針葉樹林における顕熱および水蒸気輸送の群落上と群落内の比較

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Comparison of Eddy Heat Fluxes Between Inside and Above a Coniferous Forest

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Abstract

Turbulent transport of sensible heat and water vapor inside and above a coniferous forest is investigated based on a field experiment. The fluxes of sensible heat and water vapor inside the canopy are found to be much smaller than (usually about 1/10 of) those above the canopy. The correlation coefficients $\overline{w'T'}/(\sigma_w \sigma_T)$ or $\overline{w'q'}/(\sigma_w \sigma_q)$ inside the canopy were about 1/5 of those above the canopy. The vertical velocity spectra inside the canopy lack the inertial subrange. They show a hump at the high frequency side. Cospectra of the flux of all the scalar quantities are expressed in a single function over the forest, suggesting that the same mechanism is acting on the transport of heat, water vapor or other atmospheric gasses. This similarity does not hold for the turbulence inside the canopy, where the shape of the cospectra can not be grouped into a single shape.

Key words: Coniferous forest, Cospectrum, Sensible heat flux, Water vapor flux.

1. Introduction

Turbulence within forests is receiving increasing attention since the mass and energy fluxes from and to the forest are important factors for the local and global climate. In the past ten years the turbulence in forests has been extensively studied and many experiments have been conducted. Major contributions are: Turbulent structure up to the 3rd order moments was investigated finding the skewed structure of the turbulence within forests (*e.g.*, Baldocchi and Meyers, 1988; Amiro, 1990 (a)). Velocity spectra have been measured at various heights in various forests finding peculiar nature in velocity spectra inside the canopy compared to those above short canopies (Amiro and Davis, 1988; Amiro, 1990(b)). Nature of the organized motion in a forest was found to have important roles in transporting energy and mass (Shaw *et al.*, 1990). Measurements of eddy fluxes of CO_2 have also started (Verma *et al.*, 1986).

However, the characteristics of turbulent transport in forests are still not sufficiently understood. One of the difficulties arises from the rough surface of the forest canopy, where the turbulence similarity laws established over short vegetation are not usually be applied. Another problem is that the forests are generally located in non-simple terrains in Japan which makes the experimental approach often difficult. However, information of turbulence in forests in complex terrains is needed to improve our understandings. In the present research, we conducted field experiments in a coniferous forest to investigate the characteristics of the turbulent fluxes inside and above the canopy. Relations and differences of the transports between inside and above a forest canopy are discussed.

2. Forest and Measurement

The experiment was carried out in a forest of about 35 year old Japanese red pine (*Pinus densiflora*) and Japanese cypress (*Chamaecyparis obtsusa*) in the southern part (136°00'E, 34°58'N) of Shiga Prefecture, Japan. The mean tree height was approximately 15m and the height of the tall trees was about 18m. The tree density was about 5,700/ha for the red pine and 3,000/ha for the cypress. Two identical sets of turbulence instruments were installed at 20.0 and 7.4m on a 25m tower. The upper height was about 2 to 5m above the forest crown. The lower height was in the upper part of the trunk space and about 80% of the leaves were above this height. The set of turbu-

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lence instruments consists of a one dimensional sonic anemometer with a 10 cm sound path, originally designed by Campbell and Unsworth (1971) and improved by Hamotani *et al.* (1990), to measure the vertical wind component, and fine wire thermocouple psychrometer of 0.05 mm in diameter to measure the temperature and humidity fluctuations. The response of the fine wire thermocouple psychrometer was corrected by the method described by Tsukamoto (1986). Trends in the signals were removed by applying the second order polynomials.

Vertical profiles of the mean wind speed, and dry and wet bulb temperature were measured at the height of 22.7, 18.4, 13.5, 9.2 and 4.1 m on the same tower by cup anemometers, and aspirated psychrometers respectively. Omnidirectional hot-wire anemometers (Kanomax Model 6071) were also installed to measure mean wind speed at the height of the turbulence measurements (20.0 and 7.4 m).

The tower was situated on a gentle slope facing north. The average slope angle for about 2 km near the tower was about 4 degrees. The tilt angle of the wind measured at the top of the tower when wind blew within a limited direction (from the north to northeast, i.e., the up-slope wind) was less than a few degrees. This was the usual daytime wind direction induced both by the hill slope and the large lake (Lake Biwa) about 10 km north of the site. Since the one dimensional sonic anemometer was installed vertically, the error in the heat fluxes caused by including the wind component along the slope may be typically the order of 5%. Turbulence signals were recorded on floppy disks through a personal computer at 10 Hz. The sampling duration for one run was 28 minutes. Data were obtained in the beginning of November, 1990. Results shown in this paper are from a single clear day.

The results from an additional observation using a infrared hygrometer and CO_2 fluctuation meter (Advanced System Co. E-009A) conducted on the same tower in the next year (1991) are compared here with the present results. The details of the measurements conducted in 1991 are described in Monji *et al.* (1993).

3. Results and Discussion

3.1 Profiles of wind, temperature and humidity

The vertical profiles of the mean wind speed, temperature and specific humidity are presented in Fig. 1. The mean wind speeds above the canopy were about 1 m/s in the early morning and evening, and about 2m/s during the midday. The mean wind speed inside the canopy was about 1/10 of those above the canopy. For some runs, the wind speed at the lowest height was larger than those

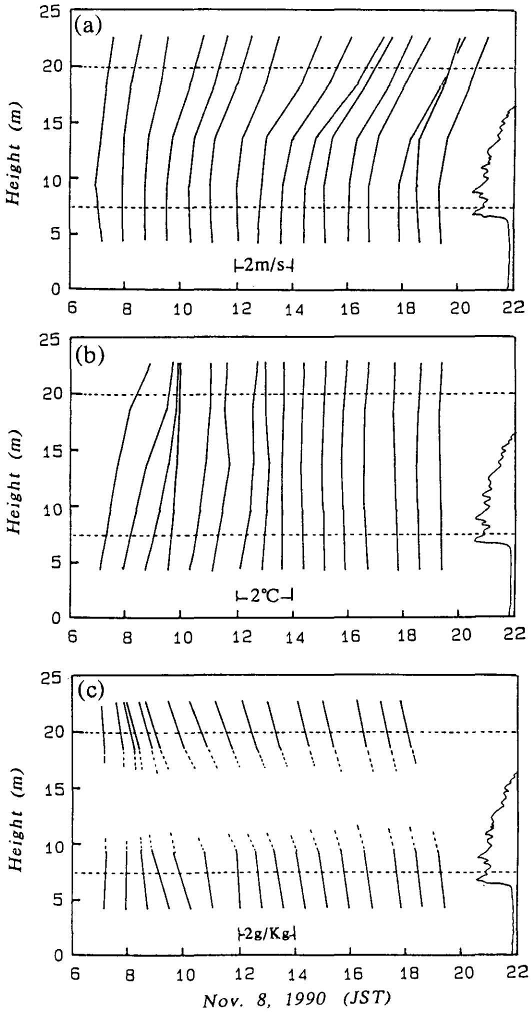

Fig. 1. Time changes in the vertical profiles of (a) wind velocity, (b) temperature and (c) specific humidity observed in the coniferous forest. The dashed lines are the height of the turbulence observation. Typical tree height is shown schematically. The time of the observation is indicated by the lowest measurement height.

at the second lowest level. This means that wind profiles for some runs may have secondary maximum in the trunk space of the canopy as pointed out previously (*e.g.* Shaw, 1977).

The mean temperature gradients were generally stable except that maximum is recognized during midday in the layer just below the tree tops. The profiles of the specific humidity lack the middle height because of the malfunction of the wet-bulb. They show monotonous increase toward the forest floor.

3.2 Turbulence statistics

Time variation of the turbulent fluxes of the sensible heat and water vapor are presented in Fig. 2. The sensible and the latent heat fluxes above the forest canopy were about the same order of magnitude. This is commonly observed except immediately after the rain when the intercepted water evaporates (see *e.g.* Munn, 1966). In the evening the sensible heat flux above the canopy shows negative values, while the latent heat flux remains positive and approaches to zero.

According to the research by Garratt (1978) and Denmead and Bradley (1985), the flux gradient relationship over tall vegetation obeys some different similarity law from those over bare soil or short grass. However, general law has not been established. In this experiment the direction of the sensible heat flux did not always match the temperature profile, although the water vapor flux was mostly down-gradient above the canopy. The fluxes are suggested not to always obey the local gradient. We should include larger range of altitude to estimate fluxes from the profiles over these non-simple terrains.

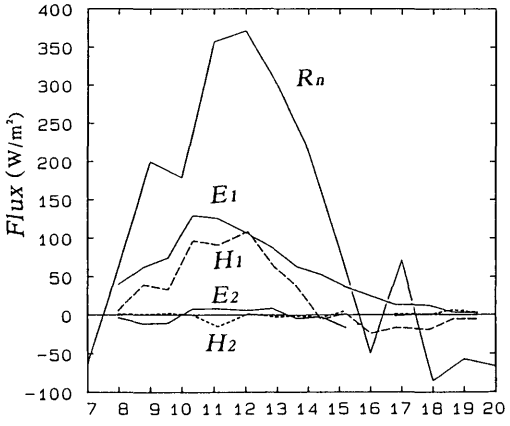

Fig. 2. Time variations of the sensible (H) and latent (E) heat fluxes observed inside (subscript 2) and above (subscript 1) the coniferous forest. Rn is the net radiation measured at the top of the tower.

Generally, inside plant canopies the fluxes are reported not to obey the gradient. Counter gradient transport was often observed (*e.g.* Denmead and Bradley, 1985). In the present research, the magnitude of the fluxes inside the canopy were about 1/10 of those above the canopy. There, the direction of the fluxes of sensible heat and

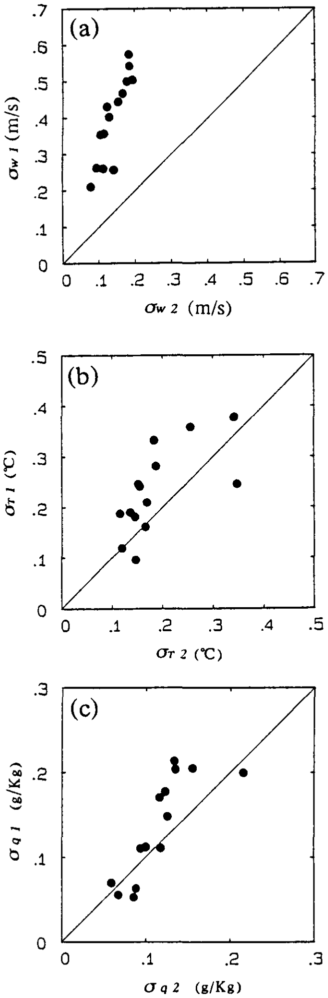

Fig. 3. Comparisons of the standard deviation of the turbulent fluctuations inside (subscript 2) and above (subscript 1) the forest canopy.
(a) vertical velocity, (b) temperature,
(c) specific humidity

the latent heat seems to be opposite. During the daytime the direction of the vapor flow was upward and that of the sensible heat was downward corresponding to the gradient inside the canopy. However, these results are not sufficient to establish a generalized law of flux gradient relationship.

The magnitudes of the fluctuations σ_T and σ_q are approximately the same both above and inside the canopy as presented in Fig. 3. This suggests that the fluctuations are contributing to the fluxes more efficiently above the forest canopy compared to those inside the canopy.

The correlation coefficient between T and w, and that between q and w are shown in Fig. 4. These are plotted as functions of stability. The stability parameter used here (L') is that similar to Monin-Obukhov length but σ_w is used instead of the friction velocity. This stability was used because correlation between u and w often has positive values inside the canopy and friction velocity is difficult to determine. The value of the correlation coefficient between T and w is about 0.5 for sufficiently unstable conditions (right side of the figure), which is about the same value obtained over the short vegetation by Haugen *et al.* (1971). Inside the canopy, however, the correlation coefficients are significantly small (about 0.1). The correlation coefficient between q and w is also 0.5 above the canopy for large instability, but the values are also smaller inside the canopy. This means that the efficiency of the turbulence fluctuations to transport heat and water vapor inside the forest canopy are much smaller than those above the canopy.

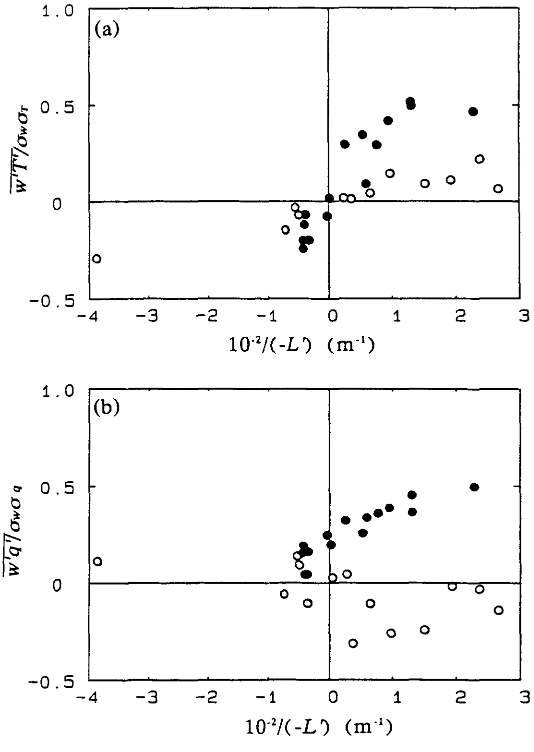

Fig. 4. Comparison of correlation coefficients between inside (○) and above (●) the canopy plotted against the stability parameter (L').
(a) $\overline{w'T'}/(\sigma_w\sigma_T)$, (b) $\overline{w'q'}/(\sigma_w\sigma_q)$.
L' is explained in the text.

3.3 Spectra and cospectra

Turbulence spectra inside and above the forest

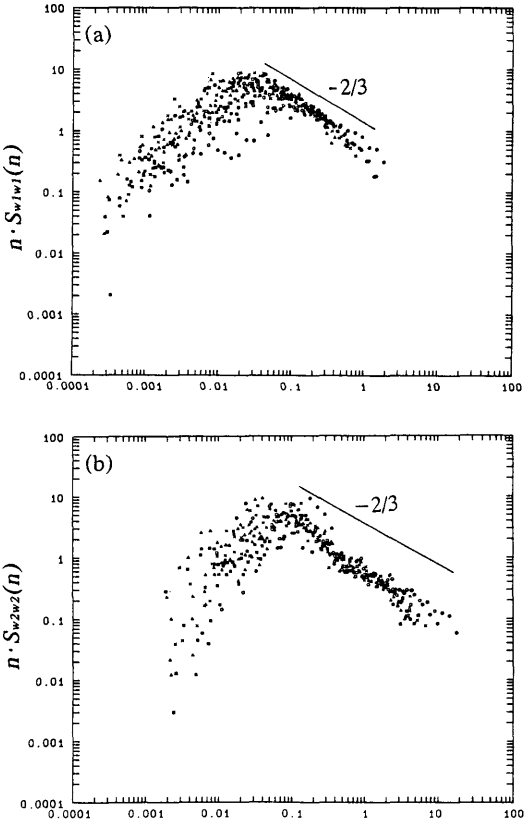

Fig. 5. W-spectra above (a) and inside (b) the canopy. The vertical position of the graphs was determined so that the energy for the frequency range from 0.1 to 1 are matched. Symbols are for the runs started in the time range of 6 to 9 (○), 9 to 12 (×), 12 to 15 (△) and 15 to 20 JST (□).

canopy have also different characteristics from each other. The power spectra of the vertical velocity (w) inside and above the forest canopy are shown in Fig. 5. The apparent wave number (frequency divided by mean wind speed) is used instead of dimensionless frequency, since the height scale inside the canopy is not simply defined. W-spectra above the canopy indicate about the same shape as those obtained over the short vegetation. However, those observed in the forest canopy are different in the high frequency region. The slope of high frequency side of the spectra is steeper than that of the theoretical inertial subrange (-2/3). Another difference is that they have

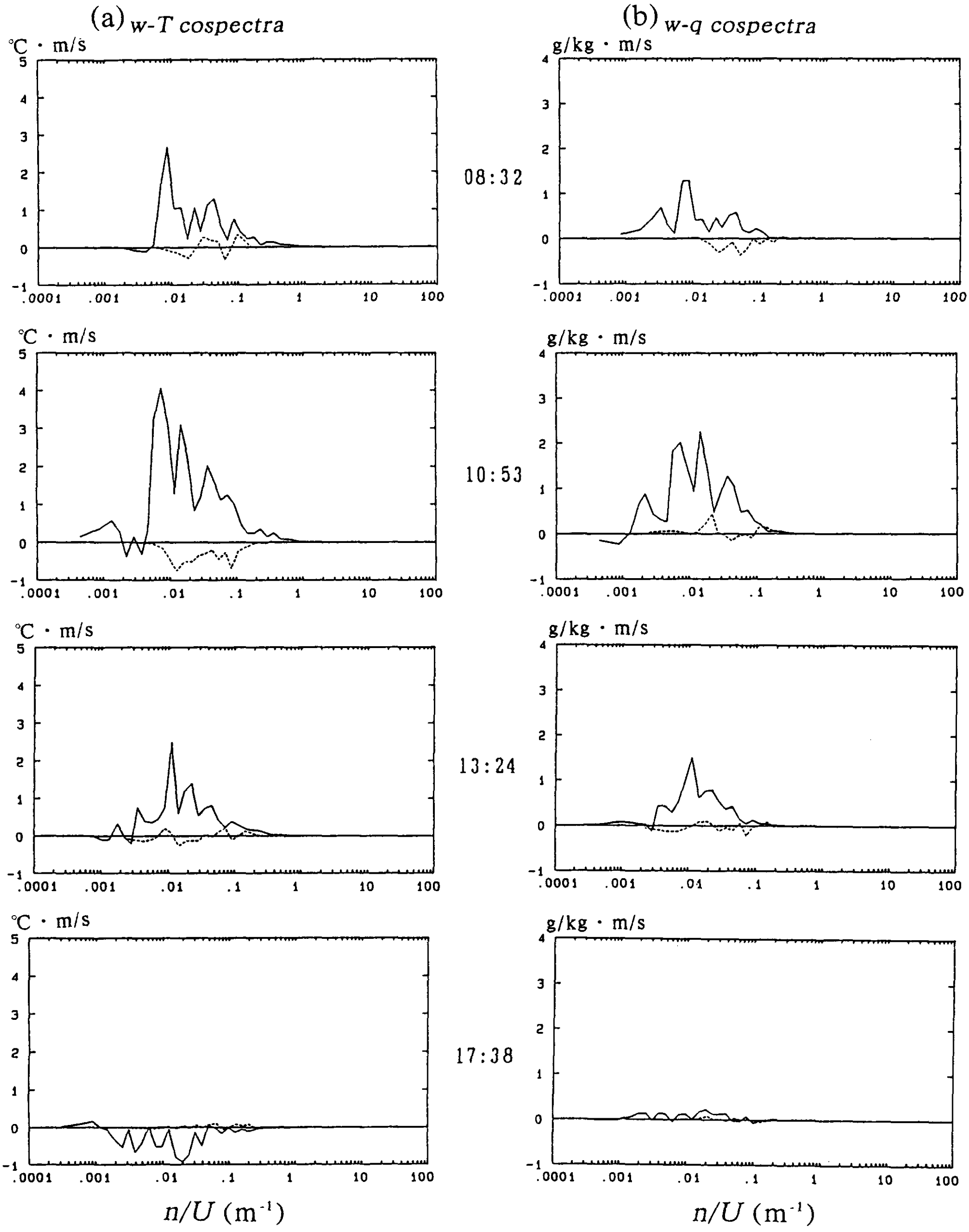

Fig. 6. Examples of the cospectra inside (dashed line) and above (solid line) the canopy. (a) wT cospectra, (b) wq cospectra. The cospectra are multiplied by the frequency.

a hump at high frequency end. These are also reported in a spruce forest by Amiro and Davis (1988) and in a deciduous forest by Baldocchi and Meyers (1988). The cause of the departure from the inertial subrange law may be explained as the loss of the energy by the canopy elements. The high frequency hump is explained as the results of the generation of the wake turbulence caused by form drag on canopy elements (Amiro and Davis, 1988).

Cospectra of the heat fluxes are also entirely different between inside and above the canopy as shown in Fig. 6. The shape of the cospectra of sensible heat flux (*wT* cospectra) and water vapor flux (*wq* cospectra) above the canopy during daytime are similar to each other. This is more evident if the cospectra are expressed in the logarithmic coordinate (Fig. 7). As discussed in Monji *et al.* (1993), all the normalized scalar flux cospectra obtained above the forest including the carbon-dioxide flux (*wc*) may be expressed approximately in a single shape. The high frequency end matches the -4/3 slope which was obtained empirically over short grass or bare soil (*e.g.* Kaimal *et al.*, 1972). This is indicated in Fig. 8. The shape of *wT* and *wq* cospectra in Fig. 7 are almost identical with those in Fig. 8. This suggests that the same mechanism is acting on the transport of heat, water vapor or other atmospheric gasses. This nature can be used to estimate the fluxes of quantities such as trace gasses in the atmosphere for which fast response instruments are not yet developed. This method was named as the band pass covariance technic by Anderson and Verma (1985) who found the cospectral similarity over a wheat crop canopy. However, the flux cospectra inside the canopy are different between each other as seen in Fig. 6, which means that the turbulence similarity does not hold inside the canopy.

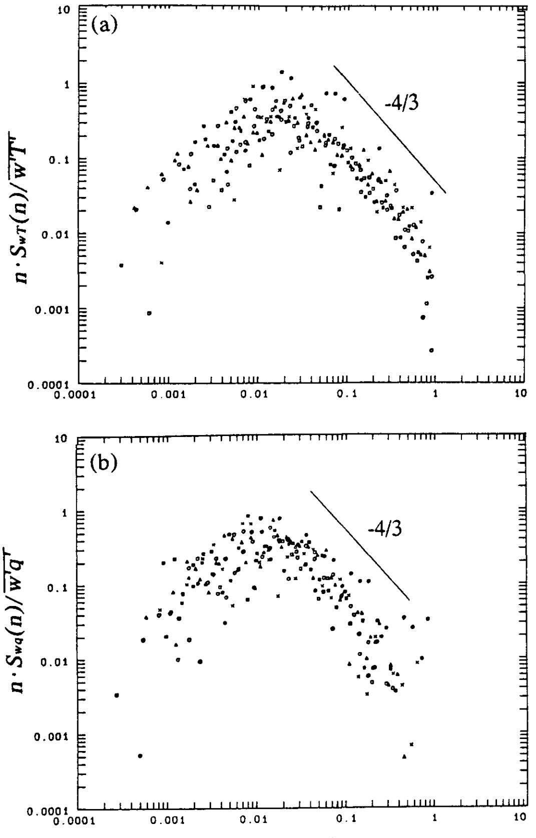

Fig. 7. Normalized cospectra above the canopy plotted in a logarithmic scale. 8 runs for which the sensible heat flux was upward are shown together. (a) *wT* cospectra, (b) *wq* cospectra. Symbols are for the runs started at 08:32 (○), 09:19 (×), 10:06 (△), 10:53 (□), 11:50 (●), 12:37 (▲), 13:24 (■).

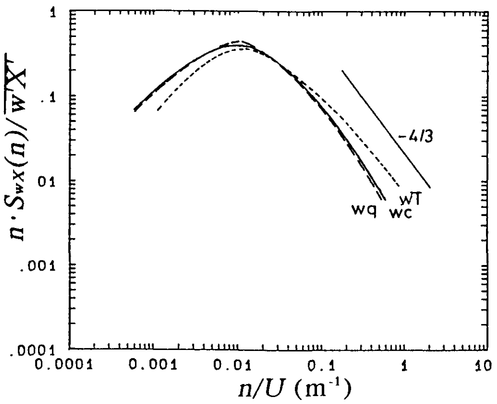

Fig. 8. Similarity among *wT*, *wq*, and *wc* cospectra (experiment in 1991).

3.4 Correlation of the fluctuations inside and above the canopy

The correlations between the fluctuations within and above the forest canopy are analyzed to find out how the turbulent phenomena are structually continuous from inside to beyond the top of the canopy. The results are shown in Fig. 9. The abscissa is the lag distance, which is the time lag multiplied by the mean wind speed. The positive lag-distance means the fluctuations proceed above the forest, and vice versa. In the other words if

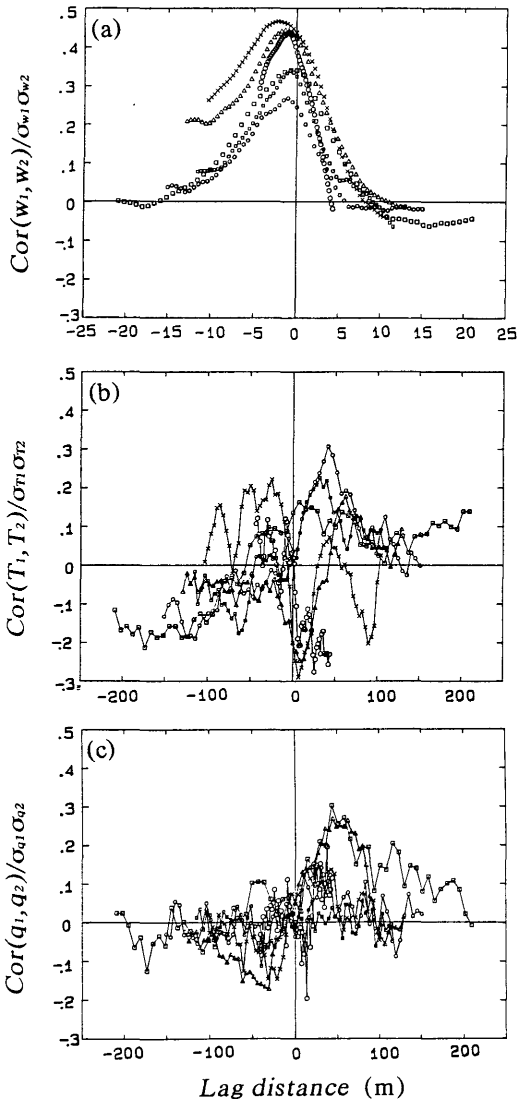

Fig. 9. Correlation function between the fluctuations inside and above the canopy.
(a) w-component, (b) temperature, (c) specific humidity. Symbols are for the runs started at 07:44 (○), 10:06 (×), 11:50 (△), 14:11 (□), 16:33 (○) and 18:25 (□).

the peak appears in the positive lag-distance side the phenomena above the canopy are occurring earlier. Correlations are different among wind speed, temperature and water vapor as shown in Fig. 9. The correlation of the vertical wind component has sharp peaks and the lag-distance between in and above the canopy is small (less than 2m). The peak appears at slightly negative side, which means the fluctuations proceed inside the canopy. The correlation of water vapor has peaks around the lag distance of about 50m, which is considerably larger compared to that for the vertical velocity component. This difference may be due to difference of the transport mechanism. The pressure force is effective in transporting momentum, but the diffusion is the main mechanism of transporting scalar quantities. Pressure force may penetrate the canopy easily, but the diffusion meets the resistance of the canopy elements. Temperature correlation indicates more complex character, since the heat release and absorption by the foliage was complex as speculated from the temperature profiles (Fig. 1).

4. Summary and conclusions

Differences between the nature of the turbulent transports inside and above a coniferous forest are discussed. The fluxes of sensible heat and water vapor inside the canopy was much smaller than (usually about 1/10 of) those above the canopy. The small value of the fluxes inside the canopy may be due to the lack of organized motions as appeared in the small value of the correlation coefficients for the turbulent fluctuations.

Fluxes were not related to the vertical profiles even above the forest canopy. The fluxes may not be correlated with the local gradient. We may have to extend the height of the profile measurements when we estimate fluxes by aerodynamic procedure.

Spectral analyses indicate that the turbulence characteristics inside the canopy are different from those above the canopy. The power spectra of the vertical velocity component inside the canopy do not indicate the existence of the inertial subrange. Besides, they have humps at high frequency end. These may be caused by the form produced by the canopy elements.

Normalized cospectra of the flux of all the scalar quantities over the forest are suggested to be modeled by a single function, which means that the same mechanism is acting on the transport of heat, water vapor or other atmospheric gasses. However, the cospectral similarity does not hold for the turbulence inside the canopy, where the shape of the spectra could no be grouped into a single shape.

This study was conducted in a forest with a gentle slope. Although we believe to have obtained general idea about the fluxes in the forest, these result should be tested in a more ideal site. At the same time, additional information for the forests in complex terrain is needed to improve our understandings.

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References

Amiro, B. D., 1990 (a): Comparison of turbulence statistics within three boreal forest canopies. *Boundary-Layer Met.*, **51**, 99–121.

Amiro, B. D., 1990 (b): Drag coefficients and turbulence spectra within three boreal forest canopies. *Boundary-Layer Met.*, **52**, 227–246.

Amiro, B. D. and Davis, P. A., 1988: Statistics of atmospheric turbulence within a natural black spruce forest canopy. *Boundary-Layer Met.*, **44**, 267–283.

Anderson, D. E. and Verma, S. B., 1985: Turbulence spectra of CO_2, water vapor, temperature and wind velocity fluctuations over a crop surface. *Boundary-Layer Met.*, **33**, 1–14.

Baldocchi, D. D. and Meyers, T. P., 1988: A spectral and lag-correlation analysis of turbulence in a deciduous forest canopy. *Boundary-Layer Met.*, **45**, 31–58.

Campbell, G. S. and Unsworth, M. H., 1976: An inexpensive sonic anemometer for eddy correlation. *J. Appl. Met.*, **18**, 1072–1077.

Denmead, O. T. and Bradley, E. F., 1985: Flux gradient relationship in a forest canopy. *The Forest-Atmosphere Interaction.* Ed. by Hutchinson and Hicks, Reidel Publ. 421–442.

Garratt, J. R., 1978: Flux profile relation above tall vegetation. *Quart. J. Roy. Met. Soc.*, **104**, 199–211.

Hamotani, K., Monji, N. and Omoto, Y., 1990: Development of a short span (3cm) sonic anemometer. *J. Agr. Met.*, **46**, 143–146 (in Japanese with English abstract and figure captions).

Haugen, D. A., Kaimal, J. C. and Bradley, E. F., 1971: An experimental study of Reynolds stress and heat flux in the atmospheric surface layer. *Quart. J. Roy. Met. Soc.*, **97**, 168–180.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y. and Coté, O. R., 1972: Spectral characteristics of surface layer turbulence. *Quart. J. Roy. Met. Soc.*, **98**, 563–589.

Monji, N., Inoue, M., Hamotani, K. and Omoto, Y., 1993: Turbulent exchange of water vapor and CO_2 over a coniferous forest. *J. Agr. Met.*, **48**, 699–702.

Munn, R. E., 1966: *Descriptive micrometeorology.* Academic Press, 163.

Shaw, R. H., 1977: Secondary wind maximum inside plant canopies. *J. Appl. Met.*, **16**, 514–521.

Shaw, R. H., Paw U, K. T., Zhang, X. J., Gao, W., Hartog, G. D. and Neumann, H. H., 1990: Retrieval of turbulent pressure fluctuations at the ground surface beneath a forest. *Boundary-Layer Met.*, **50**, 319–338.

Tsukamoto, O., 1986: Dynamic response of the fine wire psychrometer for direct measurement of water vapor flux. *J. Atmos. Ocean. Tech.*, **3**, 453–461.

Verma, S. B., Baldocchi, D. D., Anderson, D. E., Matt, D. R. and Clement, R. J., 1986: Eddy fluxes of CO_2 water vapor and sensible heat over a deciduous forest. *Boundary-Layer Met.*, **36**, 71–91.

針葉樹林における顕熱および水蒸気輸送の群落上と群落内の比較

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要　　約

森林群落上と群落内における顕熱と潜熱の乱流輸送特性の比較を，樹高が最大約18mのアカマツとヒノキの混交林において行った。群落内では顕熱および潜熱フラックスは群落上の値と比べて1/10程度の小さな値であった。温度や比湿の変動の標準偏差は，群落上と群落内で同程度であるが，それらと鉛直風速との相関係数は群落内では群落上の1/5程度であった。鉛直風速のパワースペクトルは群落上では裸地や背の低い群落上と同じ形状を示したが，群落内では慣性小領域を欠き，しかも高周波数側に植物体のウェークによると考えられるエネルギー生成領域が認められた。顕熱と水蒸気のフラックスのコスペクトルは群落上では互いに類似した形状を示した。同じ場所で別の時期に得られたCO_2フラックスのコスペクトルも顕熱と水蒸気の輸送フラックスのコスペクトルと類似の形状を示しており，スカラー量はすべて同じメカニズムで輸送されることが示唆された。一方，森林群落の内部では，これらスペクトルの間に相似性は認められなかった。

キーワード： 顕熱フラックス，コスペクトル，針葉樹林，水蒸気フラックス