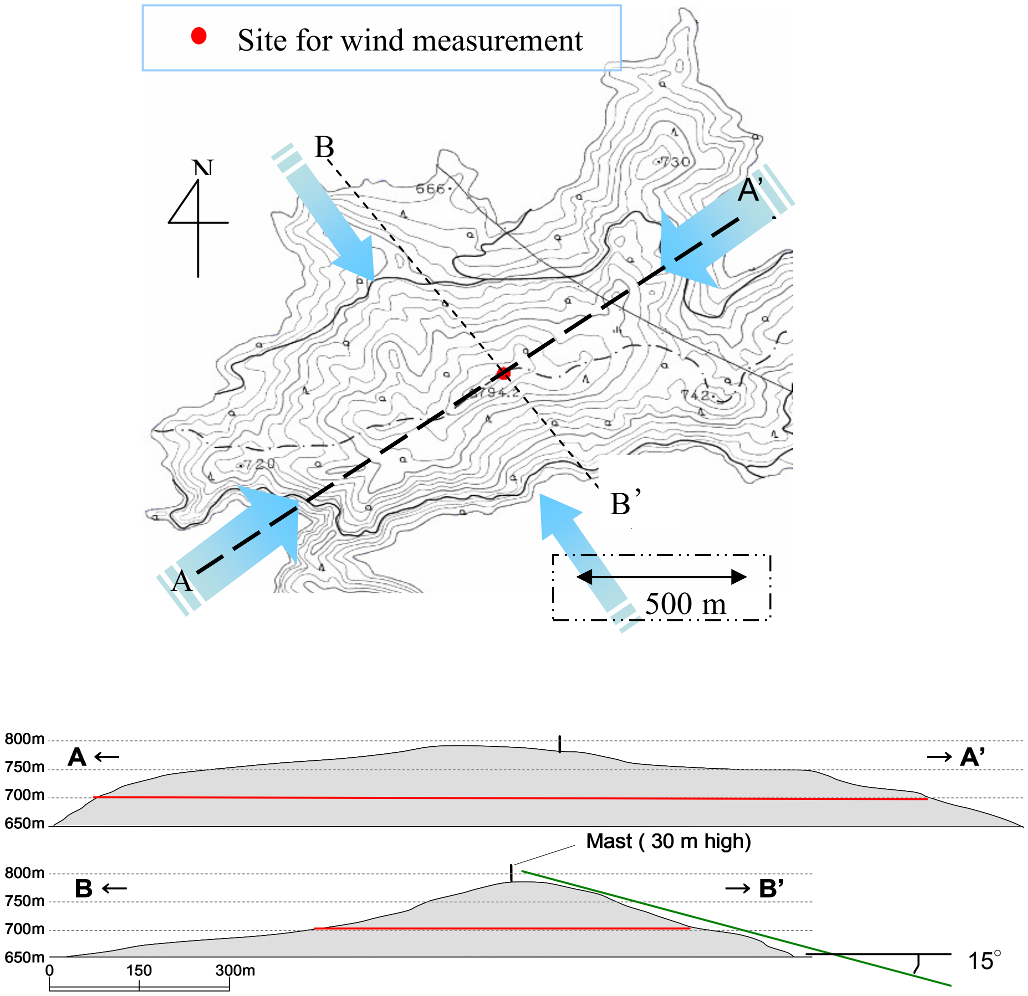

Fig. 2. The detailed contour map of the crest of the ridge. It ranges between 650 and 794 m altitudes. (Topographic map of scale 1:25,000 by The Geographical Survey Institute, Government of Japan)
Vertical cross section on the line AA' and BB' are shown below.

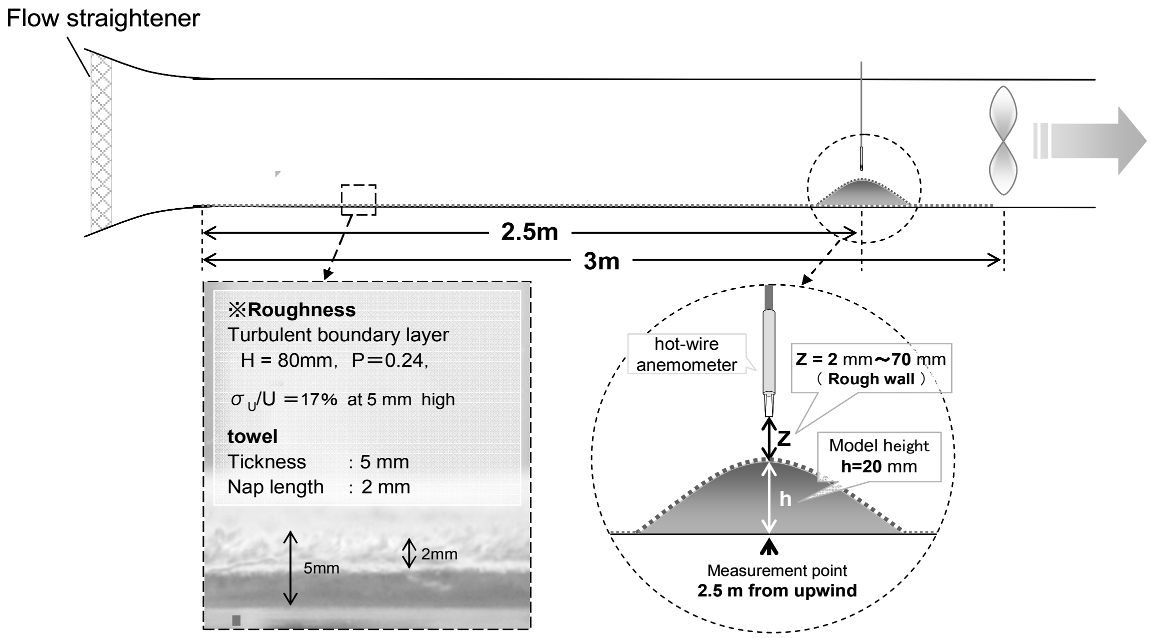

Fig. 3. Test section of the wind tunnel.

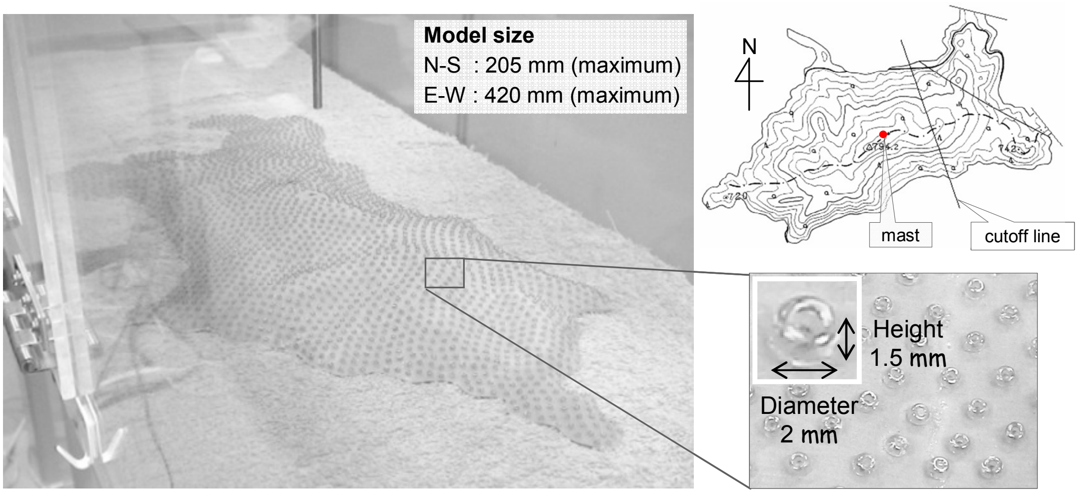

Fig. 4. Model ridge (1:4430 scale) for altitudes ranging between 700 to 794 m. The model surface is covered with beads.

The generated boundary layer was 80 mm high (H) at the reference location and had a power low vertical wind profile with p = 0.24. This p value is close to 0.3, which is the typical value over forests and urban areas (z_0=1-3 m) in neutral atmospheric condition (Counihan, 1975). The roughness length of the logarithmic wind profile was z_0=0.33 mm (1.5 m in full scale) in the wind tunnel. It was calculated using the least square method on the wind speeds U measured between 5mm and 70mm in height above the towel. The correlation coefficient between ln z and U was R=0.99.

The value of σ_u / U is 0.17 and at the reference point of 5 mm high above the towel (20 m in full scale). This value is close to the field experiment of 0.20 under neutral condition (strong wind condition) at the crest of Mt. Hyonosen and Mt. Taiko (Part 1).

The model scale of Mt. Hyonosen was 1:4430. For the model, the maximum length along the east-west direction was 420 mm (1860 m in full scale), the maximum width along the north-south direction was 146 mm (650 m in full scale), and the height of the measurement site was 20 mm (94 m in full scale).

Topographic map of scale 1:25,000 was used to construct the model. The model ridge was machined from high-density polyurethane foam (Fig. 4). It consisted of two parts along its length; one part was 265 mm in length, and the other part was 155 mm in length. One of the parts was used for winds in northern and southern directions, for which the model span is larger than the tunnel span. The sharp change in the slope angles of the model was removed by modifying the full scale contours to provide a gradual decrease in height toward the edge. The surface of the model ridge was covered with beads with a diameter of 2 mm and a height of 1.5 mm. The beads were glued and had a nearest-neighbor separation of 3 mm. The crest of model ridge was laid at x = 2.5 m fetch. The model was turned in the wind tunnel according to the wind direction.

The upstream wind speed outside the boundary layer (U_∞) was set at 5.4 to 5.9 m s^{-1}. The Reynolds Number Re = U_∞×H / ν, was 29,000 where H (= 80 mm) denotes the boundary layer height and ν (= 1.50×10^{-5} m^2 s^{-1} (20℃)), the kinematic viscosity of air. The surface Reynolds number of the approach flow, $\mathrm{Re}s_1 = u_* z_0 / \nu$ was about 6 with z_0 = 0.33 mm and the friction velocity u_* = 0.25 m s^{-1}, where $\boldsymbol{u_*}$ was measured at a reference point of z=10mm in height above the towel. Schlichting (1968) suggests as $\mathrm{Re}s_1 = u_* z_0 / \nu \geq 3$ or $\mathrm{Re}s_2 = u_* z_r / \nu \geq 70$ for fully rough flow, and $\mathrm{Re}s_1 = u_* z_0 / \nu \leq 0.2$ or $\mathrm{Re}s_2 = u_* z_r / \nu \leq 5$ for fully smooth flow, where z_r denotes the height of the roughness elements. Concerning the present model surface, $\mathrm{Re}s_2 = u_* z_r / \nu$ was approximately 20. Therefore, the approach flow was fully rough flow and the flow was expected almost fully rough flow over the ridge model except for a very thin layer on the ridge surface. Hence the flow was considered to be independent of the Reynolds number.

3. RESULTS OF EXPERIMENTS

Figure 5 shows the average wind speed and turbulence measured at the crest of the ridge for winds in various directions and at a reference location at the upstream end of the model ridge.

The measurements were performed for heights ranging from 2 mm (z/h=0.1) to 70 mm (z/h=3.5) above the crest and from 2 mm to 100 mm (z/h=5.0) above the reference point. Height z was normalized by the crest height, h=20 mm. Comparing the wind speed at the same height above the ground, the crest is larger than the reference location. However turbulent intensity σ_u /U is smaller at the crest as compare to that at the reference location. Comparing wind speed, wind speed is larger for winds blowing perpendicular to the ridge line as compare to that blowing parallel to it. However, turbulent intensity σ_u /U is smaller for winds blowing perpendicular to the ridge line as compare to that blowing parallel to it.

Figure 6 shows the vertical profiles of σ_u and σ_w. They are normalised by upwind σ_u and σ_w at z / h = 0.5.

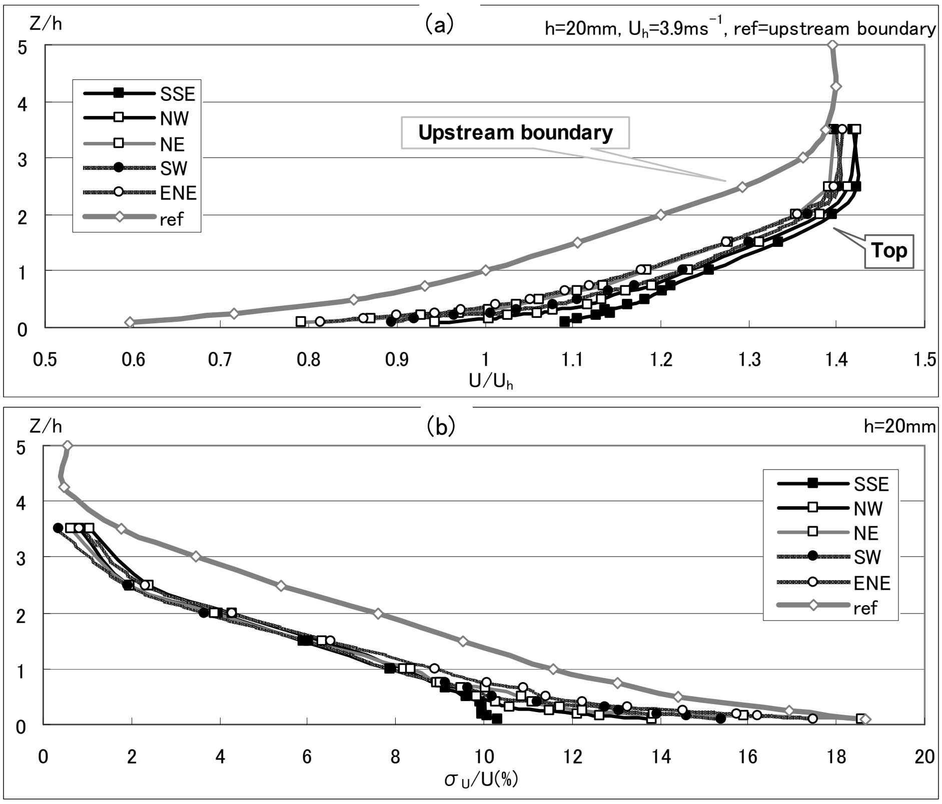

Fig. 5. Vertical profile of (a) wind speed (U / U_h) and (b)σ_u/U. U_h denotes the wind speed in the upstream of the ridge model at the crest height h = 20 mm.

σ_u decreases with increasing height for z/h = 0.1–1. On the other hand, σ_w is almost constant with height for z/h = 0.2–0.8. This behaviour is consistent with the field measurements performed on Black Mountain (Bradley, 1980).

Figure 7 shows the directional profile of σ_u /U and U at the crest of the model ridge for 10 selected wind directions and 7 selected heights. The variation in σ_u /U and U with respect to the wind direction decreases with an increase in the height.

The directional profile of the turbulence intensity is opposite to that of the average wind speed. That

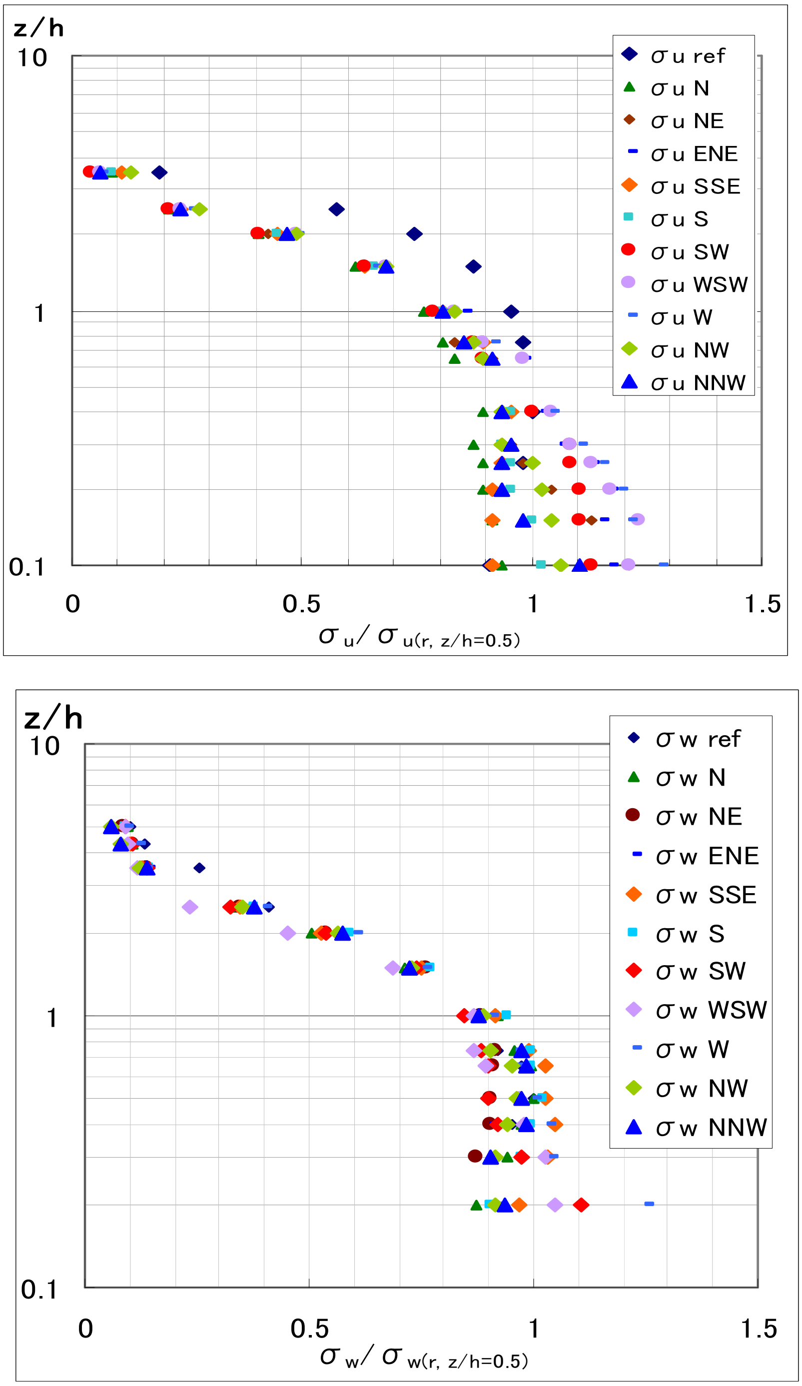

Fig. 6. Vertical profiles of σ_u and σ_w normalised by upwind σ_u and σ_w at z/h = 0.5.

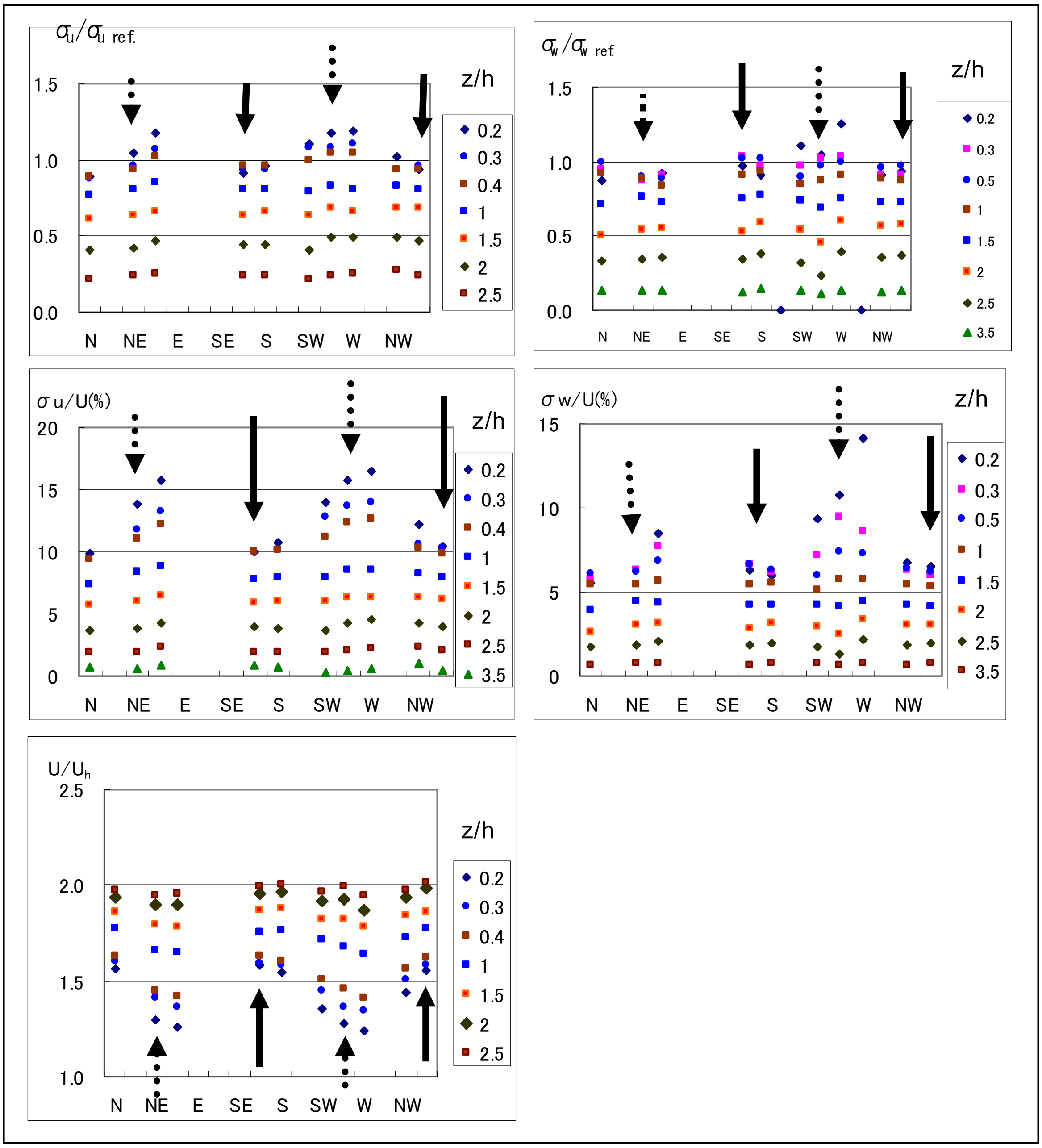

Fig. 7. Directional profiles of σ_u, σ_w, σ_u/U, σ_w/U, and U at the crest of the ridge model. (σ_u and σ_w are normalized by upwind σ_u and σ_w at z/h = 0.5. U_h is normalized by upwind U of the reference site at h in height. The dotted arrows indicate the direction parallel to the ridge, and the solid arrows indicate the direction perpendicular to the ridge.)

is the turbulence intensity of winds blowing parallel to the ridge line is higher than that of winds blowing perpendicular to it. However, the average wind speed of winds blowing perpendicular to the ridge line is higher than that of winds blowing parallel to it.

Figure 8 compares the wind tunnel experiments with the field experiments with respect to the directional characteristics of σ_u / U at heights of 4 mm (20 m in full scale) and 6 mm (30 m in full scale) on the crest of the ridge. The turbulence intensity of winds parallel to the ridge line is higher than that of winds perpendicular to it; a similar relation has been observed in the wind tunnel experiment and the field experiment.

However, the average turbulence intensities in the wind tunnel are 51% and 60% of those in the field measurements at heights of 4 mm (20 m in full sale) and 6 mm (30 m in full scale), respectively. Thus, the reduced model has underestimated the turbulence as compared to the field measurements. This has been resulted in setting the upstream turbulence intensity smaller value. Comparing σ_u / U for two different heights, the deviations are found to be larger in the field measurements as compared to the wind tunnel experiments. The large deviations between the two heights in the field must have been caused by local obstacles such as trees.

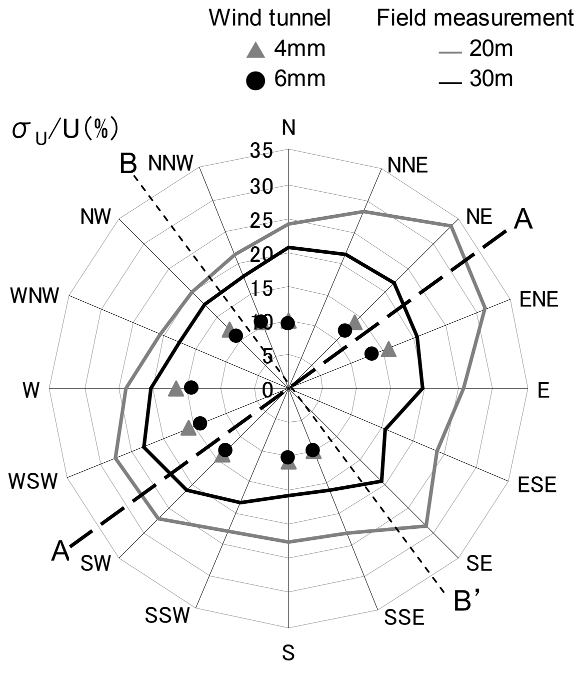

Fig. 8. Comparison between the wind tunnel experiment and the field measurement with regards to the directional characteristics of σ_u/U on the crest of the ridge. The line AA' shows the direction of the ridge line and the line BB' shows the direction perpendicular to it.

Figure 9 shows that

$$\Delta\sigma_u / U = \sigma_u / U_{[field]} - \sigma_u / U_{[model]},$$

which gives the difference in σ_u / U in the field experiment and the wind tunnel experiment. The average $\Delta\sigma_u$ / U is 8% at a height of 6 mm (30 m in full scale), which is an underestimated value. However, the variances of $\Delta\sigma_u$ / U at heights 6 mm (30 m in full scale) with respect to the wind directions are not large. In Figure 9, the differences in $\Delta\sigma_u$ / U for heights of 4 mm (20 m in full scale) and 6 mm (30 m in full scale) in directions between NE-(SSE)-SW are larger than those in directions between WSW-(NW)-N. This difference is caused because the mast in the field measurement was placed 40 m downward along the slope in the NNE direction from the crest; however, in the reduced model, the turbulence is measured at the crest.

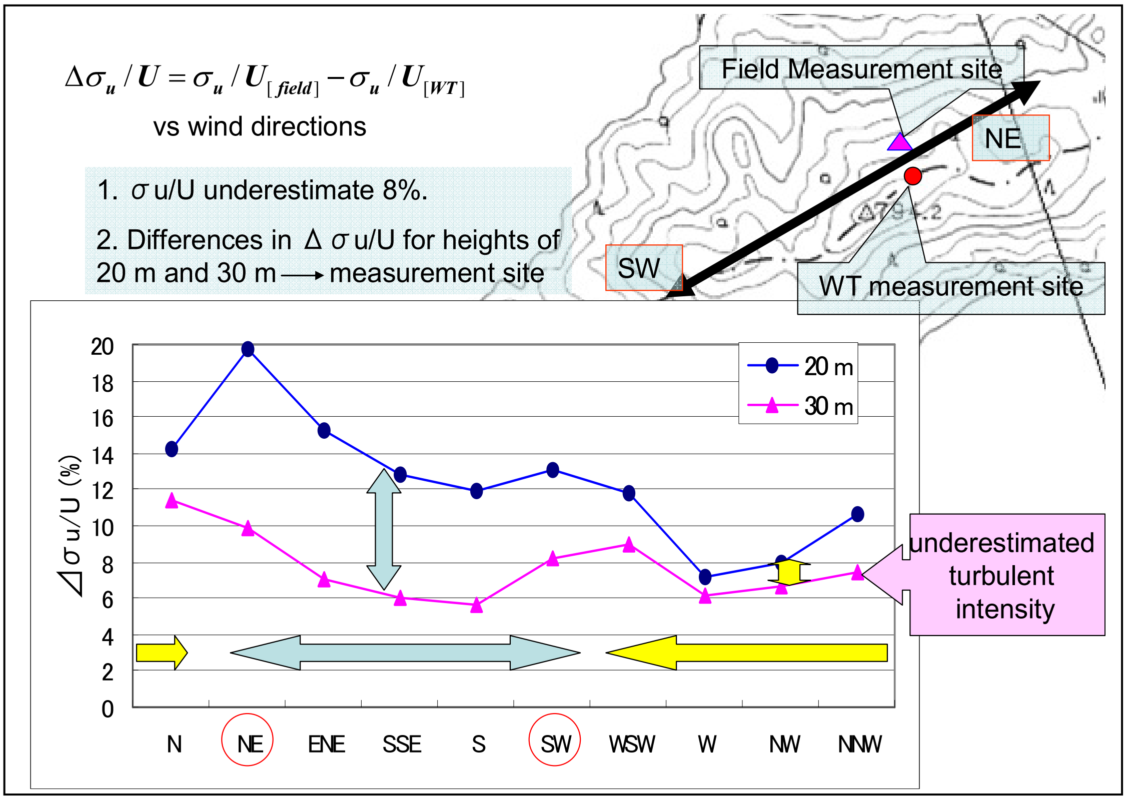

Fig. 9. $\Delta\sigma_u$/U with respect to wind directions.

Figure 10 shows the vertical profile of σ_u / σ_w observed at the crest for winds blowing perpendicular (NNW and S) and parallel (WSW and ENE) to the ridge line and at the upstream reference site. The observed σ_u / σ_w, by other researcher were 1.91 ± 0.03 at various locations on flat terrains and 3.60 on a mountain under neutral atmospheric condition (Panofsky and Dutton, 1984). In Figure 10, the ratio is 1.95 at the reference site, upstream of the model ridge, at a height of 8 mm (40

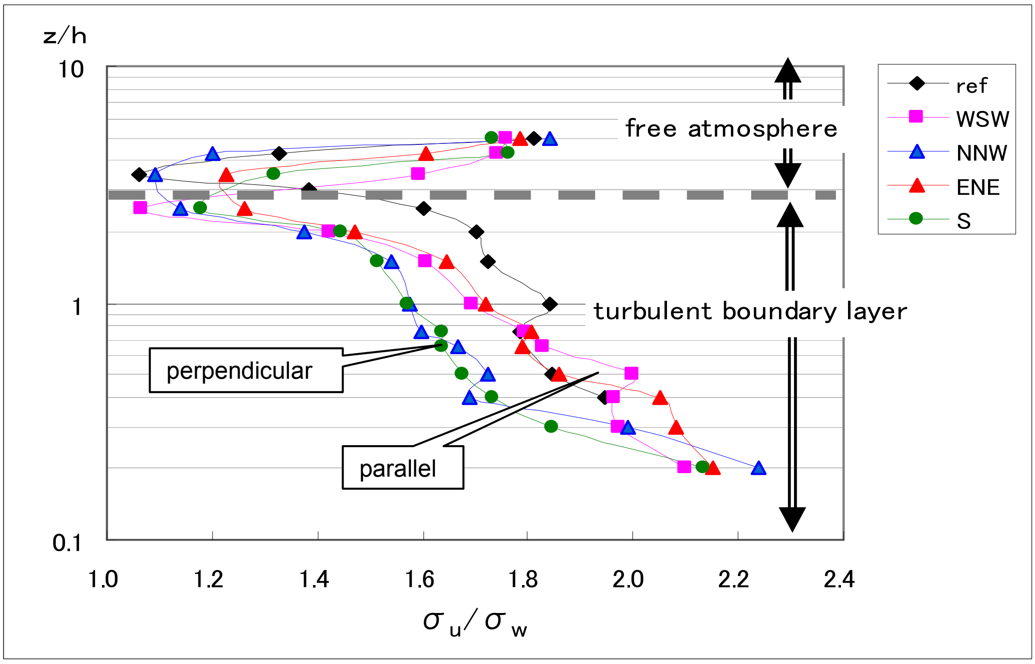

Fig. 10. Vertical profile of σ_u / σ_w (X-type hot-wire anemometer).

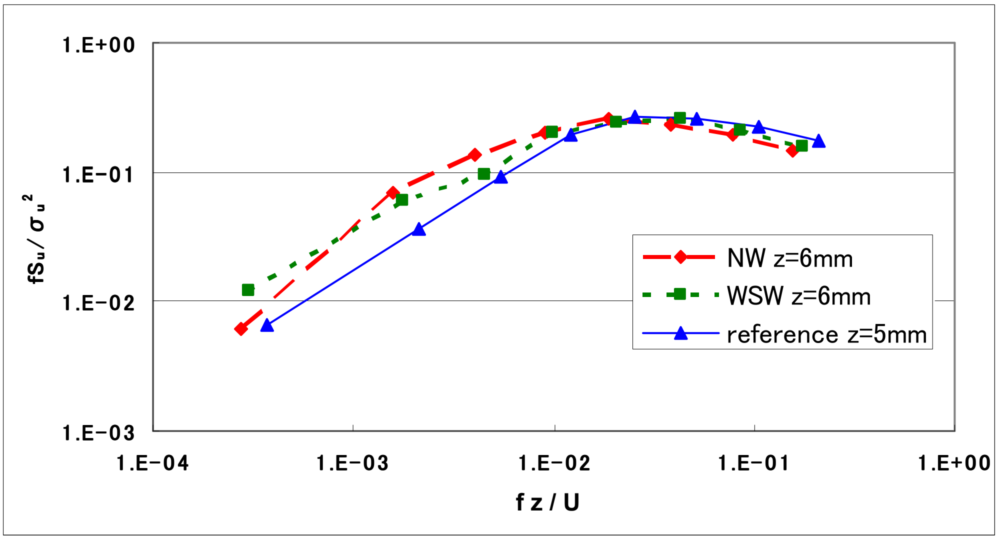

Fig. 11. Normalized velocity spectra for the u component at the crest of the ridge and the upstream reference site obtained from the wind tunnel experiments. (NW: perpendicular, WSW: parallel)

m in full scale); thus, this ratio agrees with the ratio obtained at flat terrains. The ratio σ_u / σ_w decreases with height and it is approximately 1 at the top of the turbulent boundary layer. The ratio σ_u / σ_w at z =6 mm (z/h = 0.3) on the crest is smaller for wind directions perpendicular to the ridge line as compared to wind directions parallel to it.

Figure 11 shows normalized velocity spectra for u component at the crest of the ridge and the upstream reference site in the wind tunnel experiments. The wind directions NW and WSW are perpendicular and parallel to the ridge line, respectively. The eddy size λ is defined by λ = U / 2f. The λ for which normalized energy spectra is f $S_u / \sigma_u^2 > 0.1$, ranges in 1.2 cm < λ < 21 cm at the reference point and 1.9 cm < λ < 75 cm at the crest in NW wind direction. (The eddies with λ larger than 10 cm may have been caused by the wave produced at the boundary between the turbulent boundary layer and the upper laminar flow; however, the cause has not been confirmed.) The wind perpendicular to the ridge line includes larger eddies more as compared to that parallel to the ridge line. The wind at the crest includes larger eddies more as compared to that at the reference point. (With regards to the field experiments, we cannot calculate the spectra of turbulence because only the 10-min. average wind speed and the standard deviation were recorded.)

4. DISCUSSION

The turbulent intensity was larger in wind directions parallel to the ridge line as compared to that perpendicular to it. However the wind speed was larger in wind directions perpendicular to the ridge line as compared to that parallel to it, which was the same result as discussed before by Wegley et al. (1982). This is because, when wind blows perpendicular to the ridge line, the airflow converges along the upwind slope. Therefore, the upper air, in which turbulence is smaller and wind speed is larger than those in the lower air, is mixed into the flow at a crest. It was shown in the energy spectra of wind in the wind tunnel experiments that large eddies were included in the wind blowing perpendicular to the ridge line more than that blowing parallel to it.

5. CONCLUSIONS

The turbulence intensity of winds parallel to the ridge line is higher than that of winds perpendicular to it; a similar relation has been observed in the wind tunnel experiment and the field experiment. When wind blows perpendicular to the ridge line, airflow converges along the upwind slope. Therefore, the upper air with turbulence and wind speed that are smaller and larger, respectively than those of the lower air is mixed into the flow at a crest.

The variation in σ_u/U and U with the wind direction decreased with an increase in the measuring height.

The essential relation between turbulence intensity and the wind direction with respect to the ridge line has been revealed in the experiments.

However, the model accuracy needs to be increased by the following improvements: (1) increasing in the upstream turbulence intensity, (2) bringing about perfect agreement between the measurement sites in the field and the model, (3) placing detail distribution of trees, and (4) increasing the model area. A lager wind tunnel is necessary to achieve (3) and (4).

ACKNOWLEDGEMENTS

The authors thank to Dr. Michio Nishioka, Dr. Susumu Oikawa and Mr. Osamu Kanechika for valuable comments on the manuscript. The authors also express their gratitude towards Yabu City and Kyoto Prefectural Government for providing the data for the field experiments.

REFERENCES

Arya, S. P. S., Gadiyaram, P. S., 1986: An experimental study of flow and dispersion in the wakes of three-dimensional flow. Atmospheric Environment, 26(4), 729–740.

Bradley, E. F., 1980: An experimental study of the profiles of wind speed, shearing stress and turbulence at the crest of a large hill. Quart. J. R. Met. Soc. 106, 101–123.

Counihan, J., 1975: Adiabatic atmospheric boundary layers: a review and analysis of data from the period 1880-1972. Atmospheric Environment 9, 871-905.

Finnigan, J.J., 1988: Air flow over complex terrain, flow and transport. In: Steffen WL, Finnigan, J.J., Raupach, M.R., Bradley, E.F., Aldis, G.K., 1990: A wind tunnel study of turbulent flow over a two-dimensional ridge. Boundary-Layer Meteorology. 50, 277–317.

Gong, W., Ibbertson, A.,1989: A wind tunnel study of turbulent flow over Model Hills. Boundary-Layer Meteorology, 49, 113–148.

Ishihara, T., Hibi, K., Oikawa, S.,1999: A wind tunnel study of turbulent flow over a three-dimensional steep hill. Journal of Wind Engineering and Industrial Aerodynamics, 83, 95–107.

Kameshima, C., Kono, H. and Tamura, D, 2008: Relation between the turbulent intensity on the crest of a ridge and wind direction relative to the ridge line – Part 1: field measurements, Proceedings in 13th Conference on Mountain Meteorology.

Mason, P.J., King, J. C., 1985: Measurements and predictions of flow and turbulence over an isolate hill of moderate slope. Quart. J. R. Met. Soc., 111, 617–640.

Mason, P. J., 1986: Flow over the summit of an isolated hill. Boundary-Layer Meteorology. 37, 385–405.

Panofsky, H. A. and Dutton, J.A., 1984: Atmospheric turbulence, A Wiley-Interscience publication, 1-397.

Pearse, J.R., Lidley, D., Stevenson, D.C. 1981: Wind flow over ridges in simulated atmospheric boundary layers. Boundary-Layer Meteorology, 21, 77–92.

Pearse, J.R., 1982: Wind flow over conical hills in a simulated atmospheric boundary layer. Journal of Wind Engineering and Industrial Aerodynamics, 10, 303–313.

Salmon, J.R., Bowen, A.J., Hoff, A.M., Johnson, R., Mickle, R.E., Taylor, P.A., Tetzlaff, G., Walmsley, J.L., 1988: The Askervein Hill Project: Mean wind variations at fixed heights above ground. Boundary-Layer Meteorology, 43, 247–271.

Schlichting, H.,1968: Boundary layer theory. 6^{th} edn. McGraw-Hill, New York.

Taylor, G.I., 1938: The spectrum of turbulence. Proc. R. Soc. London Ser, A 164, 476–490.

Taylor, .P.A., Teunissen, H.W., 1987: The Askervein Hill Project: Overview and background data. Boundary-Layer Meteorology. 39, 15–39.

Taylor, P.A., Mason, P.J., Bradley, E.F., 1987: Boundary layer flow over low hills (a review). Boundary-Layer Meteorology. 39, 107–132.

Teunissen, H.W., Shokr, M.E., Bowen, A.J., Wood C.J., Green, D.W.R., 1987: The Askervein Hill Project: Wind

tunnel simulations at three length scales. Boundary-Layer Meteorology. 40, 1–29.
Wegley, H.L., Ramsdell, J.V., Orgill,M.M., Drake, R.L., 1982: A siting handbook for small wind energy conversion systems. Windbooks, St. Johnsbury.