2. Materials and Methods

2.1 Site descriptions

The experimental site is located at a permanent grassland observation field of the Environmental Research Center (ERC, renamed in April of 2000 as the Terrestrial Environmental Research Center, TERC), University of Tsukuba (lat 36°06'N, long 140°06'E, 27.0 m asl)(Fig. 1). This site was established in April of 1975 in a grassland that developed from a clearcut of a red-pine (*Pinus densiflora*) forest to monitor long-term meteorological and hydrological processes and vegetation dynamics of the grassland. The field is circular with a diameter of 160 m (*c.* 20000 m^2) and has a 30-m tall scaffolding meteorological observation tower (MOT) at the center. This facility has been widely used over the past 25 years to make field experiments, for example, TABLE92 (Hiyama et al., 1995, 1996) and IGBP-Japan (Oikawa and Liu, 1993). Research over the past two decades has focused on surface-based water and heat exchanges and investigation of vegetation, and only a few experiments were on CO_2 fluxes above the grassland (Saigusa et al., 1996, 1998).

The studied area is in a zone of marine humid climate. The mean annual air temperature is about 14.0 °C. The mean annual precipitation is about 1300 mm. The predominant wind direction is from south to north in summer and vice versa in winter. The soil is volcanic ash soil with light brown color (brown Kuroboku soil), and its depth is around 2 m (Taniguchi et al., 1989).

Vegetation dynamics of this grassland has been surveyed each year since 1993. The grassland vegetation is composed of 54 perennials (46 C3 species and 8 C4 species, see Appendix 3), and dominant species are *Solidago altissima* (C3), *Festuca arundinacea* (C3), *Imperata cylindrical* (C4), and *Miscanthus sinensis* (C4) (Liu and Oikawa, 1993;

Tanaka and Oikawa, 1999). Dynamics of the species composition demonstrates that C3 species dominate the early growing season (April and May) when air temperatures are low, but C4 species dominate in mid summer and autumn when air temperatures are high (Tanaka and Oikawa, 1999). Temperature plays a very important role in determining temporal variation in species composition within the growing season (Boutton *et al.*, 1980a, b; Cavagnaro, 1988; Hattersley, 1983; Shimada et al., 1992; Takeda and Hakoyama, 1985; Takeda et al., 1985; Teeri et al., 1980; Tieszen et al., 1979). This type of grassland is commonly found in the Kanto Plain of Japan. A view of the ERC grassland is shown in Fig. 2.

In order to keep a relatively homogeneous surface condition and also to prevent the secondary succession from a grassland to a shrub-land and finally to an evergreen broad-leaf forest (a climax primarily composed of *Quercus myrsinaefolia*), the grassland is managed by mowing once a year in late autumn or winter when most aboveground parts of the vegetation is dead (Saigusa et al., 1998). The grassland was cut down on DOY (Day of the year) 349 to 352 (15 to 18 Dec.) in 1999. Generally, the grasses are cut to heights just above the ground surface, and the cuttings are left where they fall. Hence, the ground surface is covered by the litter, which may play some roles in reducing soil evaporation. No irrigation was practiced.

Field measurements of fluxes over the ERC grassland were started in the early summer (DOY 140) and continued until early December (DOY 346) when most aboveground parts of the grasses were dead, covering most of the growing season except for the *Baiu* rainy season (DOY 167 to 204).

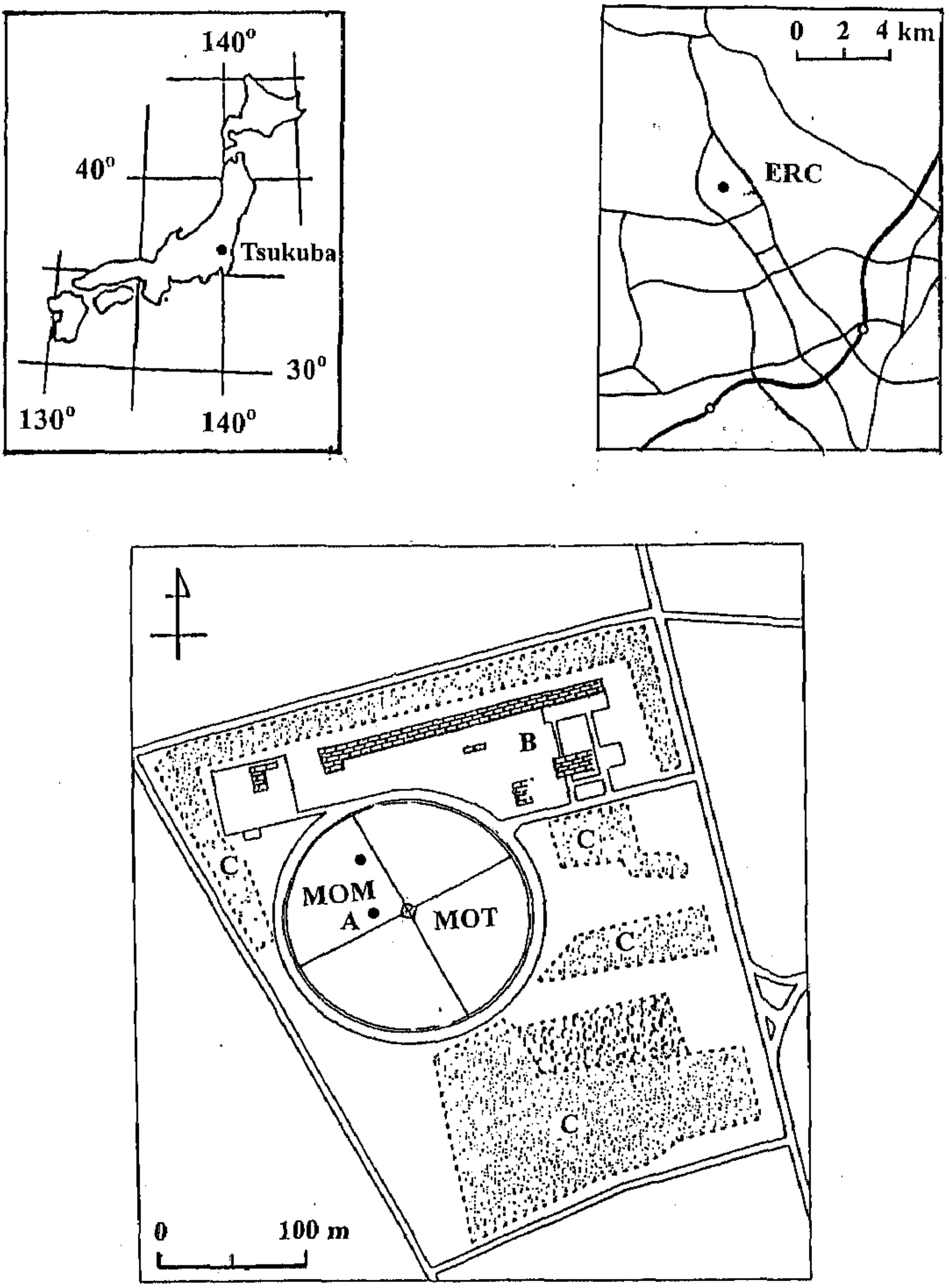

Figure 1. Location of the experiment field. MOT is the routine meteorological observation tower of the Environment Research Center, the University of Tsukuba. MOM is the micrometeorological observation mast. Two perpendicular lines across the field center are the sampling lines for vegetation investigation. Point A is the position of a weighing lysimeter. Buildings (B) and forests (C) surrounding the field are also shown.

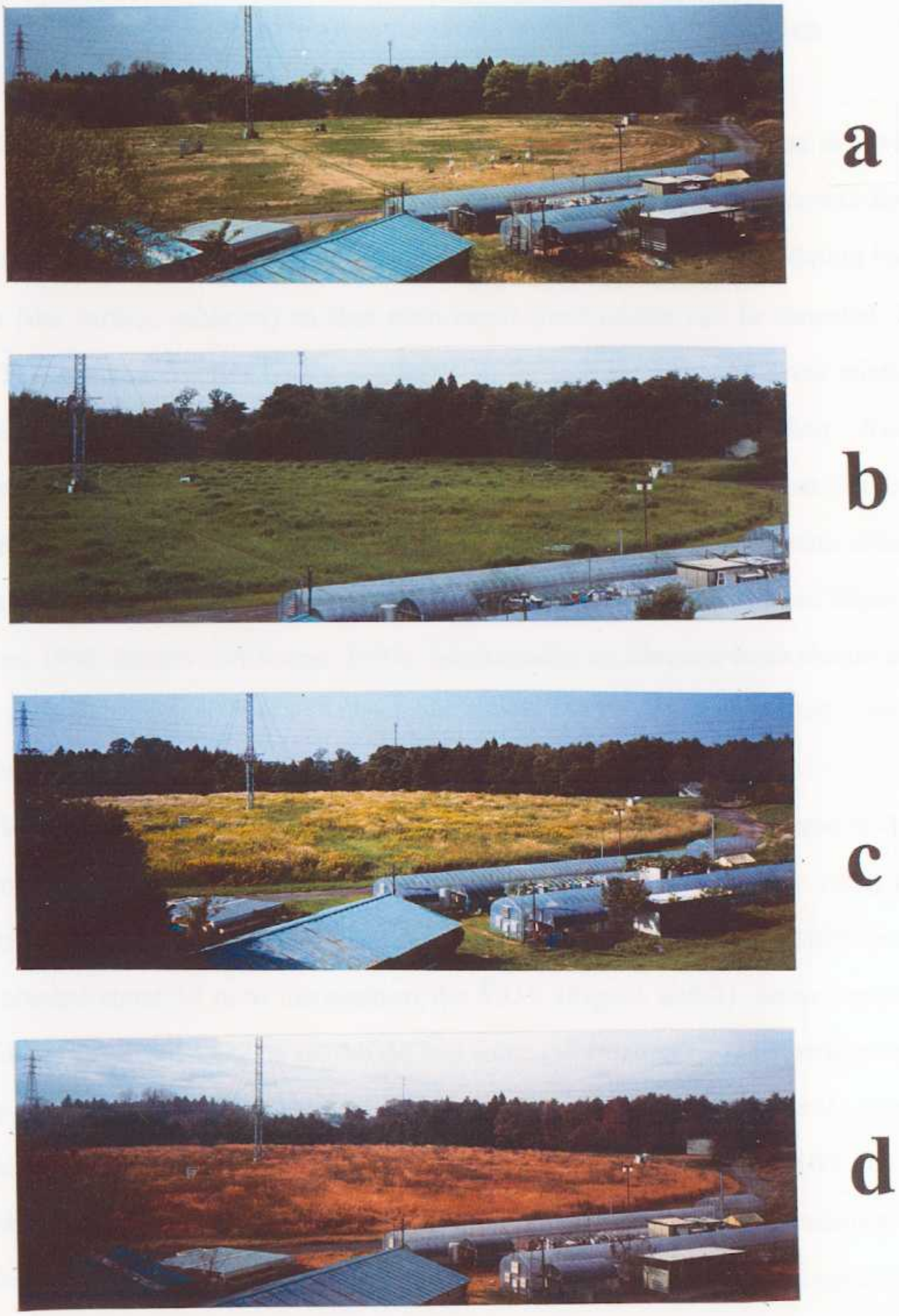

Figure 2. Photographs of the ERC grassland in different seasons of 1999. a: spring. b: summer. c: autumn. d: winter.

2.2 Measurements of canopy-scale eddy flux densities

In principle, scalar flux measurements should be conducted as close to the canopy surface as possible (Kristensen and Fitzjarrald, 1984). Therefore, the sensors for scalar flux measurements should be arrayed at an ideal height within the equilibrium boundary layer (the surface sublayer) so that even small-sized eddies can be detected. Kaimal (1975) suggested that this height is about 1 m for measurements by sonic anemometer under unstable conditions. Savage et al. (1995) concluded from their 'footprints' analysis that no statistical difference was found in the sensible heat flux density measured by the EC at heights of 0.50, 1.00 and 1.25 m. The separation distance of horizontal scalar sensors may result in underestimation of fluxes (Lee and Black, 1994; Moore, 1986; Suyker and Verma, 1993). Additionally, an adequate fetch should be taken into account in use of the EC technique (Horst, 1999; Horst and Weil, 1992,1994; Laubach et al., 1994; Schuepp et al., 1990; Stannards, 1997).

To avoid disturbance of the MOT itself on CO_2 and H_2O flux measurements, and to ensure adequate fetch for the eddy correlation measurements in the prevailing wind in the growing season, a 10 m tall micrometeorological observation mast (MOM hereafter) was erected about 50 m to the north of the MOT. (Figs. 1 and 3). Some sensors were mounted in April of 1999 on the MOM and some information on their performance and array in the field are available in Table 1. A one-dimensional supersonic anemometer/thermometer (Kaijo Denki Co., Tokyo, Japan, Model DAT-100, 20-cm path length) mounted at 2.0 m above the ground on the MOM was used to measure vertical wind speed and sensible heat flux density. A water-proof open-path fast response sensor with 20-cm path length (Advanet, Okayama, Japan, Model E900B) mounted at 2.0 m above ground on the MOM was used for CO_2/H_2O fluctuation measurements. These two sensors (both oriented toward the south) were checked and calibrated by their makers twice during the experiment. Performance of the open-path sensor was discussed in

Ohtaki and Matsui (1982) and Ohtaki (1984). To minimize underestimation of fluxes imposed by spatial sensor separation, the sensors should be placed as close to each other as possible in the field sensor array (Lee and Black, 1994). The horizontal separation distance between the vertical wind sensor and the CO_2 and H_2O analyzer was about 12 cm. The necessary response time of the sensors depends on the range of eddy sizes (surface roughness and height dependent) that carry the flux. To avoid sampling artifacts, signals must be taken at a time interval that is less than half the fastest sensor response time (Monteith and Unsworth, 1990). The signals from the eddy correlation instruments in this study were sampled at 10 Hz and recorded on a magneto-optical (MO) disk via a COMPAQ microcomputer and a data acquisition card (Keyence, Osaka, Japan, Model NR-110) for subsequent processing. The sensible heat flux density, the latent heat flux density, and the CO_2 flux density were obtained from covariances computed over 15-min averaging periods. The 15-min averaged data were further averaged over 1-hour periods to match the data measured from the MOT. Webb et al. (1980) and Leuning and Moncrieff (1990) suggest that substantial corrections should be made to the EC measurements of CO_2 flux due to the air density fluctuations resulting from simultaneous transfers of water vapor and sensible heat, the so-called density effect. Following a method described by Webb et al. (1980), values of CO_2 flux were corrected for this density effect. This correction generally amounted to 10 to 30% depending on sensible and latent heat measurements. Corrections were also performed to the latent and sensible heat flux densities but the magnitude was generally less than 1 to 3%. Other sources of errors were minimized through adequate deployment of sensors following Lee and Black (1994).

Dry- and wet-bulb air temperatures at five levels (2.18, 1.16, 0.60, 0.25, 0.12 m) were monitored using shielded, aspirated, single junction copper-constantan thermocouples (fan speed >3.5 m s-1, accuracy ±0.1 °C). The wet-bulb thermometers were covered with gauze wick wetted with distilled water. The temperature thermocouples were calibrated in a water bath against a standard thermometer before the experiment.

Three soil heat flux plates (EKO, Tokyo, Japan, Model CN-81) were triangularly buried (spacing between plates was 2 m) at a depth of 5 mm beneath the ground surface to give a spatial average of soil heat flux density; their rated accuracy was ±5% at –20 to 120 °C.

Photosynthetic photon flux density (PPFD, 0.4 to 0.7 μ m) was measured mounted 1.9 m above the canopy with a quantum sensor (Koito Industrious Ltd., Yokohama, Japan, Model IKS-25). The PPFD sensor was calibrated against the standard quantum sensor (Li-COR, Lincoln, NE, Model LI-190SB) before the measurements.

The CO_2 concentrations of four heights (2.05, 1.22, 0.59, and 0.25 m) above and within the canopy were analyzed by an IRGA (Fuji Electric, Kawasaki, Japan, Model ZRCIDE21-IEY00). It had an accuracy of ±2% at full scale per week. The air at each height was drawn continuously by a diaphragm pump (the flow meter rate is 1 L min^{-1}) through a 25 m length of polyethylene tubing (5.5 mm *i.d.*) to an electromagnetic multi-valve operated by a control unit (Akitsu Keisoku, Tokyo, Japan, Model), and finally to the IRGA for detecting. Air was continuously flowed in four tubing lines before being sampled. The air in the waiting lines was exhausted with the pumps. The inlet end of sampling tubing was oriented downward and wrapped with gauze to avoid intake of water and insects. The air was dried before reaching the IRGA. Measurement of CO_2 concentration at one height took 2 min. The sampling interval was determined based on the IRGA equilibrium time. The signals in early 110 s were not recorded for purging and equilibrating IRGA, and only the signals in the last 10 s were read. The IRGA was calibrated every one or two days against standard gases (0 ppmv CO_2/N_2 mixed gas, and 497 ppmv CO_2 gas). The analyzer was run in the absolute mode. A flow chart for the measurement of CO_2 concentration is shown in Fig. 4.

Data from the air temperature sensors, the soil heat plates, the quantum sensor, and the IRGA were sampled and recorded at 2-min intervals on a data logger (ETO, Tokyo, Japan, Model Thermodac-EF 5001A). Those data were later averaged over 1 h periods.

Table 1 Introduction of some measurement sensors on and around the micrometeorological observation mast (MOM) and their field array at the ERC grassland in 1999

Parameters	Instruments	Makers and Models	Heights or depths (cm)	Instrument resolution or accuracy
Vertical wind velocity and sensible heat flux	1-D sonic anemometer/thermometers	Kaijo-Denki, Tokyo, DA-600T	200	<0.005 m s^{-1} for wind speed and <0.025 °C for air temperature
CO_2 and H_2O fluxes	An open-path fast response sensor for CO_2/H_2O fluctuation measurement	Advanet, Okayam, E900B	200	1 ppm for CO_2 and 0.04 g kg^{-1} for H_2O
CO_2 Concentrations	IRGA	Fuji Electric, Kawasaki, ZRCIDE21-IEY00	205,122, 59,25	
Dry- and wet-bulb air temperatures	Thermocouples		218, 116, 60, 25, 12	Ventilated, fan speed > 3.5 m s^{-1}, ±0.1 °C
Soil heat fluxes	Soil heat plate	EKO, Tokyo, MF-81	-0.5, -0.5, -0.5	< ±5% at –20 to 120 °C
Photosynthetic photon flux densities	Quantum sensor	Koito Industrious LTD., Yokohama, IKS-25	186	
Wind-speeds	Hot-wire anemometer	Nihon Kagaku Kogyo, Anemomaster 6141 KANOMAX	226, 121	
Net radiation	Net radiometer	Prede, NR Lite	200	< ±3%
Canopy height	Marked poles			
Leaf area index	Canopy analyzer	Li-COR, Nebraska, LI-2000		
Photosynthesis rate	Photosynthesis system	Li-COR, Nebraska, LI-6400		± 5 µmol mol^{-1} from 0 to 1500 µmol mol^{-1} for CO_2 analyzer; ±1.0 mmol mol^{-1} from 0 to 75 mmol mol^{-1} for H_2O analyzer

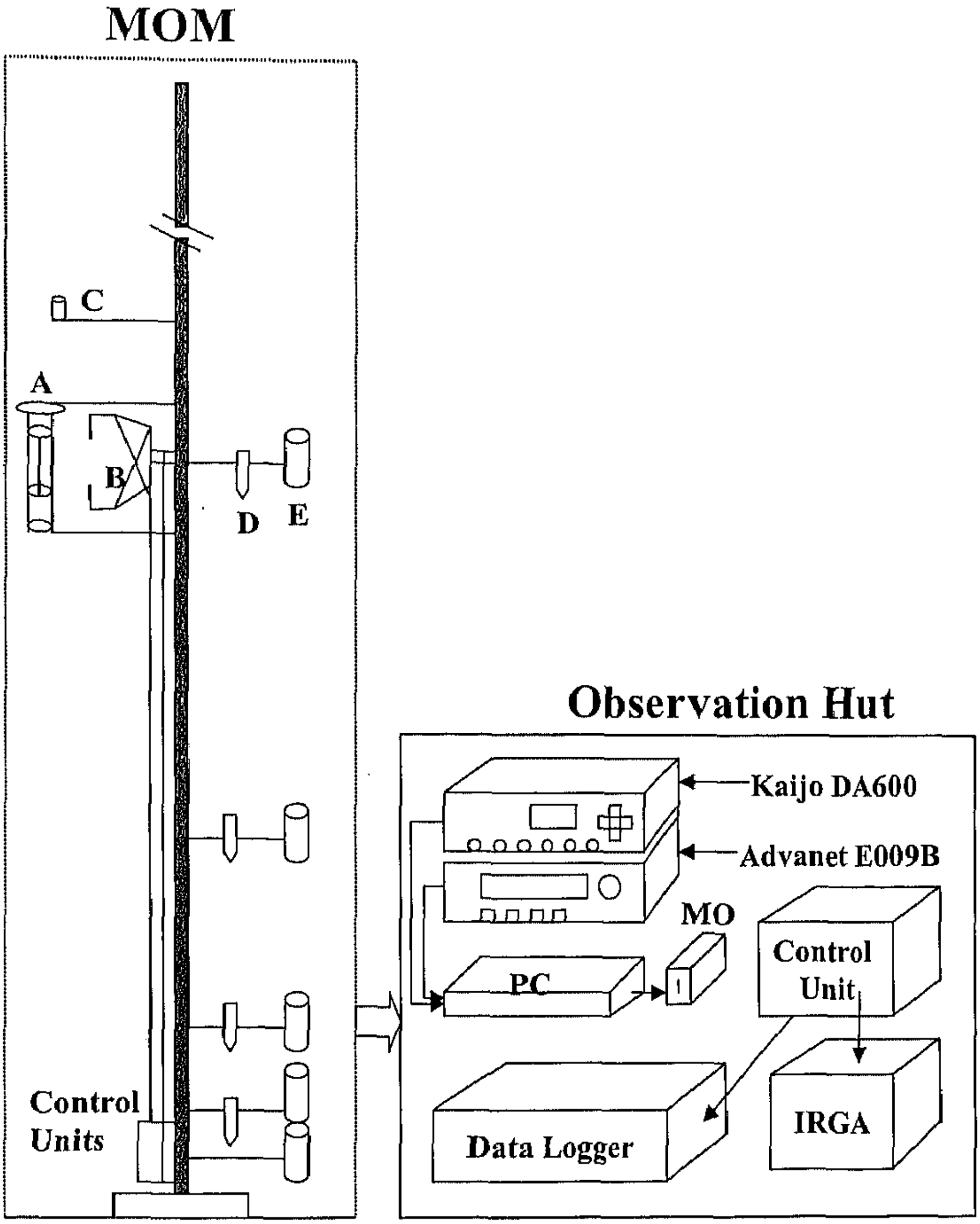

Figure 3. A schematic representation of the 10 m tall micrometeorological observation mast (MOM) on which were mounted an open-path fast response sensor for CO_2/H_2O measurements (A), an one dimensional anemometer/thermometer (B), a quantum sensor (C), 4 sampling tubes for CO_2 (D), and 5 sets of thermocouples for dry- and wet-bulb air temperature measurements (E). The detail descriptions for these sensors see the context. An observation hut was for holding computer, data logger, display units, IRGA, and other accessories.

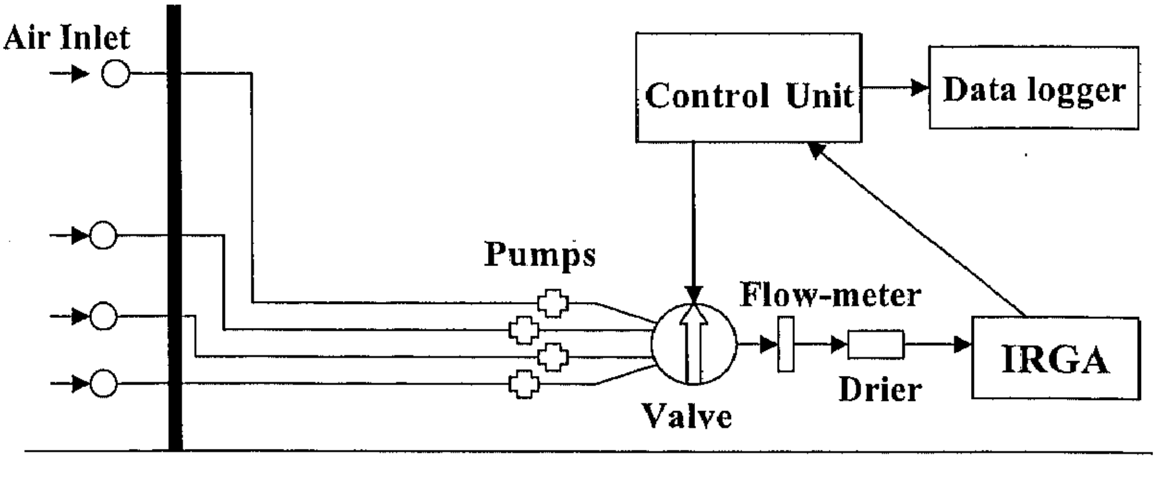

Figure 4. A flow chart shows CO_2 concentration measurements. CO_2 concentrations at four heights above ground (2.05, 1.22, 0.59, and 0.25 m) were monitored at 8 min intervals using an IRGA system.

The fetch-to-height ratio at the MOM depended upon wind direction and canopy height because the highest measurement point was fixed. In summer when the canopy was fully developed (mean canopy height *ca.* 1.0 m), it was about 130:1 in the south wind direction (prevailing summer wind direction) and only about 30:1 in the north wind direction. In winter when the grasses were dead and cut down, the fetch-to-height ratio was about 65:1 in the south wind direction (prevailing winter wind direction) and only about 15:1 in the north wind direction.

2.3 Supporting measurements of fluxes

The ERC routinely measured 32 background meteorological and hydrological variables (see Appendix 4 in detail), of which the following data were used in this study: downward shortwave radiation measured by a solarimeter (EKO, Tokyo, Japan, Model MS-43F) at 1.5 m; net radiation by a net radiometer (EKO, Tokyo, Japan, CN-11) at 1.5 m; soil heat flux by a heat flux plate (EKO, Tokyo, Japan, CN-81) at a 0.02 m depth; sensible heat flux by a 3-D sonic anemometer/thermometer (Kaijo Denki, Tokyo, Japan, PAT-311, 20-cm path length) at 1.6 m; precipitation by a tripping bucket rain gauge (Yokogawa Denshikiki, Tokyo, Japan, Model B-011-00); evapotranspiration by a weighing lysimeter (2 m in both diameter and depth, Shimazu-Seisakusho, Kyoto, Japan, Model RL-15TFA); and air temperature and dew-point temperature at 1.6 m by a ventilated platinum resistance thermometer (Ogasawara Keiki, Tokyo, Japan, Model E-731) and by a ventilated dew-point hygrometer (Yokogawa Denshikiki, Tokyo, Japan, Model E-771-10), respectively.

Maker specified maximum absolute errors were 6% for the solarimeter, 5% at –15 to 40 °C for the net radiometer, and 5% at –20 to 120 °C for the soil heat plate. The accuracy of the thermometers for air and soil measurements was ±1 °C. The accuracy of the dew-point hygrometer was ±1% at full scale. The rain gauge had an accuracy of ± 1 mm for rain rate < 20 mm h^{-1}; and ± 3% mm for rain rate < 100 mm h^{-1}. The lysimeter had an accuracy of ± 0.032 mm, and hourly mean values of evapotranspiration measured by the lysimeter were improved by replacing the measuring system since 1998 (Niimura and Sugita, 1999). The lysimeter was subject to influence of wind on instantaneous measurements. Grasses growing on the lysimeter were similar to those growing outside in terms of species composition and LAI.

Data were sampled every 0.68 s and hourly averages were calculated and stored in a portable computer (Toritani et al., 1989). Also available at ERC is the volumetric soil water content (SWC) that was monitored continuously at 2 points in the upper 15 cm of soil using two time-domain reflectometry (TDR) sensors (Campbell Scientific, Logan, Utah, Model CS615) (Higuchi et al., 1999, 2000). The fetch-to-height ratio was near 100:1 in summer when the canopy is fully developed (canopy height is *ca.* 1.0 m), and near 50:1 in winter when grasses were mowed.

2.4 Measurements of canopy height and leaf area index

Plant growth status of the grassland was monitored through measuring canopy height and leaf area during the growing season of 1999. Mean canopy height (h_c) was investigated every 10 to 20 days at 10 fixed positions with 100 measured points in all. Values of leaf area index (LAI), which was examined with a portable plant canopy analyzer (LI-COR, Inc., Lincoln, NE, Model LI-2000) at 2 to 3 week intervals on cloudy days, were correlated with the values measured by the conventional harvesting technique and an empirical linear calibration equation was obtained. The LI-2000 calculates LAI based on the measurements of light interception above and below the canopy with a 'fish-eye' optical sensor. Estimation of LAI by the LI-2000 is sensitive to field-of-view of the sensor, sky conditions and canopy structure and phenology (LI-COR, 1992). The LI-2000 underestimated LAI by about 10 to 30% when the canopy closed. This was mainly caused by the instrument's failure to accurately detect leaves close to the ground surface. The LI-2000 overestimated LAI when grasses aged because of its inability to identify senescent leaves. Overestimation of LAI was not corrected because of operational difficulties. Daily values of LAI and h_c were estimated by linear interpolation based on these measurements. Phenology of several dominant species was also monitored.

2.5 Measurements of leaf-scale fluxes

The ERC grassland is dominated by *Imperata cylindrical* (C4), *Miscanthus sinensis* (C4), *Festuca arundinacea* (C3), and *Solidago altissima* (C3). *I. cylindrical*, a perennial of Graminneae, flowers in May to June, and is distributed across Japan. *M. sinensis*, a perennial of Graminneae, flowers in July to October and is distributed across Japan and also in China and Korea peninsula. *F. arundinacea*, a perennial of Graminneae, and flowers in June to August. It is a naturalized plant introduced from Europe after World War II. This plant is still alive when other grasses are dead in winter, and its growth nearly stopped in the mid summer with higher temperatures, indicating its sensitivity to high temperature, and new leaves are often found to sprout from the ground in the late autumn when air temperature decreases. This plant did not dominate in summer except in early spring and late autumn. *S. altissima*, a perennial of Compositae, is 200 to 300 cm high, flowers in October to November and is introduced from North America in the Meiji Era.

Two sets of portable photosynthesis system (LI-COR, Inc., Lincoln, NE, Model LI-6400) were used to measure leaf-scale photosynthesis of the dominant plants. Generally, sunlit, fully expanded healthy leaves on the upper part of each species (near the top of the canopy) were used for photosynthetic measurements on a monthly basis. When monitoring their daily courses, leaves were enclosed in the cuvette with minimal disturbance to their orientation. The LI-6400 sets were calibrated with the standard gases and a dew point generator (LI-COR, Inc., Lincoln, NE, Model LI-610) following the procedure in operation manuals before measurements. The LI-6400 can measure CO_2, humidity, and leaf (T_L) and air temperatures inside the cuvette, and photosynthetical photon flux density (PPFD) inside and outside the cuvette. It output directly net photosynthesis rate (P_n), transpiration rate (TR), stomatal conductance (g_L), intercellular CO_2 concentration (C_i), vapor pressure deficit at the leaf surface (VPD_L), CO_2 concentration (C_a) etc. Air temperature, light, CO_2 and H_2O concentration in the cuvette can be automatically controlled through programming the system. An external humidity and air temperature sensor (aspirated, Vaisala Inc., Helsinki, Finland, Model Humitter 50U) was attached to the system to monitor ambient temperature and humidity and also to offer reference data to control air temperature and humidity in the cuvette. Air temperatures and vapor pressure deficit in the cuvette maintained within the same level as the ambient during the measurements. Humidity in the cuvette was controlled via a desiccant unit through which the gas flows.

2.6 Calculation

2.6.1 Flux densities

Flux can be defined as the exchange of mass or energy of any system with its surroundings. When it comes to the grassland ecosystem, flux occurs within the soil-plant-atmosphere continuum (SPAC). Practically, however, it is possible to separate SPAC into three distinct functional units: the atmospheric functional unit, the vegetation functional unit, and the soil functional unit (Fig. 5). In the present study, we investigated the fluxes to and from the grassland canopy surface, i.e. the integral fluxes at the interface between the atmospheric functional unit and the grassland canopy functional unit. We did not attempt to partition the net canopy CO_2 flux into the contributions from the plant and the soil units. The storages of atmospheric energy and atmospheric CO_2 in the canopy were also omitted.

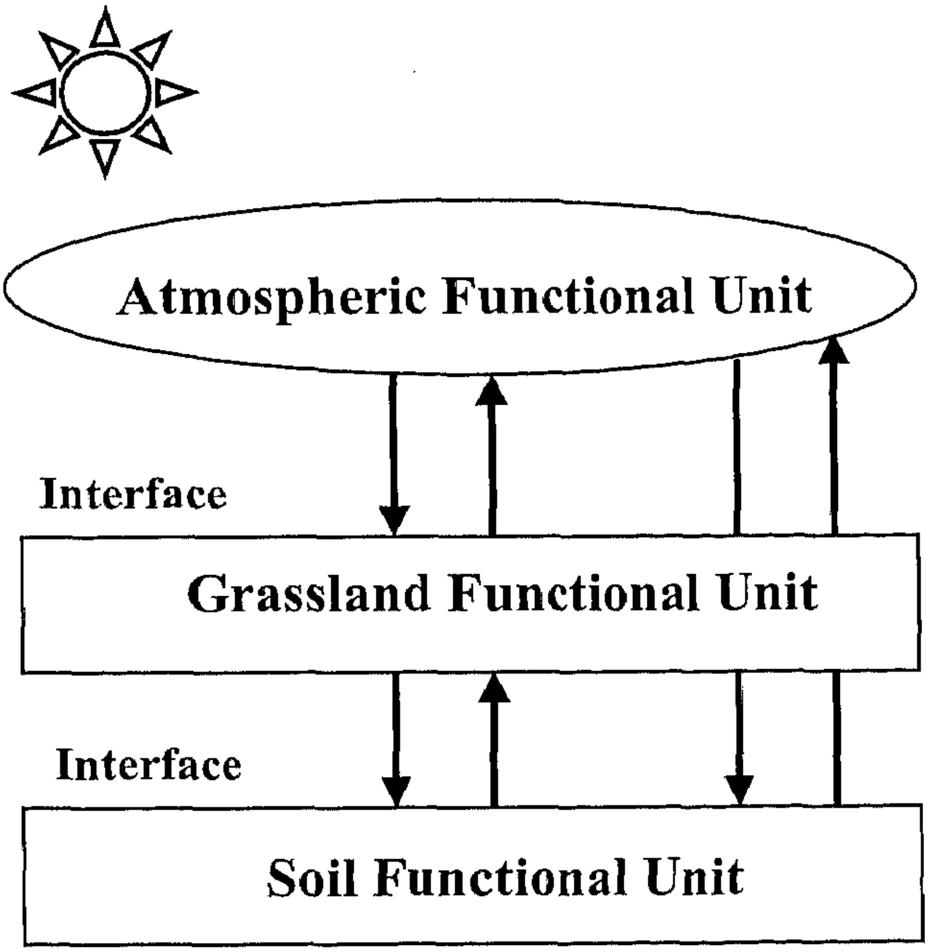

Figure 5. A schematic representation of temporal and spatial patterns in CO_2, H_2O and energy fluxes over C3/C4 co-occurring grassland at ERC

The energy budget at the grassland canopy surface can be expressed by an equation in the form (Jones, 1992; Rosenberg et al., 1989):

$$R_n - LE - H - G - P - \Delta S = 0, \qquad (1)$$

where R_n is the net radiation flux density, LE is the latent heat flux density (L is the latent heat of vaporization at air temperature, and E is the flux density of water vapor from the surface), H is the sensible heat flux density, G is the heat flux density into and out of the soil, P is the energy conversion by photosynthesis, and ΔS is the net physical storage of energy. P and ΔS are omitted in this study because they are considerably smaller in magnitude than other components. All these fluxes are expressed in units of per unit area of ground (W m^{-2}).

At present, the eddy correlation or covariance (EC) technique, firstly proposed by Swinbank (1951), is considered to be one of the best methods for monitoring canopy or ecosystem mass and energy exchange processes. The EC technique has the advantages over other micrometeorological methods (Bowen ratio and aerodynamic approaches) in its directness and accuracy, the minimal theoretical assumption of similarity, the least dependence on surface conditions, and no atmospheric stability corrections (Baldocchi et al., 1988, 2000; Dabberdt et al. 1993; Desjardins, 1991; Monteith and Unsworth, 1990; Ruimy *et al.*, 1995). According to the EC technique, the vertical flux density of any scalar quantity (F_s) is proportional to the mean covariance between the vertical wind speed fluctuation (w') and the fluctuation in scalar concentration (S'), and can be expressed in terms of (Monteith and Unsworth, 1990; Rosenberg et al., 1989):

$$F_s = \rho\, \overline{w' S'}, \qquad (2)$$

where ρ is the air density (kg m^{-3}) at a given air temperature, and overbars indicate average of the product over the sampling interval. The sensible heat flux density (H), the latent heat flux density (*LE*), and the vertical CO_2 flux density over the canopy surface (F_c), obtained by the EC technique can be computed in Eqs. (3), (4), and (5), respectively (Ruimy *et al.*, 1995).

$$H = \rho C_p \overline{w' T'}, \qquad (3)$$

$$LE = \rho L \overline{w' q'}, \qquad (4)$$

$$F_c = f \overline{w' c'}, \qquad (5)$$

where T', q', and c' represent fluctuations of air temperature, specific humidity, and CO_2 concentration, respectively; C_p is the specific heat capacity of air at constant pressure (J kg^{-1} $^oC^{-1}$) ; f is the conversion factor for CO_2 from ppm to g m^{-3}. Overbars indicate average of the product over the sampling interval.

It is necessary to integrate fluxes over a given time to understand whether mass and energy in a system is losing to (source) or acquiring (sink) from the surrounding over that time. Following Ruimy et al. (1995), the CO_2 budget at the grassland canopy surface (or net ecosystem CO_2 exchange, NEE) is computed by means of integrating the net canopy-atmospheric CO_2 flux densities over a given time as shown in Eqs. (6) to (8):

For the day: $$\mathrm{NEE_D} = \int F_c\, dt = A_c - R_D + \Delta C_D, \qquad (6)$$

For the night: $$\mathrm{NEE_N} = \int F_c\, dt = -R_N + \Delta C_N, \qquad (7)$$

For the whole day: $$\mathrm{NEE} = \int F_c\, dt = A_c - R_D - R_N + \Delta C, \qquad (8)$$

where NEE, the net ecosystem CO_2 exchange, is the integrated net CO_2 flux density above the canopy, R is the sum of soil and plant respiration, A_c is the rate of gross photosynthesis of the canopy, and ΔC is the amount of CO_2 stored in the canopy. Subscripts D and N are for daytime and nighttime. ΔC is neglected in this study. The unit for the CO_2 flux density is μmol m^{-2} (ground area) s^{-1}. Ignoring carbon storage within the canopy, F_c is equivalent to net ecosystem CO_2 exchange (NEE) (Baldocchi et al., 1997a). Hence, in the following sections, both F_c and NEE signify the same thing. The sign convention employed in this study is such that the fluxes directed toward the grassland canopy surface are positive (uptake or sink) and the fluxes directed away from the canopy surface toward the atmosphere are negative (loss or source).

2.6.2 Conductances

Aerodynamic conductance (g_a) for transfer of heat and water vapor under neutral conditions was calculated using the equation of Thom (1972):

$$1/g_a = \ln[(z - d)/z_{om}]\ln[(z - d)/z_{oh}]/k^2u, \tag{9}$$

where d is zero-plane displacement height, z_{om} and z_{oh} are the roughness parameters for transfer of momentum and sensible heat, respectively, k is von Karman's constant, and u is wind speed at the reference height z. d was assumed to be $0.67h_c$ (Brutsaert, 1982), where h_c is mean canopy height, while the roughness parameters were calculated using $z_{om} = 0.123h_c$ (Brutsaert, 1975) and $z_{oh} = 0.0123z_{om}$ (Brutsaert, 1975). No correction was made for atmospheric stability in the present study.

The Penman-Monteith combination equation (the big-leaf model) describing evapotranspiration (ET) from an extensive vegetated surface, can be written in the following form (Rosenberg et al., 1989):

$$LE = (\Delta Q_n + \rho C_p VPD\, g_a)/(\Delta + \gamma^*), \tag{10}$$

$$\gamma^* = \gamma (1 + g_a/g_c), \tag{11}$$

where LE is the latent heat flux density; Q_n is the available energy (net radiation flux density minus soil heat flux density); Δ is the slope of the saturation water vapor pressure vs. temperature curve (kg kg^{-1} ^{o}C^{-1}); C_p is the specific heat capacity of air at constant pressure (J kg^{-1} ^{o}C^{-1}); γ is the psychrometric constant (C_p/L)(^{o}C^{-1}); VPD is the air saturation vapor pressure deficit at a reference height above the canopy surface (kg kg^{-1}); g_a is the aerodynamic conductance between the effective canopy surface and the reference height at which air temperature and VPD are measured (m s^{-1}); and g_c is the canopy surface conductance (m s^{-1}). Meanings of other symbols are the same as above. Note that LE here was calculated as the residual of Eq. (1) after neglecting P and ΔS, i.e. $LE = R_n - H - G$, where R_n, H and G were obtained continuously from the measurements of the ERC Meteorological Observation Tower (MOT).

Canopy surface conductance, g_c was then calculated by rearranging Eq. (10) as follows (Baldocchi et al., 1991):

$$1/g_c = \rho c_p \, \mathrm{VPD}/(\gamma LE) + ((Q_n - LE) \;\; \Delta/(\gamma LE) - 1))/g_a. \tag{12}$$

We assumed that the stomatal conductance of individual leaves could be combined in parallel to derive the bulk canopy surface conductance (Thom, 1972). Thus, the stomatal conductance of a representative individual leaf can be computed using the following expression (Shuttleworth, 1976):

$$g_s = g_c/\mathrm{LAI}. \tag{13}$$

2.6.3 Omega factor

McNaughton and Jarvis (1983) and Jarvis and McNaughton (1986) introduced a concept to describe the coupling between the canopy and the atmosphere through rearranging Eq. (10) in terms of the omega factor (Ω), which is defined as:

$$LE = \Omega LE_{\mathrm{EQ}} + (1 - \Omega)LE_{\mathrm{IM}}, \tag{14}$$

$$LE_{\mathrm{EQ}} = \Delta Q_n/(\Delta + \gamma), \tag{15}$$

$$LE_{\mathrm{IM}} = \rho c_p g_c \mathrm{VPD}/\gamma, \tag{16}$$

$$\Omega = (\Delta + \gamma)/(\Delta + \gamma^*), \tag{17}$$

where LE_{EQ} is the equilibrium evapotranspiration rate depending only on Q_n, and LE_{IM} is the imposed evapotranspiration rate depending on VPD and g_c. Definitions for other symbols are the same as above. The values of Ω vary between 0 (for perfect coupling) and 1 (for complete isolation); they signify the contribution of LE_{EQ} or LE_{IM} to LE as well as roles of g_c in evapotranspiration. Ω is close to 1, the latent heat flux proceeds at its equilibrium rate LE_{EQ} and is independent of stomatal conductance. When Ω approaches zero, the latent heat flux is strongly determined by stomatal conductance and the vapor pressure gradient. McNaughton and Jarvis (1983) argue that for a smoother canopy, like those of grasslands and crops, Ω is generally larger than 0.5 indicating decoupling while for a rougher canopy like forests Ω is generally less than 0.5 indicating coupling.

2.6.4 Priestley-Taylor coefficient

Another coefficient, called the Priestley-Taylor coefficient (α, defined in terms of Eq. (18)), is often used in literature to describe the contribution of actual (potential) evapotranspiration (LE) relative to the equilibrium evapotranspiration (LE_{EQ}) (Priestley and Taylor, 1972).

$$\alpha = LE/LE_{EQ}. \tag{18}$$

Values of α are reported ranging from 0.7 to 1.6 (Flint and Childs, 1991) and a value of 1.26 is universal for most wet surfaces (Brutsaert, 1982; Monteith, 1995; Stewart and Rouse, 1977).

2.6.5 Bowen ratio

Bowen ratio (β) is defined as:

$$\beta = H/LE. \tag{19}$$

2.6.6 Evaporative fraction and dryness index

Evaporative fraction (*EF*) is the ratio of latent heat flux (*LE*) to available energy (Q_n, net radiation flux density minus soil heat flux density) and the dryness index (*DI*, Smith et al., 1992) is the ratio of *LE* to net radiation flux density (R_n) as follows:

$$EF = LE/Q_n, \tag{20}$$

$$DI = LE/R_n. \tag{21}$$

2.6.7 Water use efficiency

Water use efficiency (WUE) is conventionally defined as the ratio of the assimilated CO_2 amount (photosynthesis) to the consumed H_2O amount (transpiration) (Jones, 1992).

In the field, we cannot measure canopy photosynthesis and transpiration rates directly because of the occurrence of soil evaporation (Baldocchi, 1994b). Therefore, as a surrogate for conventional WUE, instantaneous WUE of the canopy in the present study was calculated as the ratio of the net canopy CO_2 flux density (F_c) and the canopy evapotranspiration (ET) (Baldocchi et al., 1985; Baldocchi, 1994b):

$$\mathrm{WUE} = F_c/ET. \tag{22}$$

Note that WUE was not corrected for the contribution of soil respiration.

2.7 Data screening criteria

The following criteria were applied to screening adequate data sets from the measured data for calculation and analysis.

1) Data were at first selected when the fetch-to-height ratio was larger than 80:1 (except for fetch analysis), corresponding to wind direction from the sector 110° to 250°, when canopy was well developed and canopy height was about 1.0 m.

2) Data were excluded when there was rain or immediately after rain because the supersonic anemometer and the open path CO_2/H_2O analyzer are extremely sensitive to rain (causing spikes in the signals or outputting unreasonable data owing to failure of the sensors).

3) Data were rejected when sensor output signals were out of specified range or during the calibration.

4) Some missing micrometeorological data were interpolated linearly from the earlier and later measurements.

5) Hourly mean values were used for analysis in the present study.

6) In analyses of the Bowen ratio, canopy and stomatal conductances, Omega factor and Priestley-Taylor coefficient, data were excluded when the available energy ($R_n - G$)

was less than or equal zero. For comparison, only midday (09:00 to 14:00, Japanese Standard Time, JST hereinafter) mean values of these parameters were used.

Data at the MOT were available throughout the year. Data at the MOM were discontinuous because of both periodical instrument calibration and instrument malfunction (mid-June to mid-July of 1999, centered in the *Baiu* rain period).

Based on field observation of phenology of some dominant species of the grassland, data analysis periods are roughly (arbitrarily sometimes) divided into four periods: rapid growth period or period prior to canopy closure, canopy closure period, flowering period, and senescence period, which corresponded to the growth stage of the grassland.