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Amplitude and seasonality of storage fluxes for CO_2, heat and water vapour in a temperate Japanese cypress forest

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ABSTRACT

Storage fluxes of CO_2, air temperature and relative humidity were measured in a temperate Japanese cypress forest for 3 yr. The 3-yr means of diurnal storage fluxes of CO_2 (S_c), latent heat (Q_a) and sensible heat (Q_w) ranged from −1.3 to 1.2 μmol m^{-2} s^{-1}, −9 to 12 W m^{-2} and −2 to 5 W m^{-2}, respectively. The mean diurnal eddy fluxes of CO_2 (F_c), sensible heat ($\boldsymbol{H}$) and latent heat ($\boldsymbol{\lambda E}$) ranged from −13.1 to 2.6 μmol m^{-2} s^{-1}, −37 to 187 and 7 to 146 W m^{-2}, respectively. The variation and amplitude of diurnal changes in S_c, Q_a and Q_w were generally similar to those reported for other forests. However, the amplitude of diurnal changes in S_c was much smaller than that of tropical rain forests. The amplitudes of diurnal changes in S_c and Q_w in summer were larger than those in winter, although the amplitude of Q_a exhibited no clear seasonal variation. This was likely because of the small seasonal change in the source (sensible heat exchange) in comparison with CO_2 and latent heat exchange.

1. Introduction

CO_2 and energy exchange between forests and the atmosphere has been studied at numerous sites using the eddy covariance method (e.g. Aubinet et al., 2000; Wilson et al., 2002). These studies determined approximate values of CO_2 and energy exchange; however, it is generally considered that CO_2 and energy exchanges consist of eddy flux, storage flux and advection flow (e.g. Lee, 1998). The estimation and understanding of storage flux, as well as advection flow, are essential to estimate CO_2 and energy exchange with accuracy. In addition to eddy flux observations, short-term profile measurements of CO_2, air temperature and relative humidity have been used to estimate CO_2, sensible heat and latent heat storage fluxes (McCaughey and Saxton, 1988; Vogt et al., 1996; Jarvis et al., 1997; Silberstein et al., 2001; Dolman et al., 2002; Turnipseed et al., 2002). Such data are required from many forest types to understand how climate, vegetation type and canopy structure characteristics such as height and leaf area index (LAI; m^2 m^{-2}) influence storage fluxes. Moreover, long-term observations are also useful to understand how meteorological conditions such as seasonality influence storage fluxes. However, few studies have analysed storage fluxes using detailed profile measurements taken over a long period of time (Oliphant et al., 2004).

We established continuous profiles of CO_2 concentration, air temperature and relative humidity for 3 yr in a temperate Japanese cypress forest. We also assessed the contribution of advection flow to: (i) CO_2 gas exchange at night by comparing it with automated closed chamber measurements of ecosystem respiration (Ohkubo et al., 2007) and (ii) evapotranspiration using the water budget method (Kosugi and Katsuyama, 2007) and energy closure (Kosugi et al., 2007). Profiles were taken in parallel with eddy covariance measurements over the canopy to examine the amplitude, as well as diurnal and seasonal patterns, of storage fluxes in comparison with other sites.

2. Materials and methods

2.1. *Site description*

The study site was located in the Kiryu Experimental Watershed (34°58′N, 136°00′E) in Shiga Prefecture, Japan. The watershed covers 5.99 ha and ranges in elevation from 190 to 255 m. A meteorological observation tower is located in a 0.68-ha catchment within the experimental watershed, which is mainly covered by *Chamaecyparis obtusa* Sieb. et Zucc. (Japanese cypress, an evergreen conifer) that was planted in 1959 (19 m canopy height, 46 m^2 ha^{-1} basal area and 1629 stems ha^{-1} for 93% of the total basal area). *Pinus densiflora* Sieb. et Zucc. and several

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deciduous broadleaved tree species are sparsely distributed throughout the area. In recent years, pine-wilt disease has decreased the *P. densiflora* stands (Hobara et al., 2001). *Eurya japonica* Thunb. dominates the forest floor. The LAI, measured using a plant canopy analyser (LAI-2000; Li-Cor, Lincoln, NE, USA), ranges from 4.5 to 5.5, with little seasonal fluctuation.

The site experiences a warm temperate climate. Precipitation occurs throughout the year, peaking in the summer, with some snowfall occurring during the winter. The mean annual air temperature and precipitation from 1997 to 2006 were 13.5 °C and 1611 mm, respectively. The mean annual air temperature in 2004, 2005 and 2006 was 13.9, 13.0 and 12.9 °C, respectively. The annual precipitation in 2004, 2005 and 2006 was 1797, 1150 and 1850 mm, respectively. The area generally exhibits a mild northward inclination of approximately 9.2°. Winds flow mainly from the north during the day and from the south at night. The forest fetch in the northwest direction was approximately 750 m, whereas fetches in the other directions exceeded 2000 m. Based on the model by Schuepp et al. (1990), the percentages of data for which >80% of the measured CO_2 flux can be expected to come from within the actual forest are 92% during the daytime and 81% during the nighttime (Takanashi et al., 2005). Other studies at this site have provided additional information regarding the estimation of biomass heat storage (Wada et al., 2002), evapotranspiration (Takanashi et al., 2003; Kosugi and Katsuyama, 2007; Kosugi et al., 2007), CO_2 flux (Takanashi et al., 2005), soil respiration (Mitani et al., 2007) and a comparison of ecosystem respiration and nighttime eddy covariance CO_2 flux (Ohkubo et al., 2007).

2.2. Measurements

Eddy fluxes of CO_2 (F_c; μmol m^{-2} s^{-1}), sensible heat and latent heat ($\boldsymbol{H}$ and $\boldsymbol{\lambda E}$; W m^{-2}) above the canopy were measured using the eddy covariance method at a tower height of 28.5 m. A three-dimensional sonic anemo-thermometer (DA-600T; Kaijo, Tokyo, Japan) was used to measure air temperature and three-dimensional wind speed. A fast-response, open-path infrared gas analyser (IRGA; LI-7500; Li-Cor) was used to measure water vapour and CO_2 molar density. Analog signals from the sonic anemo-thermometer and IRGA were sampled using a data logger (CR23X; Campbell Scientific, Logan, UT, USA) at 10 Hz and sent to a personal computer. Raw data were transferred to the laboratory approximately every 2–3 weeks.

The CO_2 concentration was measured at five heights for the vertical profile: 0.3, 1, 4, 14 and 20 m. Sampled air from each of the inlets was measured using a closed-path IRGA (LI-6251 or LI-7000, Li-Cor) and an automated closed dynamic chamber system (HT-CL-PT311, Hydrotech, Shiga, Japan). The chamber system measured ecosystem respiration in addition to vertical CO_2 concentration. The chamber measurement was not related to this study. CO_2 concentration profile measurements were recorded for 15 min every 30 min. The remaining 15 min were used to conduct chamber measurements. The sampling height was changed automatically, and the duration of intake at each height was set depending on the distance of each inlet from the IRGA. Air was sampled through a polyethylene tube (4 mm inner diameter) using a sampling pump (APN-085, Iwaki Pumps, Tokyo, Japan) and controlled using a mass flow controller (PAC-D2-SEC-400 MK3, STEC, Kyoto, Japan or MPC0005, Yamatake, Tokyo, Japan) at a flow rate of 1.8 L min^{-1}. For the vertical density profile, a purge pump sampled all air, except measured sample air, continuously at all heights. Sampled air was dehumidified using a gas dryer (MD-110-48F, GL Science, Tokyo, Japan) and then released. For the LI-6251 (1 January 2004–4 February 2004), we replaced the IRGA every 2–3 weeks and returned it to the laboratory for calibration. For the LI-7000 (4 February 2004–31 December 2006), the zero offset of the IRGA was checked against nitrogen gas every day at 12:15. We changed the chemical desiccant [$Mg(ClO_4)_2$] and soda lime in the reference cell of the IRGA every 2–3 weeks. The CO_2 concentration was logged every 2 s using a data logger (CR10X; Campbell Scientific). Considering the time from each inlet to the IRGA, we used data from the last 14 s for each cycle (2.5 min). We collected these data six times and calculated the average at each height for each 15 min.

The air temperature and relative humidity were measured at six heights, that is, 1, 4, 10, 14, 20 and 29 m, for the vertical profile using ventilated temperature and relative humidity sensors (HMP45C, Vaisala, Boulder, CO, USA). We measured temperature and relative humidity at each height using an Assman psychrometer (Tokyo Yoshino Keisoku, Tokyo, Japan) every 2–3 weeks to calibrate the equipped sensors. Short-wave downward radiation was measured using an albedo meter (CM14, Kipp & Zonen, Saskatoon, SK, Canada) 29 m above the ground. Rainfall was measured using a tipping bucket rain gauge (RT-5, Ikeda Keiki, Tokyo, Japan) at the meteorological station near the tower. These data were logged every 15 min using a data logger (CR10X, Campbell Scientific).

2.3. Calculations

F_c, $\boldsymbol{H}$ and $\boldsymbol{\lambda E}$ were calculated using 30-min averages. The double rotation method was used to calculate the sonic anemometer velocities (McMillen, 1988). If the rotation exceeded 10°, that 30 min of flux data was rejected. Linear trends in air temperature, CO_2 and H_2O were removed. The Webb–Pearman–Leuning correction for the effect of air density fluctuations (Webb et al., 1980) was applied. Data outside a set range (e.g. caused by analog communication error) were replaced. If the out-of-range data exceeded 1% of the data for each element, then that 30 min of flux data was rejected. We checked the stationarity (Foken and Wichura, 1996; Aubinet et al., 2000) by removing the average flux data if there was a difference of more than 60% between the covariances of 30-min data sets and the data divided into six 5-min intervals.

The storage flux S_c (μmol m^{-2} s^{-1}) was calculated as

$$S_c = \int_0^{z_r} \left(\frac{\delta c}{\delta t}\right) \mathrm{d}z \quad (1)$$

(Hollinger et al., 1998), where z_r, c, t and z represent the height of the eddy flux measurement (m), the CO_2 concentration, the time (s) and the height from the ground (m), respectively. The $\delta c/\delta t$ was calculated from the difference in the averaged CO_2 densities every 30 min. We replaced the CO_2 density at eddy flux measurement height with that at 20 m. This replacement resulted in few errors in S_c, which was verified by the observation of CO_2 densities at both heights using the same measurement system during 6–11 July 2004 (unpublished data).

Storage fluxes (Q_a and Q_w: W m^{-2}) were calculated as

$$Q_a = \int_0^{z_r} \rho C_p \left(\frac{\delta T_a}{\delta t}\right) \mathrm{d}z \quad (2)$$

$$Q_w = \int_0^{z_r} \left(\frac{\rho C_p}{\Gamma}\right)\left(\frac{\delta e}{\delta t}\right) \mathrm{d}z \quad (3)$$

(e.g. McCaughey and Saxton, 1998; Turnipseed et al., 2002), where ρ, C_p, T_a, Γ and e are the air density (kg m^{-3}), specific heat (J kg^{-1} K^{-1}), air temperature (K), psychrometric constant (hPa K^{-1}) and water vapour pressure (hPa), respectively. We assumed that c, T_a and e varied linearly between the points of measurement. Finally, we determined each storage flux by calculating $\delta c/\delta t$, $\delta T_a/\delta t$ and $\delta e/\delta t$ every 30 min from the differences between the averaged values for c, T_a and e, respectively.

3. Results

3.1. CO_2 storage flux (S_c)

Monthly and 3-yr average diurnal courses in 30-min S_c from January 2004 to December 2006 are shown (Fig. 1). Figure 2a shows the summer (June–August) and winter (December–February) mean diurnal variations of S_c and F_c for 3 yr. Figure 3a shows and the August and December mean diurnal variations along the isoline of CO_2 concentrations in 2006.

The 3-yr average S_c ranged from −1.3 to 1.2 μmol m^{-2} s^{-1} and showed slight seasonal fluctuation (Fig. 1). The diurnal amplitude of CO_2 concentrations near the crown (20 m) and above the forest floor (0.3 m) were 23 and 30 ppm in August and 8 and 12 ppm in December, respectively (Fig. 3a). During the summer, the S_c ranged from −2.6 to 2.2 μmol m^{-2} s^{-1} and the F_c ranged from −16.7 to 5.7 μmol m^{-2} s^{-1}. During the winter, the

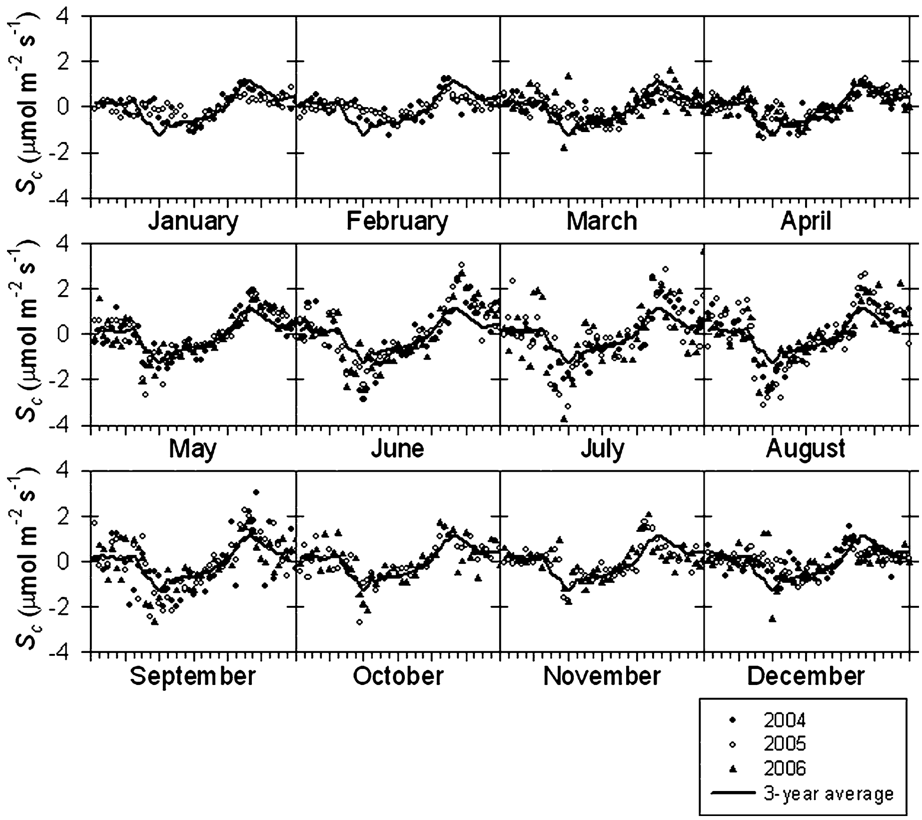

Fig. 1. Monthly and 3-yr average diurnal courses of 30-min S_c from 2004 to 2006. The plots show monthly average diurnal courses in 2004 (solid circle), 2005 (open circle) and 2006 (triangle). The line indicates the 3-yr average. No data were available for October 2004, November 2004, January 2006 and February 2006.

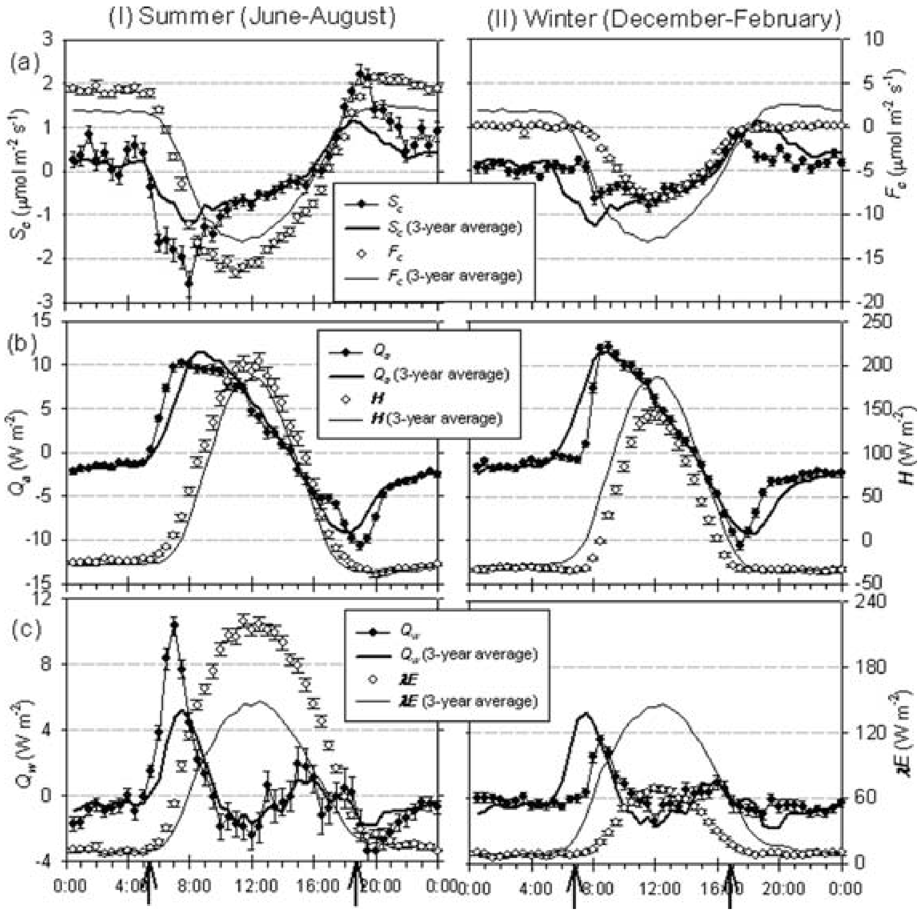

Fig. 2. Mean diurnal variation in storage fluxes in summer (June–August; I) and winter (December–February; II). Error bars indicate standard error. Arrows on the *x*-axis indicate the average time of sunrise [05:15, (I); 06:56, (II)] and sunset [18:45, (I); 16:46, (II)] throughout the year. F_c (solid circles) and S_c (open circles). $\boldsymbol{H}$ (solid circles) and Q_a (open circles). $\boldsymbol{\lambda E}$ (solid circles) and Q_w (open circles).

S_c ranged from -0.8 to 0.8 μmol m^{-2} s^{-1} and the F_c ranged from -8.2 to 0.3 μmol m^{-2} s^{-1}. The contribution of S_c to $F_c + S_c$ was small, especially during the day. The amplitudes of the diurnal changes in S_c and F_c in summer were 300 and 264% of those in winter.

The CO_2 concentrations at all heights decreased to a minimum following sunrise and then began to increase, reaching a maximum just before sunrise. The CO_2 concentration was higher near the forest floor than above the canopy because of the large efflux of CO_2 from the soil. The S_c decreased after sunrise and reached a negative peak in the morning because of absorption for photosynthesis. It began to increase again in the evening, eventually reaching a positive peak and maintaining a positive value during the night.

3.2. *Sensible heat storage flux (Q_a)*

Monthly and 3-yr average diurnal courses in 30-min Q_a from January 2004 to December 2006 are shown in Fig. 4. Figure 2b shows the summer (June–August) and winter (December–February) mean diurnal variations of Q_a and $\boldsymbol{H}$ for 3 yr. Figure 3b shows and the August and December mean diurnal variations of the isoline of air temperature in 2006.

The 3-yr average Q_a ranged from -9.2 to 11.6 W m^{-2} and showed very little seasonal fluctuation (Fig. 4). The diurnal amplitude of air temperature near the crown (20 m) and above the forest floor (1 m) was 8.4 and 6.0°C in August, and 4.6 and 3.8°C in December, respectively (Fig. 3b). During the summer, the Q_a ranged from -11 to 10 W m^{-2} and $\boldsymbol{H}$ ranged from -40 to 205 W m^{-2}. In winter, the Q_a ranged from -11 to 12 W m^{-2} and $\boldsymbol{H}$ ranged from -36 to 144 W m^{-2}. The contribution of Q_a to $\boldsymbol{H} + Q_a$ was small. The amplitudes of the diurnal changes in Q_a and $\boldsymbol{H}$ in summer were 92 and 136% of those in winter.

The air temperature at all heights increased after sunrise and reached a maximum at approximately 14:00, when there was a large vertical gradient in air temperature above the forest crown. It then decreased and remained low during the night. The Q_a increased rapidly after sunrise and reached a positive peak before it became negative at approximately 14:00, reaching a negative peak around sunset.

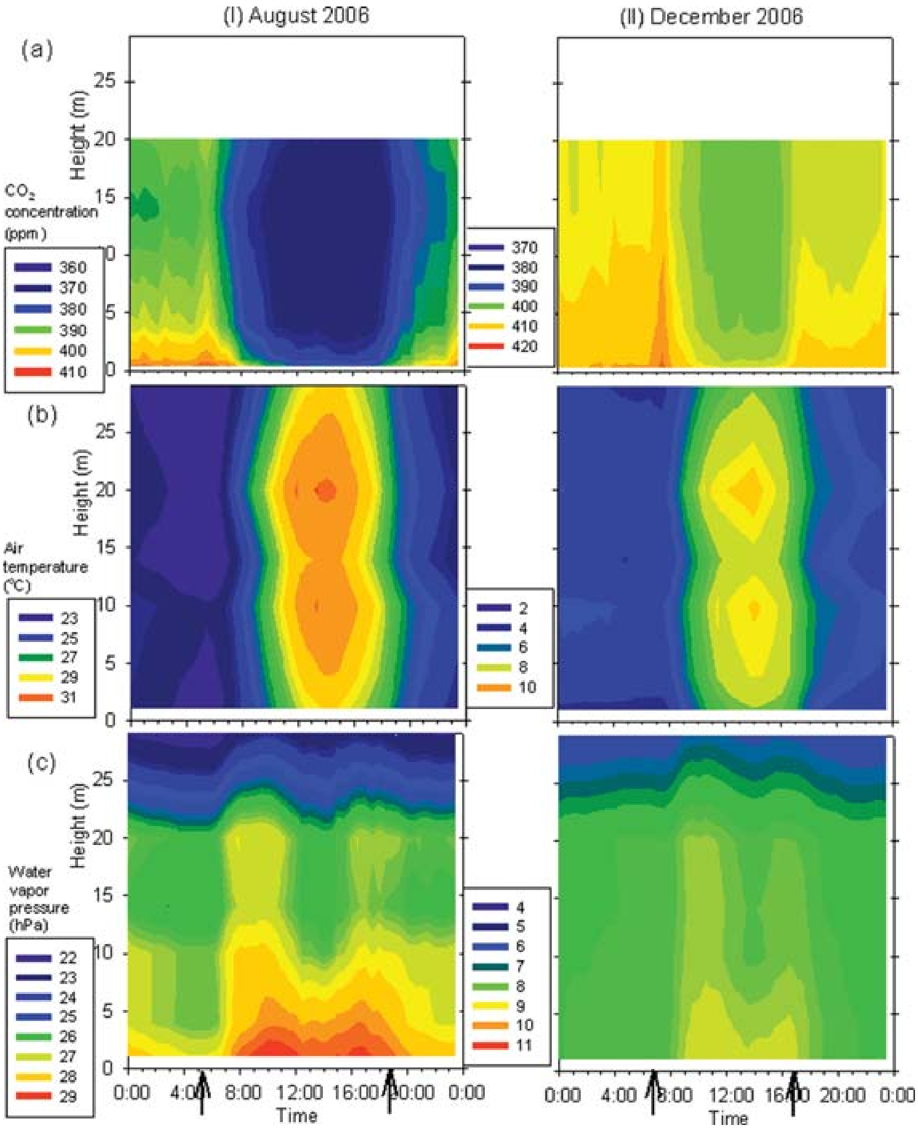

Fig. 3. Isolines of the average CO_2 (a), heat (b) and water (c) distribution within the canopy as a function of height and time of day in August (I) and December (II) 2006. The arrows are as indicated in Fig. 2.

3.3. *Latent heat storage flux (Q_w)*

Monthly and 3-yr average diurnal courses in 30-min Q_w from January 2004 to December 2006 are shown in Fig. 5. Figure 2c shows the summer (June–August) and winter (December–February) mean diurnal variations of Q_w and λE for 3 yr. Figure 3c shows the August and December mean diurnal variations of the isoline of water vapour pressure in 2006.

The 3-yr average Q_w ranged from -1.8 to 5.2 W m^{-2} and showed slight seasonal fluctuation (Fig. 5). The diurnal amplitude of water vapour pressure near the crown (20 m) and 1 m above the forest floor was 1.4 and 2.3 hPa in August, and 0.7 and 0.9 hPa in December, respectively (Fig. 3c). During the summer, the Q_w ranged from -3 to 10 W m^{-2} and λE ranged from 6 to 220 W m^{-2}. During the winter the Q_w ranged from -1 to 4 W m^{-2} and λE ranged from 6 to 69 W m^{-2}. The contribution of Q_w to $\lambda E + Q_w$ was small. The amplitudes of the diurnal changes in Q_w and λE in summer were 274 and 340% of those in winter.

The water vapour pressure increased at all heights after sunrise, decreased at midday and increased again in the early afternoon. The water vapour pressure was lowest above the canopy and highest near the forest floor throughout the day. No clear diurnal bimodal course was observed in the monthly average data. However, the 3-yr average data showed a bimodal diurnal course whereby Q_w increased after sunrise and reached a positive peak in the morning before decreasing slightly, then increased again and showed a small positive peak in the afternoon.

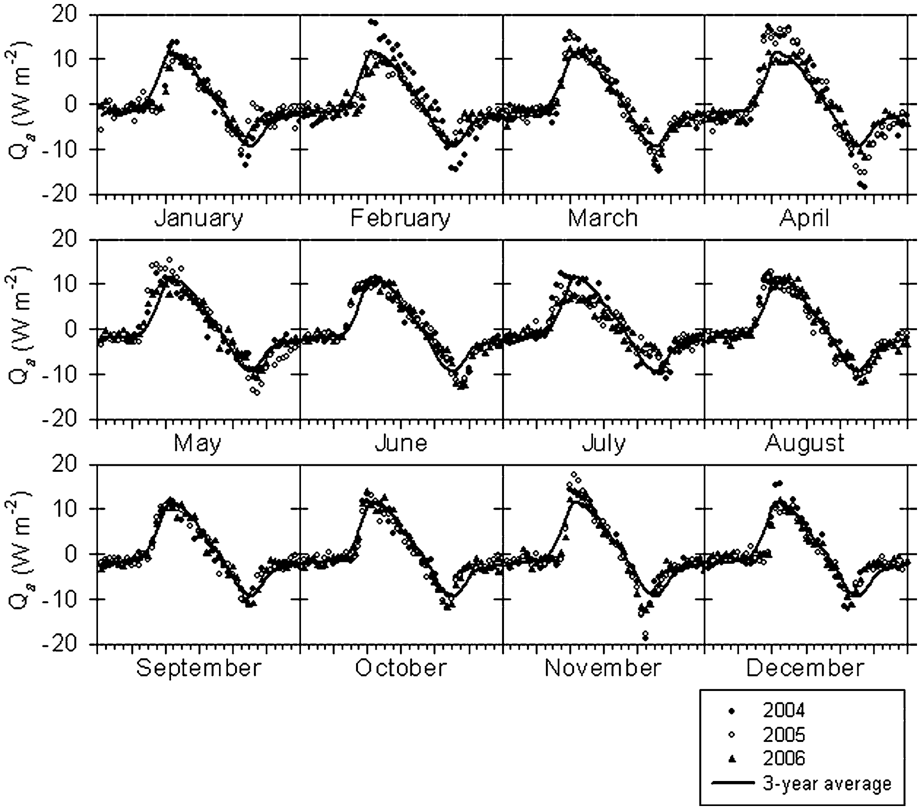

Fig. 4. Monthly and 3-yr average diurnal courses of 30-min Q_a from 2004 to 2006. The plots show monthly average diurnal courses in 2004 (solid circle), 2005 (open circle) and 2006 (triangle). The line indicates the 3-yr average.

4. Discussion

The diurnal amplitude and pattern of S_c at this site was similar to that of a boreal black spruce forest, a *Larix gmelinii* forest and a mid-latitude pine forest (Table 1). However, it was much smaller than that of a central Amazonian rain forest and a Southeast Asian rain forest (Table 1). These results suggest that climate, vegetation type and canopy structure do not strongly affect the amplitude and diurnal pattern of S_c, except in the case of tropical rain forests.

The diurnal amplitudes and patterns of Q_a and Q_w at this site were similar to those of a forest consisting of *Acer rubrum* L. and other hardwoods, a Scots pine plantation, a natural *Eucalyptus marginata* forest, a high-elevation subalpine forest and a temperate deciduous forest (Table 2). These results suggest that climate, vegetation type and canopy structure do not strongly affect the amplitudes and diurnal patterns of Q_a and Q_w within these forest types. However, we were unable to determine the difference between our values and those of tropical rain forests due to a lack of published data. In addition, the diurnal course of Q_w was similar to that recorded over a long-term study of a temperate deciduous forest (Oliphant et al., 2004). We can assume that long-term observations revealed bimodal diurnal patterns. The diurnal amplitudes of Q_a and Q_w reported by McCaughey and Saxton (1988) were slightly larger than other results, including ours; however, this is likely because of their short observation period and small number of observation heights (three) for air temperature and relative humidity profiling.

Brooks et al. (1997) described three main factors that govern the dynamics of CO_2 within a forest canopy: turbulent mixing with the atmosphere above the canopy, photosynthesis and respiration. The increased solar radiation and higher air temperatures in summer acted to increase the diurnal amplitude of S_c (Fig. 6). Conversely, the friction velocity (u_*, m s^{-1}) exhibited no remarkable difference between summer and winter.

At night, ecosystem respiration provided a large source for S_c, whereas Q_a and Q_w had small sinks/sources. Therefore, weak turbulent mixing, which mainly took place during the night, had a large effect on S_c. In the nighttime (21:00–3:00) patterns of S_c for each range of u_*, S_c decreased with increasing u_* in both summer and winter (Fig. 7). This suggests that calm conditions (i.e. at low u_*) facilitated the storage of CO_2 within the forest. Furthermore, S_c was greater during the summer than during the winter, especially at low u_*, because of the larger source of CO_2 provided by increased ecosystem respiration. The strength of a source/sink and turbulent mixing at night also controlled the vertical profile of CO_2. Low u_* and a large supply of CO_2 from soil respiration, which accounted for 48% of total ecosystem

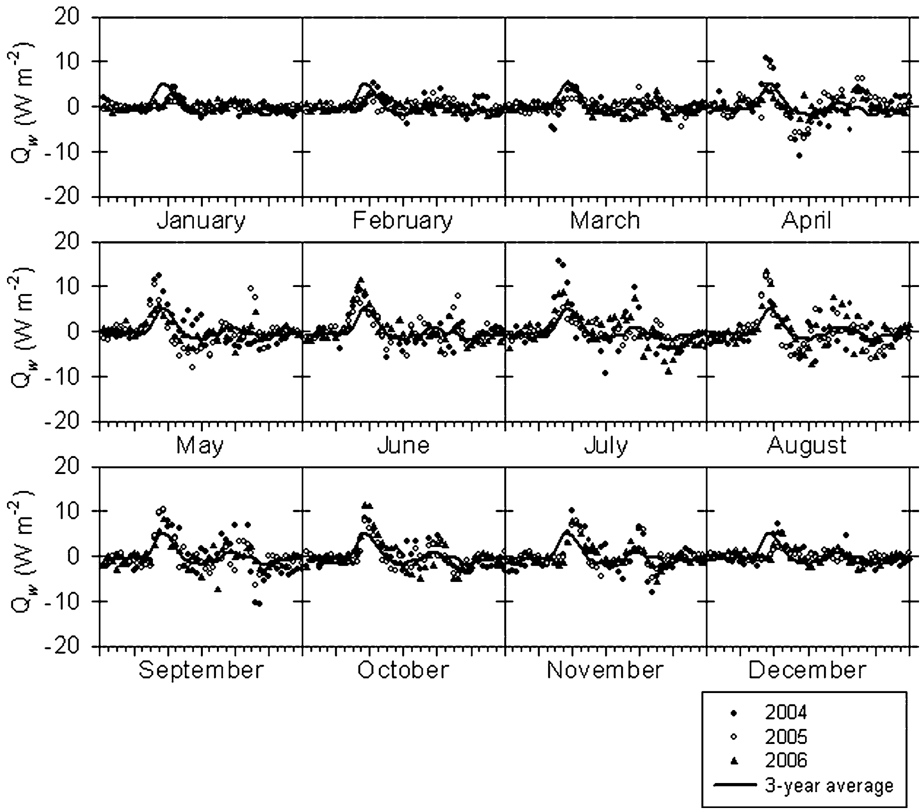

Fig. 5. Monthly and 3-yr average diurnal course of 30-min Q_w from 2004 to 2006. The plots show monthly average diurnal courses in 2004 (solid circle), 2005 (open circle) and 2006 (triangle). The line indicates the 3-yr average.

Table 1. The negative and positive peaks of S_c compared to those from other studies

	Forest type	H_c (m)	LAI (m^2 m^{-2})	Observation period	Negative and positive peaks of S_c (μmol m^{-2} s^{-1})
This study	Japanese cypress	19	4.5–5.5	3-yr average	−1.3, 1.2
				June to August (summer)	−2.6, 2.2
				December to February (winter)	−0.8, 0.8
Jarvis et al. (1997)	Boreal black spruce	10–11	4.5	May to September (114 d)	−2.5, 2.5
Hollinger et al. (1998)	*Larix gmelinii* in eastern Siberia	15–18	1.4	July (14 d)	−3.5, 2.5
Malhi et al. (1998)	Central Amazonian rain forest	30	5-6	October to December (55 d)	−12, 5
Dolman et al. (2002)	Mid-latitude pine	15.1	1.9	June to July (10 d)	−5, 3
Yasuda et al. (2003)	Tropical rain forest	35–45	6.52	March (3 d)	−14, 8

respiration at this site (Ohkubo et al., 2007), may account for the vertical CO_2 gradient at the forest floor during the night. Increasing u_* (i.e. turbulent mixing) in addition to CO_2 absorption by the vegetation might accelerate the dramatic decrease in concentration and vertical difference in CO_2 after sunrise. The nighttime u_* was in accordance with that at other sites (Hollinger et al., 1998) and was larger than that of a tropical rain forest (Malhi et al., 1998).

The amplitude of the diurnal changes in Q_w was larger in summer than in winter, which was consistent with the results of other studies (Turnipseed et al., 2002; Oliphant et al., 2004; Table 2). This could be because of the larger source (i.e. latent heat exchange) in summer. In contrast, the amplitude of the diurnal changes in Q_a was similar in summer and winter, although the sum of the stored sensible heat was larger during the summer. We can assume that the sensible heat exchange exhibited less seasonal fluctuation by comparing CO_2 and latent heat exchange. Indeed, the difference in $\boldsymbol{H}$ in summer and winter was small in comparison with the differences in F_c and $\boldsymbol{\lambda}E$ (Fig. 2). Other studies have reported larger amplitudes of diurnal changes in Q_a in summer than in winter (Turnipseed et al., 2002; Oliphant et al., 2004; Table 2). To determine the cause of this difference,

Table 2. The negative and positive peaks of Q_a and Q_w compared to those from other studies

	Forest type	H_c (m)	LAI (m^2 m^{-2})	Observation period	Negative and positive peaks of storage fluxes (W m^{-2}) Q_a	Q_w
This study	Japanese cypress	19	4.5–5.5	3-yr average	−9.2, 11.6	−1.8, 5.2
				June to August (summer)	−10.7, 10.2	−3.4, 10.3
				December to February (winter)	−10.5, 12.1	−1.4, 3.6
McCaughey and Saxton (1988)	Mixed forest in Ontario	20		4-d average	−23, 28	−34, 20
				Clear-sky conditions, May (1 d)	−27, 41	−10, 10
				Overcast conditions, May (1 d)	−23, 13	−35, 17
				Rain and variable cloud, July (1 d)	−22, 22	−70, 27
				Variable cloud, August (1 d)	−20, 37	−21, 25
Vogt et al. (1996)	Scots pine	12		May (7 d)	−10, 14	−5, 8
Silberstein et al. (2001)	Natural *Eucalyptus Marginata* (summer)	25	0.88–1.32	4-d average	−20, 25	−10, 10
				March (late summer) (2 d)	−20, 25	−10, 10
				October (mid-spring) (2 d)	−20, 25	−10, 10
Turnipseed et al. (2002)	High-elevation subalpine	11.5	3.8–4.2	20-d average	−8, 15	−4, 6
				August (summer) (10 d)	−10, 15	−5, 10
				January (winter) (10 d)	−5, 5	−2, 2
Oliphant et al. (2004)	Temperate deciduous	27		4-yr average	−12, 18	−8, 12
				August (summer), (4 months)	−15, 20	−15, 20
				December (winter), (4 months)	−8, 15	−1, 3

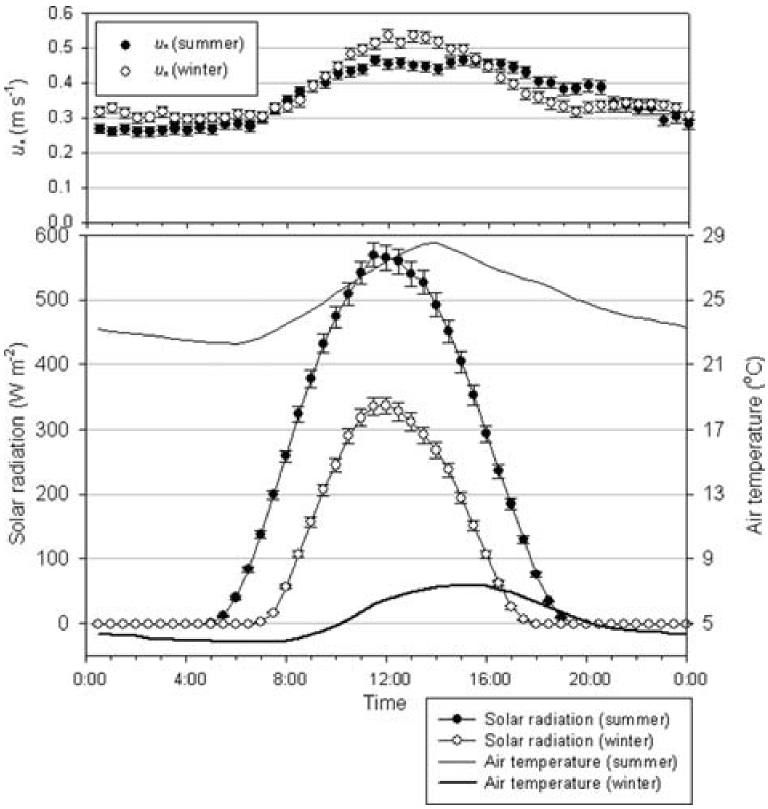

Fig. 6. Mean diurnal variation in u_* (upper panel) and in solar radiation and air temperature (lower panel) in summer (solid circle and thin line) and winter (open circle and thick line) 2006. Error bars indicate standard error.

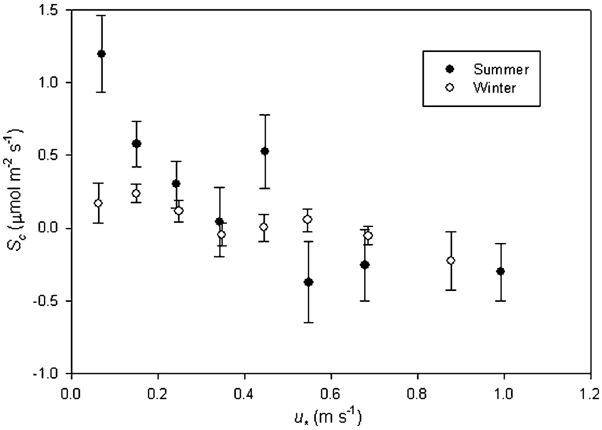

Fig. 7. Nighttime (21:00–3:00) S_c in summer (solid circle) and winter (open circle) for each range of u_*. Error bars indicate standard error.

it is necessary to conduct a comprehensive comparison of the seasonality of u_* and the source strength at each site.

5. Conclusions

We analysed the amplitude of and diurnal and seasonal changes in S_c, Q_a and Q_w based on 3 yr (2004–2006) of observations of CO_2 concentration, air temperature and relative humidity at several heights from the forest floor to the canopy top in a temperate Japanese cypress forest. The patterns of diurnal change in S_c, Q_a and Q_w were within the range of those reported in other studies, regardless of climate, vegetation type and canopy structure, with the exception of S_c in tropical rain forests. We were unable to determine the differences in the Q_a and Q_w at our site compared to those in tropical rain forests. The contributions of S_c, Q_a and Q_w to $F_c + S_c$, $\boldsymbol{H} + Q_a$ and $\boldsymbol{\lambda E} + Q_w$, respectively, were small. The 3-yr average data revealed clear diurnal variation. The diurnal amplitudes of eddy and storage fluxes in summer were generally greater than those in winter. This was likely due to seasonal differences in the source/sink strengths. Smaller seasonal differences in the amplitude of Q_a in summer and winter were likely the result of decreased seasonal variation in the source (i.e. sensible heat exchange). Seasonal changes in plant activity would also affect the storage fluxes.

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