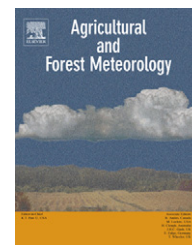


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Temporal and spatial variations in the seasonal patterns of CO₂ flux in boreal, temperate, and tropical forests in East Asia

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ABSTRACT

Measurements of net ecosystem production (NEP) over forest stands were conducted from 11 flux towers in sub-arctic, temperate, and tropical regions in East Asia between 2000 and 2005. The sites extend over a wide latitude, ranging from 3 to 64°N, and include sub-arctic and temperate needle-leaf deciduous forests (larch) (central Siberia, Mongolia, China, and northern Japan), temperate mixed, broadleaf deciduous, needle-leaf evergreen forests (northern and central Japan), and seasonal and tropical rain forests (Thailand and Malaysia).

The sub-arctic larch forests had short growing periods of 3–4 months. The temperate deciduous forests showed the greatest positive NEP after leaf expansion in early summer. Among the 11 sites, the maximum gross primary production (GPP) was observed in a temperate larch forest during the early stages of the growing period due to the high productivity of the larch species. The temperate evergreen sites displayed positive NEP earlier in the spring than the deciduous sites and had long growing periods (>10 months). The tropical seasonal forests showed negative NEP during the dry period from February to April, and turned positive after the rainy season started. The tropical rain forest showed a small flux (<30 g C m⁻² month⁻¹) throughout the year without a clear seasonal change.

In 2002 and 2003, several significant weather anomalies were observed, such as increased temperature in the temperate sites and less precipitation than average in the tropical sites in the beginning of 2002, and decreased solar radiation in the temperate sites in the 2003 summer. The seasonal patterns of NEP were sensitive to the anomalies, and the variations were caused by: (1) high spring air temperature, which induced an early start of the growing period in the temperate forests, (2) summer solar radiation, which controlled the summer GPP in the temperate forests with a slight variation among sites due to different responses of

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GPP to the temperature and water vapor pressure deficit (VPD) conditions, and (3) a long dry season, which significantly reduced GPP in a tropical seasonal forest.

The dataset, which was obtained from a wide variety of forest ecosystems in East Asia over several years, is essential to validate ecosystem models and to generate technological developments of satellite remote sensing in the distribution of the terrestrial carbon budget in Asia.

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1. Introduction

Forest ecosystems located in East Asia have several different characteristics when compared with their counterparts in the European, North, and South American continents. For example, forested areas in the East Eurasian continent exist in a wide latitude range, spreading continually from the sub-arctic, through the temperate, to the tropics (Yu et al., 2006). In addition, heat, water, and CO₂ exchanges are under the strong influence of atmospheric and water vapor circulations induced by the Asian monsoon (Kim et al., 2006). A temperature contrast between the Eurasian continent and the oceans is considered as a key factor for characterizing monsoon intensity. In addition, the influence of the Asian monsoon, which is related to El Niño Southern Oscillation (ENSO) events, has been observed in the inter-annual climatic variations of Asia, particularly land surface temperature, summer rainfall, and snow depth (Yasunari and Seki, 1992; Kitoh et al., 1999). A distinct influence of ENSO events is also observed in tropical Asian ecosystems, especially in the year-to-year change in temperature and precipitation (Malhi and Wright, 2004). After ENSO events, tropical Asian forests often experience a longer dry season. This change significantly affects the carbon and water cycles in the ecosystem and triggers the flowering of dominant species in tropical forests (Sakai et al., 2006), which are typically observed once every several years. Thus, the data gathered from the monitoring of long-term fluxes at multiple sites in addition to phenological and eco-physiological activities is indispensable for interpreting the mechanism of seasonal and year-to-year variability in heat, water, and CO₂ exchanges. This information can be applied to a wide variety of terrestrial ecosystems in Asia and used to predict long-term biological responses to climatic systems which change dynamically in the multi-year time-scale.

Recent studies using a tower flux measurement network have shown that the seasonal changes in NEP and its year-to-year variations are affected by various meteorological and biological factors, which are stated in the following. In several broadleaf deciduous forests in the boreal and temperate zones, the annual NEP is primarily controlled by the length of the growing period (Black et al., 2000; Carrara et al., 2003; Saigusa et al., 2005). Summer drought stresses greatly influence temperate ecosystems in North America and the Mediterranean region (Law et al., 2001; Irvine et al., 2002; Reichstein et al., 2002; Powell et al., 2006) while temperate forests in East Asia are relatively free from severe drought stress in summer. This difference is due to the influence of the Asian summer monsoon in the rainy season of the East Asian temperate forests during the early stages of their growing period. In addition, these forests are often exposed to natural

disasters, such as destructive typhoon storms and landslides. Unexpected defoliation caused by heavy rainstorms occasionally impacts the annual carbon budget of the forests (Ito et al., 2005). The body of knowledge on the seasonal and inter-annual variations of the carbon cycle in tropical Asian forest ecosystems based on long-term flux measurements has been increasing (Yasuda et al., 2003; Saitoh et al., 2005; Kosugi et al., 2008). However, our data and understanding of these variations in a larger spatial scale are still quite limited.

Until recently, most integrated studies based on the flux tower network were developed mainly in Europe and North America. This work revealed the seasonal patterns and annual values of the net ecosystem CO₂ exchange (NEE), GPP, and ecosystem respiration (RE) in different ecosystems (Falge et al., 2002; Reichstein et al., 2005; Amiro et al., 2006; Coursolle et al., 2006; Owen et al., 2007). In Asia, studies have been started to clarify the control factors of the seasonal change and annual values of NEE based on the data obtained at several flux sites (Yamamoto et al., 2005; Yu et al., 2006). Few studies, however, have been reported using Asian ecosystems to generalize our understanding of the temporal and spatial variability of NEE, GPP, and RE from a dataset consisting of multiple sites over several years.

Thus, the objectives of the present study are: (1) to describe important characteristics of seasonal and inter-annual changes in NEP, GPP, and RE during the 2000–2005 employing more than 10 flux observation sites in sub-arctic, temperate, and tropical forests in Asia, and (2) to demonstrate how ecosystems respond to meteorological anomalies widely observed in East Asia during this same period. The results of three case studies will be presented. The first case exhibited less solar radiation in the mid-latitude temperate zone in the summer of 2003. Next, the warm winter of 2002 with unusually high air temperature in northeastern Asia and, lastly, the long dry period in tropical southeastern Asia at the beginning of 2002.

2. Methods

2.1. Study sites

The present comparative study consists of 11 forest sites in East Asia. Four deciduous coniferous forests (larch) in the high- and mid-latitudes are in the study, i.e., a sub-arctic larch forest in a continuous permafrost region of central Siberia, Russia (the site name is Tura; the abbreviated site code is TUR), a sub-arctic larch forest in a mountainous region in Mongolia (Southern Khentei Taiga; SKT), a planted temperate larch forest in northeastern China (Laoshan; LSH), and a planted temperate larch forest in Hokkaido, Japan (Tomakomai Flux

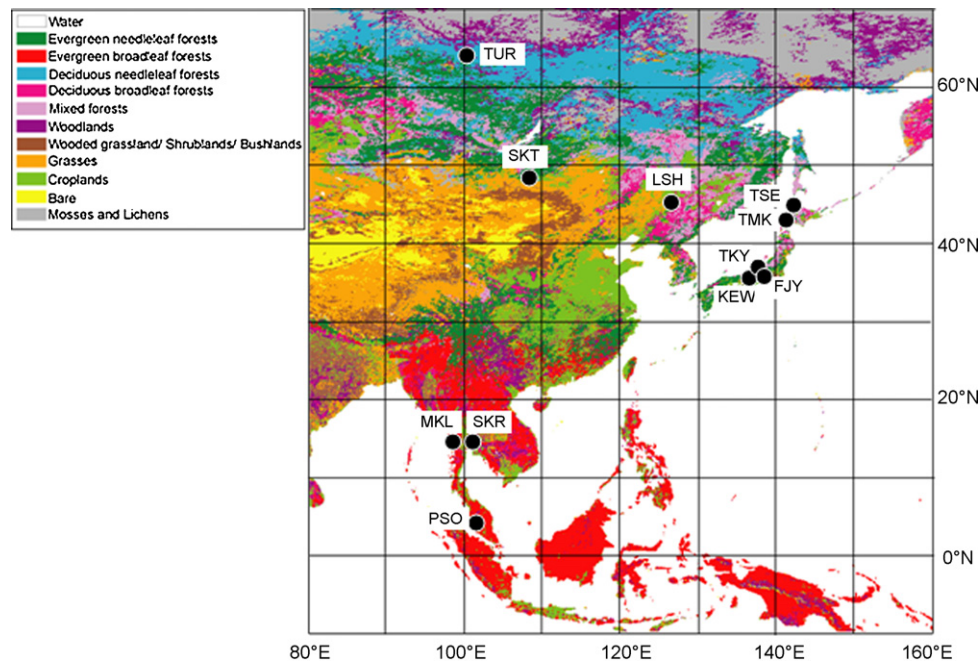


Fig. 1 – Location of study sites in East Asia plotted on a land classification map illustrated according to De Fries et al. (1998).

Research Site, TMK). Four temperate mid-latitude forests are also in the study, i.e., an old conifer-hardwood mixed forest in Hokkaido, Japan (CC-LaG Experiment Site, Teshio; TSE); a birch-oak secondary forest in central Japan (Takayama; TKY); a red pine forest in central Japan (Fujiyoshida Forest Meteorology Research Site; FJY) and a planted Japanese cypress forest (Kiryu Experiment Watershed; KEW) in central Japan. In the low-latitude, three tropical dipterocarp forests were selected, a tropical mixed deciduous forest (Mak Klong; MKL) and a tropical dry evergreen forest (Sakaerat; SKR) in Thailand, and a tropical rain forest (Pasoh Forest Reserve; PSO) in Malaysia. MKL and SKR are two seasonal forests. The locations of the study sites are shown in Fig. 1. The ecosystem type, dominant species, and approximate age are described in Table 1 and the climatic conditions are presented in Table 2.

2.2. Measurement system

Continuous long-term flux observations were performed at each site with the exception of TUR and maintained by different research organizations. The observation at TUR (central Siberia) was only conducted during the summer from June to September. All sites had an eddy covariance measurement system installed on a tower, which consisted of a three-dimensional sonic anemometer-thermometer, an infrared gas analyzer (IRGA) for CO₂ and water vapor, and a data acquisition system. Open and closed-path IRGAs were utilized depending on the site. Continuous high frequency (mostly from 5 to 10 Hz) data were recorded and the covariance was calculated at 30 min intervals. To test the energy balance closure and to monitor basic environmental variables, net radiation (or downward and upward short- and long-wave radiation), photosynthetically photon flux density

(PPFD), ground heat flux, vertical profiles of air temperature, humidity, CO₂ concentration, and vertical profiles of soil temperature, and volumetric soil water content were measured at most sites. The measurement systems for each site as used in the study period are listed in Table 3.

2.3. Data processing and gap filling

The net ecosystem CO₂ exchange was estimated from the CO₂ flux over the canopy, taking into account the temporal change in CO₂ storage below the height of the flux measurement system. The total RE was estimated by the nighttime NEE with data filtering by the friction velocity (u_*). The threshold values of u_* -filtering were determined by Hirata et al. (2008) and varied slightly among sites as listed in Table 3. Site-specific differences to mitigate the effects of nighttime NEE in the estimation of RE are described in Appendix A.

For the present study, the observed nighttime NEE were fitted to the equation of Lloyd and Taylor (1994):

$$F_{RE} = F_{RE,T_{ref}} \exp \left\{ \frac{E_0}{R} \left(\frac{1}{T_K + T_{ref} - T_0} - \frac{1}{T_K + T_a - T_0} \right) \right\}, \quad (1)$$

where $F_{RE,T_{ref}}$ is the ecosystem respiration rate (F_{RE}) at the reference temperature T_{ref} (10 °C), E_0 is the activation energy ($J mol^{-1}$), R is the ideal gas constant ($8.314 J mol^{-1} K^{-1}$), T_K and T_0 are constants (273.15 K and 227.13 K), and T_a is the air temperature (°C). The two regression coefficients, E_0 and $F_{RE,T_{ref}}$, were estimated for every site and each day with a 29-day moving window using the least-squares method. Gaps in the nighttime NEE were filled by Eq. (1) as a function of the nighttime air temperature.

Table 1 – Description of the study sites

Code	Site name	Country	Location (°N, °E)	Elevation (m)	Ecosystem type	Dominant species	Age (year)	Canopy height (m)	References
TUR	Tura	Russia	64° 12', 100° 27'	250	DC	Larch (<i>Larix gmelinii</i>)	105	3	Kajimoto et al. (2006); Nakai et al. (in press)
SKT	Southern Khentei Taiga	Mongolia	48° 21', 108° 39'	1630	DC	Larch (<i>Larix sibirica</i>)	70–300	20	Li et al. (2005)
LSH	Laoshan	China	45° 20', 127° 34'	370	DC	Larch (<i>Larix gmelinii</i>)	35	18	Wang et al. (2005a)
TSE	CC-LaG Experiment Site (Teshio)	Japan	45° 03', 142° 06'	70	MX	Oak (<i>Quercus crispula</i>), Birch (<i>Betula ermanii</i>), Fir (<i>Abies sachalinensis</i>)	–	18–25	Koike et al. (2001); Takagi et al. (2005)
TMK	Tomakomai Flux Research Site	Japan	42° 44', 141° 31'	140	DC	Larch (<i>Larix kaempferi</i>)	45	16	Hirano et al. (2003); Wang et al. (2004)
TKY	Takayama	Japan	36° 08', 137° 25'	1420	DB	Birch (<i>Betula ermanii</i>), Oak (<i>Quercus crispula</i>)	50	15–20	Saigusa et al. (2002)
FYJ	Fujiyoshida Forest Meteorology Research Site	Japan	35° 27', 138° 46'	1030	EC	Red pine (<i>Pinus densiflora</i>)	90	20	Ohtani et al. (2005)
KEW	Kiryu Experiment Watershed	Japan	34° 58', 135° 59'	250	EC	Japanese cypress (<i>Chamaecyparis obtusa</i>)	45	18	Takanashi et al. (2005a); Ohkubo et al. (2007)
MKL	Mae Klong	Thailand	14° 35', 98° 51'	160	TR	Dipterocarp (<i>Shorea siamensis</i>)	–	30	Gamo et al. (2005)
SKR	Sakaerat	Thailand	14° 29', 101° 55'	535	TR	Dipterocarp (<i>Hopea ferrea</i>)	–	35	Kondo et al. (submitted)
PSO	Pasoh Forest Reserve	Malaysia	2° 58', 102° 18'	75–150	TR	Dipterocarp (<i>Hopea ferrea</i>)	–	35–45	Kosugi et al. (2008); Takanashi et al. (2005b)

Description of ecosystem type: DC, deciduous coniferous forest; MX, mixed forest; DB, deciduous broadleaf forest; EC, evergreen coniferous forest; TR, tropical forest.

The observed daytime NEE ($F_{NEE,day}$) were fitted to the following equation based on the non-rectangular hyperbola relationship (Thornley, 1976) as a function of PPFD (Q):

$$F_{NEE,day} = - \frac{\phi Q + P_{max} - \sqrt{(\phi Q + P_{max})^2 - 4\phi Q \theta P_{max}}}{2\theta} + R_d \quad (2)$$

Here, ϕ is the initial slope, P_{max} is the maximum level of GPP at light saturation, θ (=0.9) is a parameter of convexity, and R_d is the intercept. The regression coefficients ϕ , P_{max} , and R_d were determined for every site and each day with a 15-day moving window by the least-squares method. Gaps in the daytime NEE were filled by Eq. (2) as a function of PPFD.

The gross primary production (GPP; F_{GPP}) was calculated as the sum of NEP ($-F_{NEE}$) and RE:

$$F_{GPP} = -F_{NEE} + F_{RE} \quad (3)$$

The temperature dependence of RE in the daytime was assumed to be equal to the nighttime estimation, and the daytime RE was calculated by Eq. (1) using the daytime air temperature. The procedure of gap filling and flux partitioning for the present analyses were described in detail by Hirata et al. (2008).

3. Results and discussion

3.1. Monthly values of GPP, RE, and NEP (2000–2005)

Fig. 2a–k represents the monthly values of GPP estimated at each site. Sites represented in Fig. 2a–d are larch forests (DC) in central Siberia (the annual air temperature is -9°C), Mongolia (-1°C), northeastern China (5°C), and northern Japan (6°C), respectively. The maximum values of GPP in the larch forests were observed during the early stages of their growing period, such as, July (Fig. 2a–c) and June (Fig. 2d). As clearly shown in Fig. 2a–d, the maximum values of GPP and the length of the growing period increased with the annual air temperature. In contrast, the seasonal variations of GPP are shown to display similar behavior (the rapid increase after leaf expansion, the peak in early growing period, and the slow decrease from mid-summer to fall). Among the eleven sites shown in Fig. 2a–k, the maximum value of GPP was the highest in the temperate larch forest TMK ($\sim 420\text{ g C m}^{-2}\text{ month}^{-1}$; Fig. 2d). This result is supported by previous eco-physiological studies, such as those by Koike et al. (2000) and Wang et al. (2005b). Both indicate that the larch species in northeastern Asia have a high photosynthetic capacity and may act as an important CO_2 sink.

Fig. 2e and h represents the monthly values of GPP estimated in a temperate mixed forest (MX), a birch-oak forest (DB), a red pine forest (EC), and a Japanese cypress forest (EC), respectively. The EC forests (Fig. 2g and h) had a longer growing season (>10 months) compared with mixed or deciduous forests (Fig. 2e–f). Even during the mid-winter (December–February), EC forests showed weak but detectable positive GPP, which is similar to the results of Ohtani et al. (2005). These results indicate a temperate red pine forest in central Japan has enough potential to assimilate CO_2 even in

Table 2 – Climatic conditions of the study sites

Code	Air temperature			Precipitation annual (mm)	Climatic zone	Observation period
	Annual mean (°C)	Monthly minimum (°C)	Monthly maximum (°C)			
TUR	-9 ^a	-	-	360 ^a	Sub-arctic	2004
SKT	-1	-21	16	250	Sub-arctic	2004–2005
LSH	5	-16	21	640	Temperate	2004
TSE	5	-8	16	970	Temperate	2002
TMK	6	-7	18	1040	Temperate	2001–2003
TKY	7	-8	19	2030	Temperate	2000–2004
FJY	10	-3	22	2060	Temperate	2000–2004
KEW	15	2	29	1600	Temperate	2001–2004
MKL	25	22	29	1200	Tropical	2003–2004
SKR	24	22	27	1500	Tropical	2002–2003
PSO	26	25	28	1700	Tropical	2003–2005

^a Climatic data from TUR was obtained from a meteorological station near the site (Nakai et al., in press).

Table 3 – Measurement systems

Code	Measurement height (m)	Sonic anemometer	IRGA	u_c threshold ($m s^{-1}$)
TUR	20	R-3, Gill ^a	LI-7500, LI-COR ^b	0.1
SKT	30	SAT-550, Kaijo ^c	LI-7500, LI-COR ^b	0.3
LSH	29	SAT-550, Kaijo ^c	LI-7000, LI-COR ^b	0.2
TSE	32	DA600-3TV, Kaijo ^c	LI-7000, LI-COR ^b	0.0
TMK	27	DA600-3TV, Kaijo ^c	LI-6262, LI-COR ^b	0.3
TKY	25	DA600-3T, Kaijo ^c	LI-6262, LI-COR ^b	0.5
FJY	26	DA600-3T, Kaijo ^c	LI-6262, LI-COR ^b	0.2
KEW	29	DA600-T, Kaijo ^c	LI-7500, LI-COR ^b	0.4
MKL	42	SAT-540, Kaijo ^c	LI-6262, LI-COR ^b	0.2
SKR	45	Wind Master, Gill ^a	LI-6262, LI-COR ^b	- ^d
PSO	54	SAT-550, Kaijo ^c	LI-7500, LI-COR ^b	- ^d

^a Gill Instruments Ltd., Lymington, UK.

^b LI-COR, Inc., Lincoln, NE, USA.

^c KAIJOSONIC Corporation, Tokyo, Japan.

^d See Appendix A for detail.

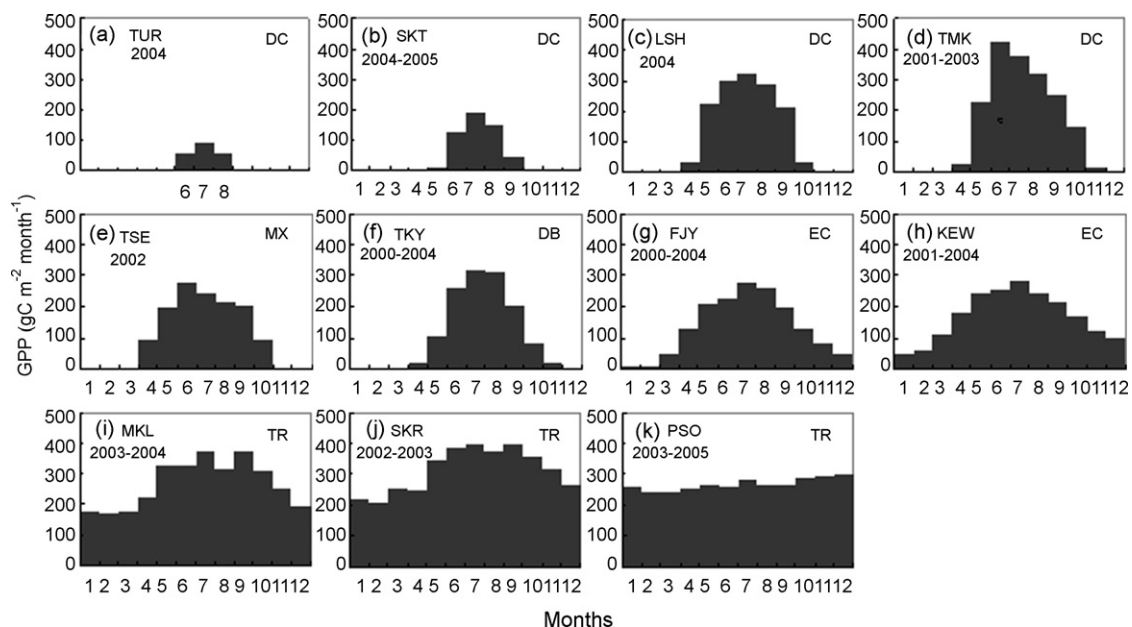


Fig. 2 – Monthly GPP observed at the 11 sites listed in Table 1. The site code, year(s) of GPP evaluation, and ecosystem type are indicated in each figure.

mid-winter when the climatic conditions are favorable. It should be also mentioned that the GPP in the temperate DC and DB forests started to increase before the leaf foliage period of canopy trees, which was typically from May to June (Fig. 2c, d, and f). This early increase in GPP was primarily caused by the photosynthetic activity of understorey plants, particularly ferns (*Dryopteris crassirhizoma*) at TMK and dwarf bamboo (*Sasa senanensis*) at TKY.

The seasonal variations of GPP estimated in tropical forests (Fig. 2i-k) had completely different aspects from sub-arctic and temperate forests. GPP values for the tropical rain forest in Malaysia (PSO; Fig. 2k) were high throughout the year with little seasonality. GPP values measured in PSO were similar to the maximum level of those observed in the temperate MX and EC forests. The GPP of tropical seasonal forests in Thailand (Fig. 2i and j) decreased from December to April, due to the dry season. Drought stress is likely the main cause for the photosynthetic rate reduction.

Fig. 3a-k displays the monthly values of the total RE. From sub-arctic to temperate (Fig. 3a-h), the maximum values of RE were observed in mid-summer (July and/or August) and the seasonal variations were quite similar. This observation is likely due to the fact that the most important controlling factor of RE in sub-arctic and temperate forests was the temperature, and other factors, such as drought stress, were not dominant. The maximum monthly value of RE was highest in the temperate larch forest in mid-summer (Fig. 3d). This high RE might be related to the high photosynthetic activity of needles during the growing period of the temperate larch forest. The RE of tropical seasonal forests (Fig. 3i and j) decreased from December to April, due to the dry season. In the tropical rain forest (Fig. 3k), the seasonality of RE was less clear.

Fig. 4a-k represents the monthly values of NEP at each site. The NEP at the sub-arctic and temperate deciduous forests (Fig. 4a-f) indicates clear seasonal change, and the maximum value of NEP tended to increase with the annual air

temperature. In the TMK and TSE sites (Fig. 4d and e), the values of mid-summer NEP reduced to almost zero or negative. One reason for this reduction was the high respiratory activity in both sites during mid-summer as indicated in Fig. 3d and e. The NEP at temperate EC forests and a tropical rain forest (Fig. 4g, h, and k) had less clear seasonal changes compared with sub-arctic and temperate deciduous forests. Slight decrease in NEP was observed in winter at temperate EC forests (Fig. 4g and h) caused by low temperature conditions. In tropical seasonal forests (Fig. 4i and j), zero or negative NEP was observed from February to April due to the dry season.

Seasonal patterns for GPP, RE, and NEP estimated from the various ecosystems in East Asia are a valuable dataset, which can be used for validation and sensitivity tests of various terrestrial ecosystem models. In addition, this data can be applicable for advanced technological development of satellite remote sensing; however, the patterns still include considerable uncertainty depending on the observational conditions and the data processing, such as topography and fetch around the towers, different data correction and quality control, and so on. A critical source of uncertainty, and also the most difficult problem to be solved, lies is the nighttime underestimation of NEE and data corrections. As indicated in Appendix A, this study used the usual *u*-filtering for most sites, while site-specific data filtering was applied at two tropical sites. Currently, comparative studies are being performed for the better estimation of nighttime RE and the annual NEP by multiple methods at the sites, such as the Eddy covariance method, chamber method, and other biometric methods (Kosugi et al., 2008; Kondo et al., submitted; Hirata et al., 2008). However, the uncertainty in the nighttime flux might still be great especially for tropical forests with large year-round CO₂ emissions and frequent calm atmospheric conditions (Kosugi et al., 2008), and absolute values of GPP and RE in Figs. 2 and 3 might include some bias. Further studies are

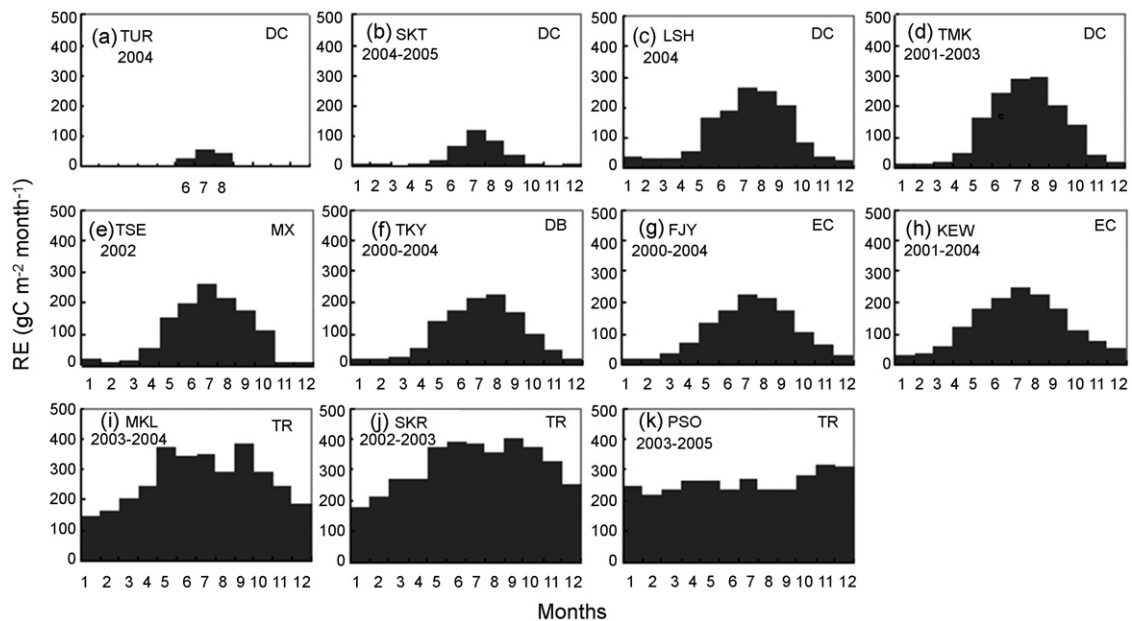


Fig. 3 – Monthly RE observed at the 11 sites listed in Table 1. The site code, year(s) of RE evaluation, and ecosystem type are indicated in each figure.

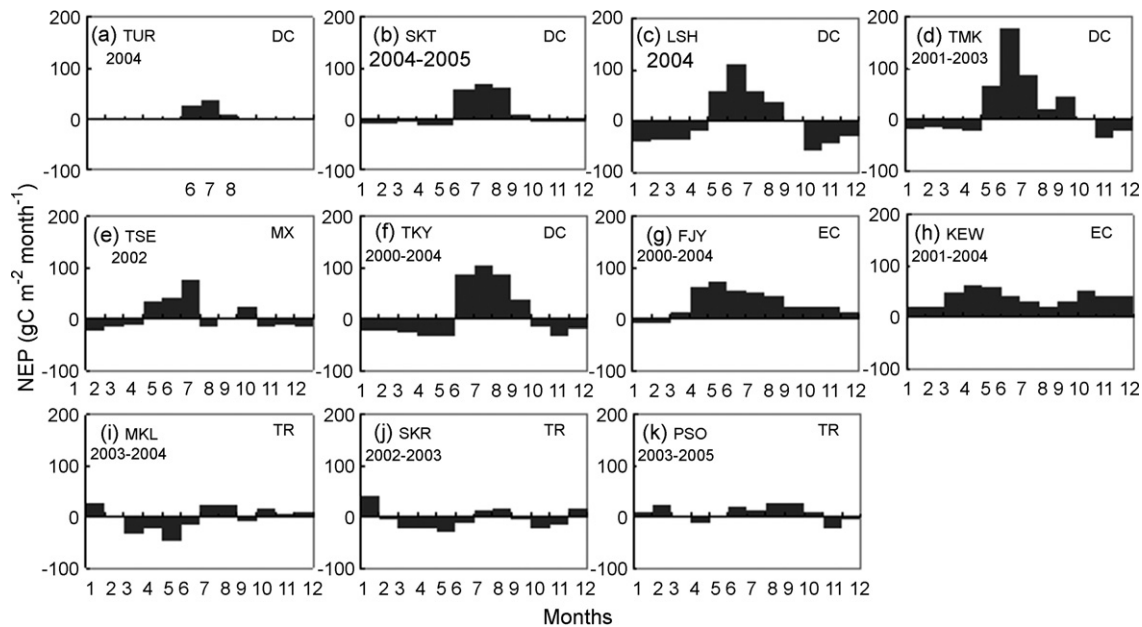


Fig. 4 – Monthly NEP observed at the eleven sites listed in Table 1. The site code, year(s) of NEP evaluation, and ecosystem type are indicated in each figure.

clearly necessary to establish an effective and practical way to avoid nighttime data problems.

3.2. Meteorological anomalies and ecosystem responses

During our study period from 2000 to 2005, several significant anomalies in the meteorological conditions were observed, such as solar radiation, air temperature, and precipitation. In the following analyses, results of three case studies are presented showing how each forest ecosystem responded to the meteorological anomalies. The first case is the negative anomaly of solar radiation observed in the mid-latitude zonal area during the 2003 summer. The second case occurred in the beginning of 2002 when unusually high surface air temperature widely appeared in northeastern Asia. The third case happened during the same period as the second case and presented as a negative precipitation anomaly in tropical Asia. The data were obtained from NCEP/NCAR reanalysis data (Kistler et al., 2001), and the anomalies in the meteorological variable refer to the 1971–2000 base period.

3.2.1. Case 1: effect of negative anomaly of solar radiation in the 2003 summer

To demonstrate the meteorological conditions of the first case, the spatial distribution of the anomaly within the summer solar radiation (3-month average of July–September) in 2003 is displayed in Fig. 5. In a zonal area at mid-latitude around 35–40°N from China to the main island of Japan through South Korea, a clear negative anomaly of solar radiation was observed. The anomaly was stationary during the 2003 summer with a wide longitude range from 80° to 150°E, under the influence of an active rain front which remained for an unusually long period. In the 2003 summer, several meteor-

ological stations on the main island of Japan broke records for the minimum daylight hours, especially in July 2003 (Japan Meteorological Agency, 2005).

We examined PPFD at each site and found that a significant negative anomaly was observed in the 2003 summer at three temperate forests in the central part of the main island of Japan. Fig. 6a–c shows monthly values of GPP from 2001 to 2003 at the three sites: TKY, FJY and KEW, respectively. At two of the three sites (TKY and FJY), a significant decrease was observed in GPP especially in July 2003 compared with previous years. The mean GPP of July was 19% (TKY) and 32% (FJY) lower in 2003 than in other years. The significant

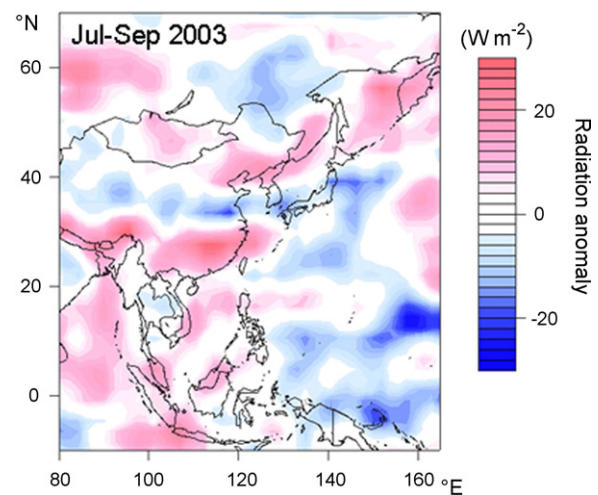


Fig. 5 – The spatial distribution of the anomaly in summer solar radiation (3-month average of July–September) in 2003 obtained from NCEP/NCAR reanalysis data (base period 1971–2000).

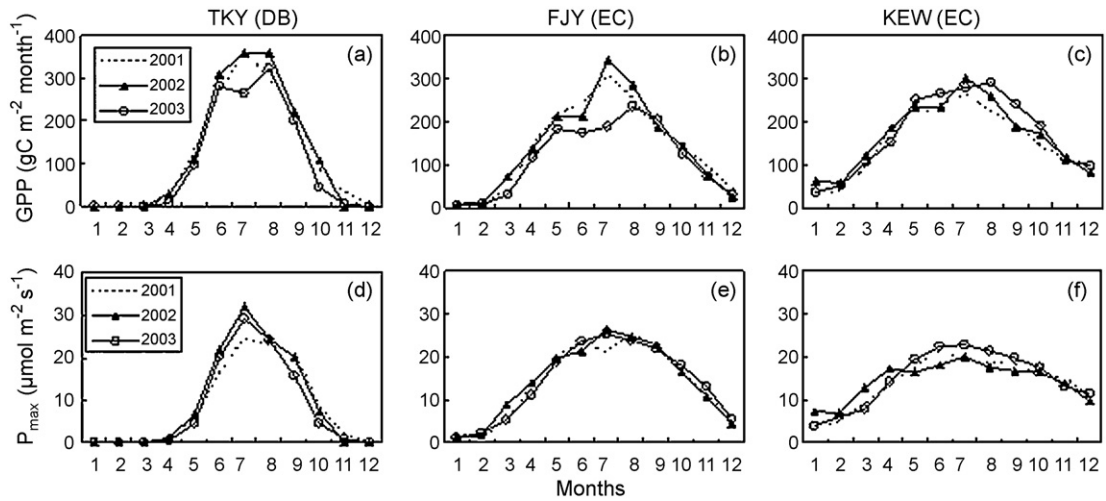


Fig. 6 – Monthly GPP at (a) TKY, (b) FJY, and (c) KEW, and monthly mean P_{max} at (d) TKY, (e) FJY, and (f) KEW from 2001 to 2003.

decrease in GPP was mainly due to an unusually low PPFD in July, which was 32% (TKY) and 44% (FJY) lower in 2003 than in previous years. Monthly values of GPP in the KEW site, however, did not show a clear decrease in the 2003 summer, even though the monthly PPFD in July was 35% lower in 2003 than in other years.

To investigate the cause for the different responses to summer GPP, we compared monthly mean P_{max} (the maximum level of GPP at light saturation condition) among the three sites. Fig. 6d–f indicates the monthly P_{max} at the first two sites (TKY and FJY) did not show systematic year-to-year difference from 2001 to 2003. In contrast, the values of P_{max} at the KEW site were obviously higher in the 2003 summer than in other years from June to September. To discuss the cause for different year-to-year changes in P_{max} , the monthly mean daytime air temperature and daytime water vapor pressure deficit (VPD) were shown in Fig. 7a–f for the three sites. A clear decrease was observed in daytime temperature in the 2003 summer especially in July for each

site. Here, it should be noted that the monthly mean daytime VPD was relatively lower at the TKY and FJY sites (<0.9 kPa) even during mid-summer due to cool climatic conditions in high altitude (>1000 m a.s.l.), while those at KEW site had higher VPD (>1.2 kPa) in July and August except for 2003. The decreased daytime VPD and decreased water stress in the 2003 summer are possible causes for the increased P_{max} at the KEW site.

These results suggest the following interpretations of the different response seen among the three forests to the negative anomaly of solar radiation during the 2003 summer: (1) at the TKY and FJY sites, the decrease in the monthly GPP in 2003 summer was caused mainly by a significant reduction (from 32 to 44%) in monthly PPFD, which was lower than observed in previous years; (2) at the KEW site, a similar level of decrease (35%) in the monthly PPFD was also observed, however, a decrease in the monthly GPP was not obvious. The effect of low PPFD may have been compensated by the increase in P_{max} in this forest.

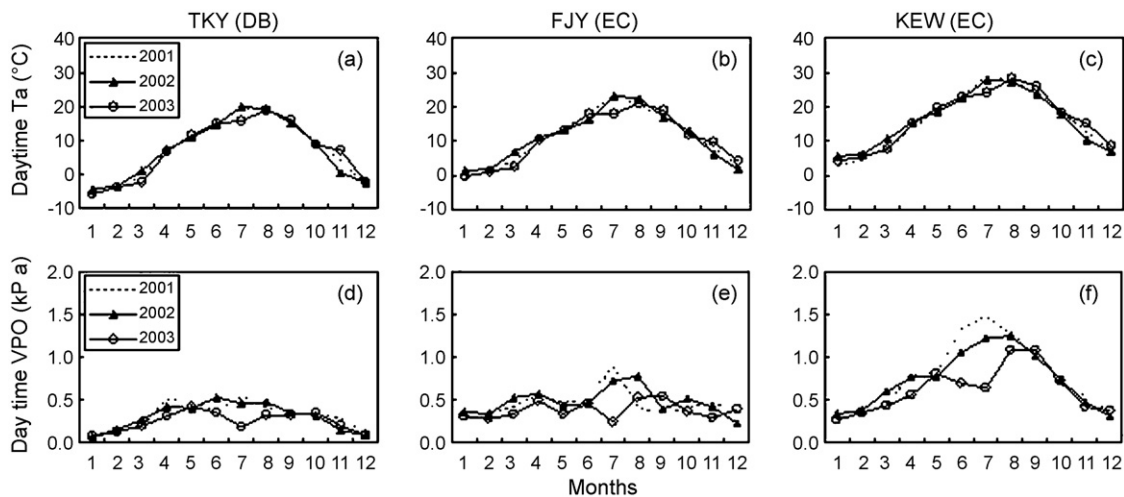


Fig. 7 – Monthly averaged daytime (PPFD > 0) air temperature at (a) TKY, (b) FJY, and (c) KEW, and monthly averaged daytime VPD at (d) TKY, (e) FJY, and (f) KEW from 2001 to 2003.

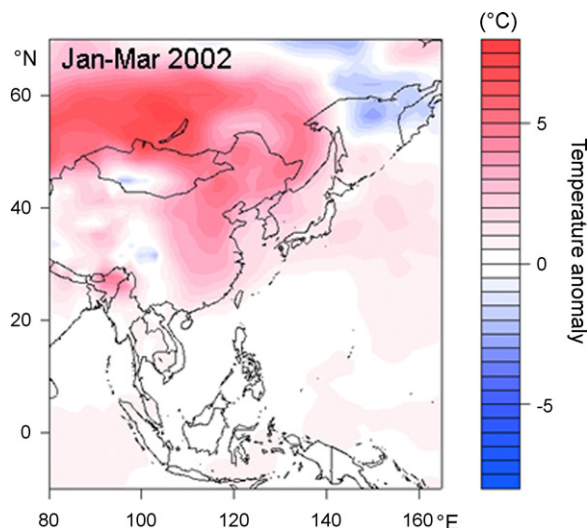


Fig. 8 – The spatial distribution of the anomaly in a 3-month mean surface air temperature (January–March) in 2002 obtained by NCEP/NCAR Reanalysis data (base period 1971–2000).

3.2.2. Case 2: effects of the positive anomaly of surface air temperature in the beginning of 2002

The second case is the effect of a positive anomaly of surface air temperature. Fig. 8 shows a spatial distribution of the anomaly in the surface air temperature from the winter to spring 2002 (3-month average of January–March). A significant anomaly of positive surface air temperature was observed over a large area which encompasses the eastern part of China, North- and South-Korea, Japan, Mongolia, and the southern part of Russia. A significant high spring air temperature anomaly was observed in northeastern Asia during the El Niño year of 1998. The high temperature anomaly observed in the beginning of 2002 was, however, slightly before the onset of the 2002/2003 El Niño. The winter air temperature in North Eurasia is highly influenced not only by ENSO events but also by the arctic atmospheric pressure pattern and polar atmospheric circulation, which varies with a period of several years or longer (Yamazaki, 2004). Currently, the mechanism of unusually high (or low) temperature anomalies in northeastern Asia has not been clarified.

Responding to the positive temperature anomaly at the beginning of 2002, NEP in several forests increased during the early stage of the growing period. Fig. 9a–d shows the monthly values of NEP at four temperate forests in central Japan from 2001 to 2003. The deviation of monthly mean air temperature in 2002 from the 3-year average (2001–2003) is shown in Fig. 9e–h. At two EC forests (Fig. 9c and d), a higher NEP was observed from March to April, probably due to the enhancement of needle photosynthetic activity under the warm weather condition. On the other hand, at two deciduous forests (Fig. 9a and b), no obvious year-to-year difference was observed from January to April, since the forests were leafless. The monthly NEP was higher in 2002 than observed in 2001 and 2003 at the beginning of the growing season (May in TMK, and June in TKY) for the deciduous forests. At the TKY site, the NEP in the beginning of the growing season (June) was highest in 2002 compared to 2001 and 2003 though the high temperature deviation was finished by May.

The main cause for this result was due to the earlier timing of leaf expansion during 2002 than had occurred in 2001 and 2003. At the TKY site, the leaf expansion had a year-to-year variation for about 2–3 weeks, and the timing of the expansion in 2002 was earlier than normal years (Saigusa et al., 2005). At the TMK site, Hirata et al. (2007) reported that the larch needles foliated 2-weeks earlier in 2002 than in 2001 and 2003.

As a result, the unusually warm winter in 2002 affected temperate forests as follows: (1) the warm weather condition enhanced photosynthesis rates of temperate evergreen coniferous forests and increased NEP, (2) in the temperate deciduous forests, the high air temperature caused early leaf expansion, which enhanced NEP at the beginning of the growing period even after the high temperature deviation was over.

3.2.3. Case 3: effects of negative precipitation anomaly at the early stage of 2002

The third case is the effects of less precipitation in tropical Asia during the same period that unusually high temperature was observed in northeastern Asia (from January to March 2002). Fig. 10 indicates the spatial distribution of the anomaly of 3-month averaged precipitation in January–March in 2002. There was a significant negative precipitation anomaly in Southeast Asia, ranging from around 0° to 20°N and from 90° to 150°E. The area of the negative precipitation anomaly covered

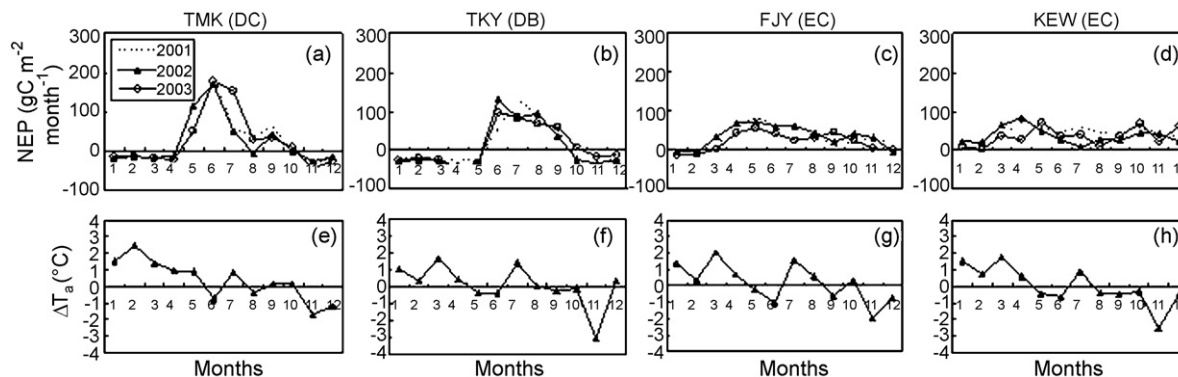


Fig. 9 – Monthly NEP from 2001 to 2003 at four temperate forests (a) TMK, (b) TKY, (c) FJY, and (d) KEW. The deviation of monthly mean air temperature of 2002 (ΔT_a) from the 3-year average (2001–2003) was also shown at each forest.

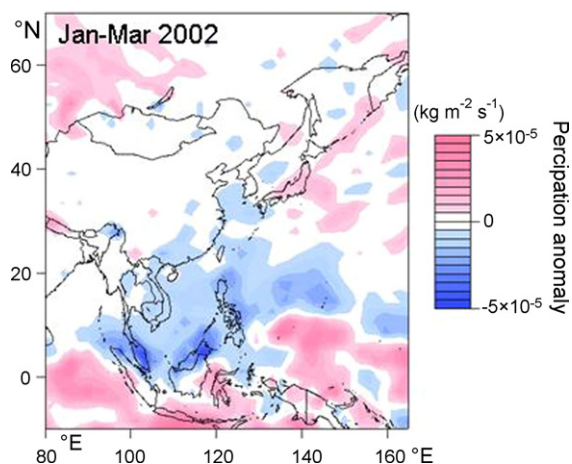


Fig. 10 – The spatial distribution of the anomaly in 3-month mean precipitation (January–March) in 2002 obtained by NCEP/NCAR reanalysis data (base period 1971–2000) ($5 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ is equivalent to 4.3 mm day^{-1}).

the northern part of Kalimantan, Philippine Islands, the northern part of Sumatra, the Malay Peninsula, and Indochinese Peninsula.

As a response to decreased precipitation, Fig. 11a and b shows that the monthly values of GPP at the tropical seasonal forest in Thailand (SKR) were reduced from January to April 2002 compared with 2003, and the monthly NEP was negative (carbon release) from February to May. This forest has a dry season in winter (December–February) in a normal year; however, there was an unusually longer dry season at the beginning of 2002, which continued until the end of April. Fig. 11c shows the 10-day mean volumetric soil water content (SWC) measured at 10 cm depth. Values of SWC was quite low (<0.1) from January to April (day of year (DOY) <110) in 2002. The long dry period with low SWC at the early stage of 2002 was probably a main cause for the reduction in GPP. As observed in the tropical seasonal forests in Thailand, recent studies have reported that significant reductions in the CO_2 uptake of tropical forests have been widely observed in Southeast Asia caused by severe droughts and wild fires every several years. Hirano et al. (2007) reported that the highest CO_2 release was observed in 2002 at a tropical peat swamp forest in Indonesia during their study period from 2002 to 2004, due to dry condition and a dense smoke emitted from large forest fires associated with severe droughts. Kobayashi et al. (2005) estimated the net primary production (NPP) by satellite images, and suggested that the year-to-year variations of NPP in Southeast Asia were affected by El Niño drought years. Patra et al. (2005) mentioned that changes in meteorology (i.e., rainfall and air temperature) associated with ENSO events were the most dominant controlling factors of CO_2 flux in tropical Asia, based on the estimation of global distribution of source/sink of CO_2 using atmospheric transport models.

Inter-annual variation of CO_2 uptake in tropical Asia is, as discussed above, closely related to the large scale climatic variations, and further studies are necessary to generalize our understandings of a variety of interactions between terrestrial

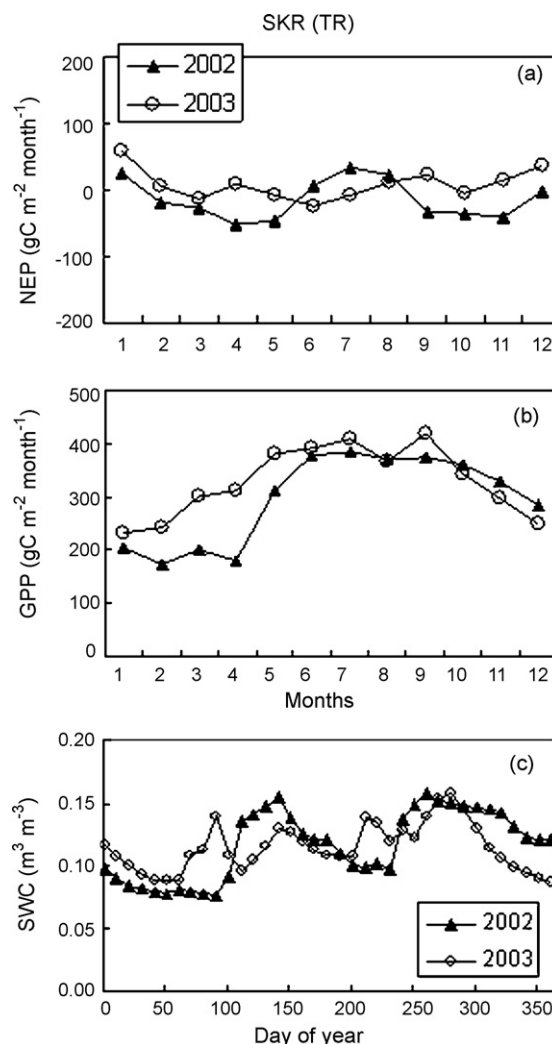


Fig. 11 – Seasonal changes in the monthly values of (a) NEP and (b) GPP, and (c) 10-day mean values of volumetric soil water content at 10 cm deep in tropical seasonal forest site (SKR).

ecosystems and the atmosphere in tropical Asia. The focus of the analysis in this section was on the seasonal and year-to-year changes in the CO_2 flux observed from 2002 to 2003 at a tropical seasonal forest, and more thorough analyses are clearly necessary using multiple years and sites to investigate spatial variations in the seasonal patterns of CO_2 flux in tropical Asia. In addition to the strong negative anomaly for precipitation discussed in this section, some positive anomalies appeared simultaneously to the south of the equator and in the mid- and high-latitudes, as shown in Fig. 10. Further studies should focus more on the spatial distributions of CO_2 flux and such effects as phenological changes in severe droughts, reduction in photosynthesis, and respiration by water limitations, forest fire, and the recovery process from such disturbances. Studies should be based not only on the ground observation network, but also on satellite remote sensing and modeling analyses. Clarifying the variety of ecosystem responses to climatic variations in tropical Asia is indispensable for a better prediction of future changes in the

terrestrial carbon cycle processes and also in the growth rate of atmospheric CO₂ concentration.

4. Conclusion

In East Asia, where few long-term and multi-site datasets have been available, continuous flux observations were made for 1–5 years during the study period from 2000 to 2005 at 11 forest sites distributed in the sub-arctic, temperate, and tropical zone. In addition, the seasonal patterns and amplitudes of GPP, RE, and NEP were discussed.

Larch forests, distributed over a vast area in northeastern Asia, have a characteristic that the maximum values of GPP and the length of the growing period clearly increased with the annual air temperature. Among the 11 study sites, the maximum values of the monthly GPP were the highest in the temperate larch forest (TMK) ($\sim 420 \text{ g C m}^{-2} \text{ month}^{-1}$). The high maximum GPP was probably caused by the high photosynthetic capacity of the larch species achieved during their short growing period. This result reveals the important role of larch species, which produce seasonal and year-to-year variations of carbon uptake by the boreal ecosystems.

The seasonal patterns of RE were compared among 11 sites and found to be similar at eight sites from the sub-arctic to temperate zone and in different ecosystems (DC, MX, DB, and EC). This result was interpreted to indicate that the temperature was the most important factor controlling RE and that other factors, such as drought stress, were not dominant in the sub-arctic to temperate forests. These ecosystems are relatively free from severe drought stress in summer, due to the influence of the Asian summer monsoon in the rainy season of the East Asian temperate forests during the early stages of their growing period.

Three case studies were presented to illustrate how GPP and NEP for several ecosystems responded to significant meteorological anomalies observed in East Asia from 2002 to 2003. The productivity in the temperate forests (TMK, TKY) typically decreased when summer solar radiation was unusually less than normal years, due to an active rain front stationary during the 2003 summer. However, the effect of a decrease in PFD could be compensated for by the increased maximum level of photosynthetic activity due to less VPD and less water stress depending on the site.

The effects of unusually high air temperatures at the beginning of 2002 differed between evergreen and deciduous forests in the temperate zone. For evergreen forests, photosynthesis was directly enhanced in March and April under warm weather conditions. On the other hand, unusually early leaf expansion was observed in deciduous forests, which increased NEP at the beginning of the growing season. The earlier timing of leaf expansion during 2002 enhanced NEP in deciduous forests from May to June even after the high temperature deviation was over.

Finally, decreased precipitation at the early stage of 2002, which happened during the same period as the unusually high air temperature in the temperate zone, significantly decreased GPP in a tropical seasonal forest due to a long dry period and severe drought stress. Year-to-year change in CO₂ uptake in tropical forests in Southeast Asia is closely related to the large

scale climatic variation such as El Niño events and also large forest fires associated with severe droughts.

Although this study is still preliminary as an integrated study of Asian scale, the results showed some important aspects, i.e., that forest ecosystems in Asia responded dynamically to meteorological anomalies depending on the climatic zone and forest type, particularly, summer solar radiation in temperate forests, air temperature at the early stage of year in temperate and sub-arctic forests, and severe drought that is typically observed once every several years in tropical forests.

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Appendix A

nighttime data correction is one of the most critical sources of uncertainty at many sites. Several effects such as complex topography in mountainous regions and horizontal advection in tall canopies are expected to be important sources of error; however, effective protocols for data correction have not been established. We applied *u*-filtering method for most sites in the present study. Practical validations of the method have been conducted in some sites, for example, *u*-filtering worked well so that the values of nocturnal NEE in high *u*-conditions were almost equivalent to those estimated by the integration of chamber measurements for soil, trunk, and foliar respiration at a temperate site (KEW) (Ohkubo et al., 2007). However, the nocturnal NEE estimated by the eddy covariance method

showed a serious underestimation even in high u -conditions in the following two tropical forests.

At a tropical seasonal forest (SKR) where the mean tree height was approximately 35 m, the value of u -threshold was not determined successfully because the relationship between the nighttime NEE and u under the same temperature conditions were unclear. The values of nighttime NEE were not “saturated” even in turbulent (high u -) conditions (Gamo et al., 2005).

Kondo et al. (submitted) tested three methods of data filtering to estimate RE. One technique was originally proposed by van Gorsel et al. (2007). This method used the maximum value of the nighttime NEE each night to construct a temperature response function (such as Eq. (1)) instead of using all the nighttime NEE data of windy (high u -) conditions. Using biometric estimations (Kondo et al., submitted) as the standard, the annual RE estimation based on van Gorsel’s filtering was more realistic than u -filtering. Therefore, the present study used regression parameters of Eq. (1), which are estimated based on the van Gorsel’s filtering, for the SKR site.

At tropical forest PSO, where mean canopy height was higher than 35 m, RE by the eddy covariance measurement was difficult to estimate (Kosugi et al., 2008). Estimation of total RE based on detailed chamber measurements was first attempted. The results suggested a serious underestimation of RE when calculated using the eddy covariance with u -filtering. In addition, an original method of data filtering was used in which all nighttime NEE data were replaced with the values estimated based on the chamber measurements. They concluded that the values of annual NEP estimated by their method were more reliable compared to the estimations based on biometric studies in their forest. Therefore, the present study used nighttime NEE data which were estimated with differing techniques depending on the site.

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