Satellite Observations of Decadal Scale CO₂ Fluxes Over Black Spruce Forests in Alaska Associated with Climate Variability

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Abstract

We improved the satellite-based empirical model (Kitamoto *et al.*, 2007) by adding additional effective parameters on vapor pressure deficit (VPD) and photosynthesis, and estimated the CO₂ budget within black spruce forests in Alaska. In the stand scale validation, our modified model successfully reproduced the observed gross primary productivity (GPP), ecosystem respiration (RE), and net ecosystem exchange (NEE) by the eddy covariance measurement. The 10-day average of the model output was highly correlated with the observed GPP ($r^2=0.9$), RE ($r^2=0.9$), and NEE ($r^2=0.7$).

We used the modified model to estimate the regional GPP, RE, and NEE of black spruce forests over Alaska from 1982 to 2003 by using the normalized difference vegetation index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR) and climate data. The estimated regional averages of GPP, RE, and NEE were 2,172, 2,008, and $-164 \text{ g CO}_2 \text{ m}^{-2} \text{ y}^{-1}$ during the past 22 years. Our model analysis showed that GPP was mainly affected by spring air temperature, whereas RE was affected by summer air temperature, indicating that the sink strength of the black spruce forests was controlled by the seasonality in air temperature between spring and summer. Path analysis enforced the notation that spring warming increased the CO₂ sink, but summer warming decreased the sink.

Key words: Alaska, AVHRR, Black spruce forests, CO₂ fluxes, High latitude warming.

1. Introduction

Climate change in the Arctic has been observed over the past few decades (IPCC, 2007). The Arctic Climate Impact Assessment (ACIA; Hassol, 2004) reported that winter surface air temperatures in the Arctic have risen 3 to 4°C over the past half century. Recently, the warming trends have become obvious in summer on land, hence terrestrial ecosystems in northern high latitudes have responded to the changes (Chapin *et al.*, 2005; Hinzman *et al.*, 2005). Although several studies reported that the warming increased the vegetation productivity and thus the CO₂ sequestration (Keyser *et al.*, 2000; Euskirchen *et al.*, 2006), other studies reported that CO₂ emission by increased decomposition canceled out the increase in the CO₂ sink (Goulden *et al.*, 1998; Piao *et al.*, 2007). Since the warming trend

is projected to become remarkable in the twenty-first century (Chapman and Walsh, 2007), it is necessarily to elucidate the ecosystem response to the warming climate.

Remote sensing is a useful tool to monitor the spatial and temporal characteristics in terrestrial ecosystems, especially in Arctic and boreal ecosystems. Since 1981, the time series observations of vegetation activity from the Advanced Very High Resolution Radiometer (AVHRR) have been applicable to climate change research. The best-known vegetation index is the normalized difference vegetation index (NDVI) (Tucker, 1979; Tucker and Sellers, 1986), which has been widely used to document widespread photosynthetic activities (Myneni *et al.*, 2001; Nemani *et al.*, 2003). Recent studies have reported a decreasing trend in the satellite-derived NDVI of the boreal forest in North America (Angert *et al.*, 2005; Bunn and Goetz, 2006). Although these studies inferred that the decline was related to high latitude warming and drying

Received; March 24, 2008.

Accepted; October 7, 2008.

(Angert *et al.*, 2005; Bunn and Goetz, 2006), it still remains uncertain.

Synthesis of observed data and satellite data has been applied to estimate ecosystem responses on a regional basis. As most of the model parameters and processes are based on the observed results, we developed a satellite-based empirical model to scale up the eddy covariance data (Kitamoto *et al.*, 2007). Although the model by Kitamoto *et al.* (2007) reasonably estimated regional CO₂ fluxes within black spruce forests in Alaska, the modeled results remained uncertain due to the limited parameters involved.

In this study, we improved the empirical model by Kitamoto *et al.* (2007), and estimated the spatial and temporal changes in the CO₂ fluxes within black spruce forests in Alaska. Subsequently, we calculated the regional CO₂ fluxes of black spruce forests over the entire state during the period from 1982 to 2003 by using the NDVI of the AVHRR dataset and the climate dataset. The calculated CO₂ fluxes were used to infer the terrestrial response to recent climate change, such as the air temperature trend.

2. Method

2.1 Field observations

We conducted field observations at a sub-arctic forest in Fairbanks, interior Alaska (64° 52'N, 147° 51'W). The mean monthly temperature of Fairbanks between 1971 and 2000 was lowest in January, at -23.2°C, and highest in July, at 16.9°C, with an annual mean of -2.9°C (Shulski and Wendler, 2007). The average annual precipitation was 263 mm, of which approximately 37% fell as snow, and the rest as rain.

The observation site is covered by black spruce (*Picea mariana*) and several understory species, such as *Rhododendron groenlandicum*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Betula glandulosa*, and some *Carex* species. The black spruce canopy is sparse. The average canopy height is about 1.5 m, with occasional taller trees of up to 6 m in height. The forest around the observation tower is old growth, up to 120 years (Vogel *et al.*, 2005). The leaf area index (LAI) measured by a plant canopy analyzer (Li-Cor, LAI-2000, USA) was 2.0 m² m⁻² above ground, whereas the LAI at 1.0 m above ground was 0.25 m² m⁻² in mid-summer (Ueyama *et al.*, 2006).

Fluxes of CO₂, water vapor, heat and momentum were measured at 6.0 m above ground, using the eddy covariance method with a sonic anemometer (CSAT3,

Campbell Scientific Inc., USA) and an open-path gas analyzer (LI-7500, Li-Cor, USA). The data were recorded at 10Hz, averaged for 30-minute periods, and calculated according to the guidelines of AmeriFlux (Baldocchi, 2003). Details of the measurements and data analysis were shown in previous papers (Ueyama *et al.*, 2006; Kitamoto *et al.*, 2007). We used the flux tower data from 2003 to 2006 for the model parameterization, and GPP, RE, and NEE observed in 2003 were used for the model validation.

2.2 Study region and period

Our study focuses on black spruce forests in interior Alaska covering the region of 60-70° N, 135-150° W. In order to identify pixels of dominant black spruce cover within the region, we used a land-cover map (1.1 km-grid spatial resolution) provided by the Alaska Geospatial Data Clearinghouse (AGDC, Fleming, 1997) and converted to 8 km-grid spatial resolution for model input. We selected the following pixels as black spruce forests from the vegetation classification; 1) spruce woodland shrubs, 2) open spruce forest-shrub-bog mosaic, and 3) open and closed spruce forest.

The study period was determined based on the available data records. As the model input of this study were calibrated NOAA-AVHRR data products (shown in the next section) that covered the period between July 1981 and December 2003, the analysis period of the model calculation was set between January 1982 and December 2003.

2.3 Data

We used NOAA-AVHRR NDVI data, which were produced as part of the National Aeronautics and Space Administration Global Inventory, Monitoring and Modeling Studies (GIMMS) project (Tucker *et al.*, 2005). The GIMMS data have been calibrated to take account of the effects of orbital drift, cloud cover, sensor degradation, and the emission of volcanic aerosols that attenuate the reflectance spectra. The GIMMS NDVI data are based on 15-day temporal and 8 km-grid spatial resolutions. In this study, we reproduced the 10-day average NDVI by averaging the original 15-day data for the model input.

We used air temperature data sets provided by the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis-1 (NNR) (Kistler *et al.*, 2001). The NNR data is provided every 6 hours in a global Gaussian grid with a spatial resolution of approximately 1.9° × 1.875°. In this study, we used the air temperature 2 m above

the ground. The extracted data for the study region were averaged at 10-day intervals, and then linearly interpolated to an 8 km-grid resolution. Since air temperature data by NNR have a significant large bias in northern high latitudes (Zhang *et al.*, 2007), we eliminated the bias by using the observed air temperature from the National Climate Data Center (<http://www.ncdc.noaa.gov/oa/ncdc.html>). In this study, we used the 10-day average, maximum and minimum air temperatures as the model input.

We used a surface radiation dataset provided by the International Satellite Cloud Climatology Project Radiation Flux Profile (ISCCP-FD) (Zhang *et al.*, 2004). Surface radiation by ISCCP-FD was produced globally every 3 hours at a spatial resolution of $2.5^\circ \times 2.5^\circ$ and was available after July 1983. In this study, the 10-day average shortwave radiation was re-formed into a spatial resolution of 8 km by linear interpolation. Compared to daily shortwave radiation data from 17 sites by the National Solar Radiation Data Base (NSRDB, http://rredc.nrel.gov/solar/old_data/nsrdb/), ISCCP-FD radiation data was found to be overestimated by about 10% in the study region, hence we eliminated the bias. In order to cover the insufficient period (before July 1983) of ISCCP-FD data, we applied the averages between 1984 and 2003 for the period. The surface radiation was converted to the model input of photosynthetically active radiation (PAR) by applying the ratio of 45%.

2.4 Statistical analysis

To evaluate the effectiveness of the input parameters on NEE, we used path analysis (Li, 1981; Sokal and Rohlf, 1981; Kojima, 2003) with a regional average of the calculated CO₂ fluxes from 1982 to 2003. Path analysis is similar to multiple regressions and is especially useful as an analysis tool when a priori causal or correlative information is known concerning the relationships among variables (Li, 1981). This method was previously used to understand the terrestrial carbon fluxes (Huxman *et al.*, 2003; Murphy *et al.*, 2008). We applied the Excel-GM (Kojima, 2003) to generate the path diagrams of model outputs.

3. Model

We developed a simple model to calculate GPP, RE, and NEE by using satellite data (hereafter, original model; Kitamoto *et al.*, 2007). The original model generated the diurnal pattern of surface air temperature from daily average of the land surface temperature

(LST) by using the empirical convert functions (Fig. 2 in Kitamoto *et al.*, 2007), and then calculated the hourly GPP, RE, and NEE by using 10-day composite NDVI and LST by AVHRR. The hourly GPP was calculated by rectangular hyperbola functions with a suppression function by air temperature, whereas hourly RE was calculated by air temperature alone. Hourly NEE was calculated as the balance of GPP and RE, where negative NEE represents CO₂ uptake, whereas positive NEE represents CO₂ emission. More details in the original model were shown in Kitamoto *et al.* (2007).

In this study, we modified several logics, such as the introduction of suppression effects by vapor pressure deficit (VPD) and PAR. While the original model generated the diurnal pattern of PAR from empirical functions, the modified model used radiation as an input variable. Input data were changed from the previous study; instead of NDVI and LST from the original AVHRR, we used NDVI by GIMMS, air temperature by NNR, and PAR by ISCCP-FD in the modified model.

3.1 Gross primary productivity

GPP was defined by the products of the potential photosynthetic rate (P_0) and several suppression functions. Although the previous model (Kitamoto *et al.*, 2007) introduced the suppression effect by air temperature, they pointed out that the suppression effect by high VPD and low light conditions had to be incorporated into the model to improve the calculations. We modified the calculation algorithm of GPP as follows:

$$\begin{aligned} GPP &= P_0 g_c \\ &= P_0 g_{\max} f(Ta) f(VPD) f(PAR) f(Ta_{\min}) \end{aligned} \quad (1)$$

where g_c and $g_{\max}$ represent the canopy conductance and maximum normalized canopy conductance, respectively. The value of $g_{\max}$ was chosen to be 0.70 according to the measured data at the site (Ueyama *et al.*, 2006). The functions of $f(Ta)$, $f(VPD)$, $f(PAR)$, and $f(Ta_{\min})$ represent the suppression effects by air temperature (Ta), VPD, PAR, and minimum temperature ($Ta_{\min}$), respectively. P_0 is calculated by rectangular hyperbola functions (Monsi and Saeki, 1953). The maximum photosynthetic rate and the initial slope in the photosynthesis-light curve are parameterized by NDVI in the original model (Eq. 3 in Kitamoto *et al.*, 2007), however, several studies

reported that the initial slope was more sensitive to air temperature than the vegetation amount (e.g. Ohtani *et al.*, 2005; Chen *et al.*, 1999). In this study, we calculated the initial slope by using air temperature rather than NDVI. The relationship between the initial slope and air temperature was obtained from the field observation (Fig. 1).

$f(Ta)$ is the suppression function of air temperature (Ta) as follows (Jarvis, 1976):

$$f(Ta) = \left(\frac{Ta - Ta_l}{Ta_{opt} - Ta_l} \right) \left(\frac{Ta_h - Ta}{Ta_h - Ta_{opt}} \right)^{\left(\frac{Ta_h - Ta_{opt}}{Ta_{opt} - Ta_l} \right)} \quad (2)$$

where Ta_{opt} is the optimal temperature, Ta_h is the maximum temperature at which $f(Ta)$ is reduced to zero, and Ta_l is the minimum temperature at which $f(Ta)$ is reduced to zero. Ta_{opt} , Ta_h , and Ta_l are determined as 22°C, 45°C, and -25°C from field observations (Ueyama *et al.*, 2006) and a previous study (Jarvis, 1976). We found that GPP decreased linearly with increasing VPD at the observed forest (Ueyama *et al.*, 2006), so that $f(VPD)$ was determined as follows:

$$\begin{aligned} f(VPD) &= 1 \\ (VPD_{open} &\geq VPD) \\ f(VPD) &= \frac{VPD_{close} - VPD}{VPD_{close} - VPD_{open}} \\ (VPD_{open} &< VPD < VPD_{close}) \\ f(VPD) &= 0 \\ (VPD_{close} &\leq VPD) \end{aligned} \quad (3)$$

where, VPD_{open} and VPD_{close} were VPD levels at the

Fig. 1. Relationship between air temperature and the initial slope in the photosynthesis-light curve of the black spruce forest observed from 2003 to 2006. The initial slope was empirically determined from the observed flux for each 28-day period.

start and end of conductance reduction, respectively. According to the study for various ecosystems (White *et al.*, 2000), we set 500 Pa of VPD_{open} and 4000 Pa of VPD_{close} . VPD was calculated from the air temperature according to Waring and Running (1998).

$f(PAR)$ was determined by a rectangular hyperbola function presented by Kosugi *et al.* (1995) as follows:

$$f(PAR) = \frac{PAR}{PAR + g_{max}/a_g} \quad (4)$$

where a_g was the initial slope of the light-conductance curve, 0.006 (Ueyama *et al.*, 2006).

In boreal forest ecosystems, frost substantially affects photosynthetic activity during the late growing season (e.g. Goulden *et al.*, 1997). The frost effect was introduced into the canopy conductance logic by using the minimum air temperature as follows:

$$\begin{aligned} f(Ta_{min}) &= 1 \\ (Ta_{min} &\geq Ta_{min open}) \\ f(Ta_{min}) &= \frac{Ta_{min close} - Ta_{min}}{Ta_{min close} - Ta_{min open}} \\ (Ta_{min close} &< Ta_{min} < Ta_{min open}) \\ f(Ta_{min}) &= 0 \\ (Ta_{min} &\leq Ta_{min close}) \end{aligned} \quad (5)$$

where $Ta_{min open}$ and $Ta_{min close}$ were Ta_{min} at the start and end of conductance reduction, respectively. According to the previous study for black spruce forests (Lamontagne *et al.*, 1998), we set 0°C of $Ta_{min open}$ and -10°C of $Ta_{min close}$. According to Lamontagne *et al.* (1998), the sensitivity of black spruce to the frost intensified in autumn and photosynthesis did not recover after a frost occurred. We introduced this effect as Eq. 6 by selecting a lower value of $f(Ta_{min})$ in the current and previous periods, for the period in the late growing season.

$$\begin{aligned} f(Ta_{min})_{DOY} &= \min(f(Ta_{min})_{DOY-10}, f(Ta_{min})_{DOY}) \\ (DOY &> 200) \end{aligned} \quad (6)$$

where $f(Ta_{min})_{DOY}$ is $f(Ta_{min})$ on a given day of the year (DOY) by Eq. 5, and $f(Ta_{min})_{DOY-10}$ is $f(Ta_{min})$ for the previous 10 days. In Eq. 6, $f(Ta_{min})$ on a given DOY is chosen as the minimum value among those on the current DOY and the previous 10 days.

Fig. 2. Relationship between leaf area index (LAI) by a canopy analyzer and ecosystem respiration at 0°C (R_0) of the black spruce forest by the ground observation.

Consequently, $f(Ta_{\min})$ at the given DOY does not exceed the value at previous periods on DOY > 200. The same characteristic for frost suppression during the autumn is also documented for understory species of boreal ecosystems (Martel *et al.*, 2005).

3.2 Ecosystem respiration

RE was calculated by the function of air temperature in the current model as follows:

$$RE = R_0 \exp[Ta \ln(Q_{10})/10] \quad (7)$$

where R_0 is RE at the reference temperature of 0°C, and Q_{10} is the temperature sensitivity coefficient of RE. In the current improvement, R_0 was functioned by LAI. The relationship between R_0 and LAI was determined by the field observations (Fig. 2), which provided the response of RE to vegetation change, both temporally and spatially. In the regional calculation, LAI was obtained from NDVI by using the relationship between LAI and NDVI (Kitamoto *et al.*, 2007).

4. Results and discussions

4.1 Model validation and implication

To validate our improved model, we compared the seasonal GPP, RE, and NEE between observations and calculations (Fig. 3). The seasonal variations of calculated CO₂ fluxes reasonably agreed with the observed daily fluxes. The calculated peak of GPP and RE was 18.6 g CO₂ m⁻² d⁻¹ and 15.3 g CO₂ m⁻² d⁻¹, respectively, which was almost equivalent to the observed peak of the 10-day average (17.9 g CO₂ m⁻² d⁻¹ for GPP and 16.0 g CO₂ m⁻² d⁻¹ for RE). Calculated GPP and RE correlated closely to the observed results, with a slope of about 1.0 and $r^2 = 0.9$ (Fig. 4a). The root mean square errors (RMSE)

Fig. 3. Seasonal variations of GPP, RE and NEE of the black spruce forest comparing between calculated (open circle) and observed (closed circle) at the tower site in 2003.

Vertical bar with closed circle means standard deviation of observed fluxes during each 10-day averaging period. Arrows in the figure are explained in Section 4.1.

in GPP and RE were 0.291 and 0.196 g CO₂ m⁻² d⁻¹, respectively. The calculated NEE was also correlated with the observation (Fig. 4c; slope of 0.980, $r^2 = 0.728$, and RMSE = 0.229 g CO₂ m⁻² d⁻¹). Compared with the results from the original model by Kitamoto *et al.* (2007), the modification significantly improved the model, where the original model overestimated GPP with a slope of about 1.2 and underestimated RE with a slope of about 0.8 (Fig. 4b). The overestimated CO₂ sink by the original model (Fig. 4d; slope of 1.528 and offset of 1.270 g CO₂ m⁻² d⁻¹) was also corrected by the modifications. These results suggested that the modified model could provide a better estimation than previous satellite-based model studies (e.g. Xiao *et al.*, 2004; Sasai *et al.*, 2005).

Although the modified model successfully reproduced the observed CO₂ fluxes, there were several discrepancies between the calculations and observations, one of which occurred during the late winter between DOY61 and DOY90 (arrow A in Fig. 3),

Fig. 4. Comparisons of 10-day mean GPP, RE and NEE between observed and calculated by the modified (a, c) and the original (b, d) model for the tower site in 2003. Linear regression and root mean squared error (RMSE) are shown in the figures.

when the forest floor was almost covered by snow, the observed NEE were negative, while the calculated NEE showed positive values. The uptake of CO₂ measured under snow-covered conditions remains under debate. Burba *et al.* (2006) reported that the self-heating of the open-path sensor resulted in an unreasonable downward flux, but the CO₂ exchange before snowmelt in ecosystems is still unknown, especially at high latitudes. Further observations during the cold period and further synthetic analyses are required. During the early spring between DOY111 and DOY130 (arrow B in Fig. 3), the model overestimated GPP and thus provided high CO₂ uptake. This was probably caused by different temporal resolution between the observation and calculations. Since the transition from full snow cover to the summer condition of the forest can happen in under a month, NDVIs in GIMMS products might select higher values for this period because the maximum value NDVI composites were formed twice a month (Tucker *et al.*, 2005). Therefore, the overestimated spring CO₂ uptake might be caused by an unsuitable input, rather than the model. A similar discrepancy happened in autumn (arrow B' in Fig. 3).

Nonetheless, cumulative observed GPP, RE, and NEE during 2003 were 2,390, 2,110, and 280 g CO₂ m⁻² y⁻¹, whereas the calculated fluxes were 2,390, 2,120, and 270 g CO₂ m⁻² y⁻¹, suggesting that our improved model can estimate annual CO₂ fluxes with high accuracy. We use the model to estimate the regional CO₂ fluxes over black spruce forests in Alaska in the following sections:

4.2 Seasonal cycle of regional CO₂ fluxes

The calculated seasonal cycle of the regional CO₂ fluxes and the input data of NDVI, air temperature, and shortwave radiation are shown in Fig. 5 as interannual variations between 1982 and 2003. The regional averages of the calculated seasonal cycles for GPP, RE, NEE, and the inputs are also shown in Fig. 6 in the form of temporal averages, standard deviations, and coefficients of variance during the past 22 years. The onset of GPP, which was defined as the first term when GPP rose 10% above the annual maximum, appeared in late April (DOY111 to DOY120, in Fig. 6). Maximum GPP was calculated between mid-June and early-July (DOY161 to DOY190) with a value of about 18 g CO₂ m⁻² d⁻¹. The peak of negative NEE, namely the net uptake of atmospheric CO₂, appeared

Fig. 5. Time series of calculated GPP, RE, NEE of black spruce forests in Alaska (a) and those of inputs of NDVI (b), air temperature (T_a) (c) and shortwave radiation (RS) (d) between 1982 and 2003. Each line represents spatial average over pixels of black spruce forests. Arrows in the figure are explained in Section 4.3.

during June (DOY151 to DOY170) with a maximum NEE of $6 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$. The peak period of NEE and the average level were similar to previous observations over black spruce forests in Canada (Bergeron *et al.*, 2007; Dunn *et al.*, 2006) and Alaska (Ueyama *et al.*, 2006; Welp *et al.*, 2007). After the peak, NEE declined while GPP showed an increasing trend. Since NEE was the balance between GPP and RE, an earlier increase in GPP compared with RE created the earlier peak period of NEE.

Standard deviations and coefficients of variance in NEE over the past 22 years showed significant variations in April (DOY90 to DOY150, in Fig. 6) compared with other periods. This large variation in NEE was mainly caused by large variations in GPP, where both the coefficient of variance and the standard deviation of GPP peaked in April. The significant variations of NDVI under high shortwave radiation during this period resulted in significant variations of GPP, in turn, causing significant interannual variation of GPP in spring. During mid-summer, on the other hand, interannual variation of GPP was small (Figs. 5 and 6), suggesting that photosynthetic activities of the forests kept similar levels during mid summer over the

Fig. 6. Seasonal cycles of GPP (a), RE (b), NEE (c), NDVI (d), air temperature (T_a) (e) and shortwave radiation (RS) (f) of black spruce forests within Alaska between 1982 and 2003. Open circles and vertical bars represent mean and standard deviation during 22 year, respectively. Gray block bars represent coefficient of variance.

past 22 years, despite relatively significant deviation in shortwave radiation. The calculated seasonal trends and their deviations suggested that the variations of climate and NDVI in spring affect GPP effectively, whereas the variations in summer could affect RE.

4.3 Temporal changes of CO₂ fluxes

To investigate the long-term CO₂ balance and the interannual variation, the annual sum of CO₂ fluxes and the maximum and average of NDVI between May and September are shown in Fig. 7. Related climate anomalies during the same period are shown in Fig. 8 for cumulative air temperatures above 0°C (hereafter, growing degree days; GDD), air temperature (DOY120 and DOY170), and shortwave radiation.

The calculated annual GPP ranged between 2,000 and 2,400 $\text{g CO}_2 \text{ m}^{-2} \text{ y}^{-1}$, whereas the annual RE ranged

Fig. 7. Interannual variations in spatial average of GPP, RE, NEE (a) and maximum and average NDVI between May and September (b) within black spruce forests in Alaska.

Fig. 8. Interannual changes in anomaly of growing degree days (GDD) (a), air temperature (T_a) in DOY120 and DOY170 (b) and shortwave radiation (RS) during the past 22 years within black spruce forests in Alaska. GDD is cumulative air temperature above 0°C .

Fig. 9. Spatial distributions of slope of linear trend of GPP, RE, and NEE of the black spruce forests and those of inputs of maximum NDVI and GDD. The trends were determined as differences per year by linear regression analysis within two periods, 1982–1990 (a) and 1993–2000 (b).

between 1,900 and 2,100 $\text{g CO}_2 \text{ m}^{-2} \text{ y}^{-1}$. The average GPP, RE, and NEE were calculated as 2,172, 2,008 and $-164 \text{ g CO}_2 \text{ m}^{-2} \text{ y}^{-1}$, respectively. The long-term

calculation by our model with observed NDVI showed that black spruce forests in Alaska acted as a net CO_2 sink for the past 22 years.

We found a steady increase in GPP and RE from 1982 to 1990, which was associated with increased trends of average NDVI with a rate of 0.0058 y^{-1} (Fig. 7) and GDD with a rate of $22^{\circ}\text{C day y}^{-1}$ (Fig. 8). During the 1980s, the increase of air temperature (Fig. 8b) was significant in spring (rate of $0.35^{\circ}\text{C y}^{-1}$ and $p < 0.01$; DOY120) while the air temperature in mid-summer showed a declining trend, despite the insignificant p value (rate of $-0.12^{\circ}\text{C y}^{-1}$ and $p = 0.10$; DOY170). Although both GPP and RE showed increasing trends during the period when both NDVI and spring air temperature increased, NEE showed no clear trend from 1982 to 1990.

The NDVI and air temperature record showed a decline from 1991 to 1992, which was the response of the forests to the Pinatubo cooling event (Lucht *et al.*, 2002). Stratospheric aerosol generated by the Pinatubo eruption in mid-June 1991 depressed incoming shortwave radiation (e.g. Stenchikov *et al.*, 1998), hence anomalous cooling of -0.5°C was observed in the northern high-latitude growing season of 1992–1993 (Yang and Schlesinger, 2001). The event clearly appeared in our study region (arrow A in Fig. 5). NDVI also decreased after the event (arrow B in Figs. 5 and 7). The decreased air temperature and NDVI (Figs. 7 and 8) might affect the decreases in both GPP and RE (Fig. 7). At this time, the calculated decline of GPP was obvious compared to that of RE, resulting in an obvious decline in sink strength. This effect of the Pinatubo eruption was consistent with other simulation results from a process-based ecosystem model and an inverse model (Lucht *et al.*, 2002).

After the Pinatubo event, the NDVI value (Figure 5) and the maximum NDVI (Fig. 7) did not recover for several years, while anomalies of GDD and air temperature showed increase. GPP recovered after the event, despite a slight decrease in maximum NDVI. Interannual changes after the Pinatubo event in air temperature, NDVI, and calculated GPP and RE suggested that the increased air temperature in the spring (Fig. 8) prompted a recovery of sink activity. The model calculation showed that the warmer air temperature in spring increased GPP rather than RE, which resulted in a $90\text{ g CO}_2\text{ m}^{-2}\text{ y}^{-1}$ increase of NEE during the period until 1994. This trend of the CO₂ budget before and after the Pinatubo eruption was consistent with a previous study (Lucht *et al.*, 2002).

4.4 Spatial variations of trends in the carbon fluxes

To examine the spatial variation in trends of CO₂ fluxes during the two periods before and after the Pinatubo event, slopes of linear regression of GPP, RE, NEE, maximum NDVI, and GDD were calculated separately between 1982 and 1990 and between 1993 and 2000 (Fig. 9), respectively. Before the event, spatial variations in changing trends of GPP and RE showed a similar pattern, where GPP and RE had an increased trend throughout the black spruce forests. On the other hand, distribution of the calculated NEE trend showed a different pattern regionally, where the positive trend in NEE was distributed in the western region, whereas the negative trend, namely the increasing CO₂ sink, was distributed in the eastern region.

Distributions of changing trends in GPP and RE after the event also showed similar patterns, with general decreases after the event, which was a clear contrast to those before the event. On the other hand, distribution of a changing trend in NEE was different, where the negative NEE, namely increasing sink strength, was distributed in the southwestern region, whereas a positive NEE, namely decreasing sink strength, existed in most of the rest of the region. Compared to the regional distributions of the model inputs between NDVI and GDD, GDD significantly decreased and NDVI slightly decreased in the southwestern region.

4.5 Implications of understanding the long-term CO₂ budget by path analysis

The calculated temporal and spatial trends of CO₂ fluxes within black spruce forests in Alaska showed different responses to seasonal climate variability. To examine the relationship among seasonal climate variability and calculated responses (fluxes), we applied the Excel-GM (Kojima, 2003) to generate path diagrams for the model outputs. In this analysis, we considered the following paths and their controls over GPP, RE, and NEE: (1) the direct effects of shortwave radiation, air temperature, and NDVI; (2) the indirect effect of air temperature through influences on NDVI; and (3) the direct effects of both GPP and RE on NEE. To determine the path values for each component, we used standardized partial regression coefficients to describe the path strengths.

The obtained path diagram for the relationship between climate and the CO₂ fluxes is shown in Fig. 10, where values with an arrow represent path coefficients. The analysis was conducted for DOY120 as the climate

Fig. 10. Path diagram that illustrates the effects of NDVI and climate variables, such as air temperature (T_a) and shortwave radiation (SR), on the CO_2 fluxes (a), and the different seasonal effects of NEE in spring (DOY120), mid-summer (DOY170), and autumn (DOY270) on the annual NEE (b). Symbols of M, J, O, and A in (a) represent March (DOY120), June (DOY170), October (DOY270), and Annual, respectively. Numbers with symbols are path coefficients of each plotted path arrows. Arrows indicate causation between exogenous or intermediary variables and the dependents.

in spring (symbolized as M), DOY170 as mid-summer (symbolized as J), DOY270 as autumn (symbolized as O), and the annual mean climate (symbolized as A), where the symbols of M, J, O, and A represent March, June, October, and Annual, respectively.

According to the path analysis (Fig. 10a), GPP and RE were mostly affected by NDVI as the annual scale. These results are consistent with the time series of GPP, RE and average NDVI, where GPP and RE showed virtually identical interannual variations over two decades and the variation of average NDVI was reasonably close (Fig. 7). The annual mean air temperature, T_a , also affected both GPP and RE as the annual scale, but the contributions were relatively small. Annual mean shortwave radiation has an insignificant effect on the GPP, meaning the annual mean NDVI was the best indicator to explain the interannual variations of GPP and RE.

On the other hand, for the seasonal scale, major contributors on GPP were T_a in spring (0.78), NDVI in summer (0.92), and T_a in autumn (0.69) too, while T_a contributed to RE throughout the seasons (spring 0.76, summer 0.78, and autumn 0.89, respectively). No direct positive effects of shortwave radiation on GPP were obvious, especially in spring and autumn.

Since NEE was the balance of GPP and RE, the contributions of GPP and RE on NEE determined by the path analysis differed among the seasons. In spring, NEE was affected by GPP (−1.36) more than RE (0.38). Since GPP in the spring was analyzed as highly sensitive to air temperature, spring warming

resulted in enhanced sink strength of the black spruce forests.

For mid-summer, RE was analyzed as more sensitive to T_a than GPP, and RE mainly affected NEE (1.22) rather than GPP (−0.55), whereas there was no relationship between NDVI and T_a (−0.09) in summer. Thus, the path analysis suggested that warming in summer tended to decrease the sink strength, even though other factors, such as soil-water condition, might be considered as controlling factors on NDVI as well as GPP and RE.

To examine the contribution by season to the annual CO_2 budget, we conducted path analysis for spring, summer, autumn, and the annual NEE (Fig. 10b). Analysis suggested that the sink strength in spring and summer strongly affected the annual CO_2 sequestration (0.54 in spring and 0.42 in autumn), but that NEE was slightly more effective on the annual CO_2 sequestration in spring than in summer. These results suggested that potential small changes in the future climate in spring and summer might obviously affect the CO_2 budget of black spruce forests in Alaska. According to our model results, the black spruce forests will increase sink strength under spring warming, and decrease NEE under summer warming, respectively.

4.6 Limitations and future model improvements

Although our study successfully estimated the ecosystem response to air temperature and radiation, we have pointed out a limitation to its applicability. Modeling of the response to different soil-water conditions is required to enhance understanding of

the carbon cycle in boreal forests. Several observation results reported that changes in soil-water conditions affected CO₂ fluxes, and thus the CO₂ sequestration in boreal forests (Iwashita *et al.*, 2005; Dunn *et al.*, 2006). Although several microwave remote sensors have the capacity to estimate soil-water conditions from space (Njoku *et al.*, 2003), the available data were limited from recent satellites, meaning the record periods were not compatible with that of AVHRR. When we can apply indexes with relevant soil-water conditions, our understanding of the CO₂ fluxes in northern ecosystems may be improved.

5. Conclusion

The synthesis of satellite observations, climate data, and empirical modeling based on field observations has improved the understanding of the temperature responses of black spruce forests in Alaska. The estimated regional averages of GPP, RE, and NEE between 1982 and 2003 were 2,172, 2,008 and -164 g CO₂ m⁻² y⁻¹, respectively. According to our model results, spring air temperatures mainly affected GPP, whereas summer air temperatures affected RE. Consequently, the sink strength of the black spruce forests was affected by air temperatures in spring and summer; spring warming increased the sink strength and summer warming decreased it.

The methodology of this study is applicable to scale up the observed fluxes to the regional scale, by applying meteorological data and satellite-derived parameters related to observed CO₂ fluxes. The results obtained concerning the temperature response on the carbon cycle may reveal a unique characteristic of high latitude ecosystems. Our satellite-based modeling to estimate regional CO₂ flux may lead to satellite-based modeling applications to other ecosystems.

Acknowledgements

The flux observations at the UAF campus site and the synthesis with modeling were supported by the International Arctic Research Center (IARC) through funding from the U.S. National Science Foundation (NSF). The synthesis study among satellite data and field observation was supported by grants from the Initiative for Attractive Education in Graduate Schools by MEXT Japan, 2005, "Environmental Ethics-Health and the Environment," and the IARC/JAXA Information System. We thank the above organizations and Drs. Masahiro Hori of JAXA, and Kazuhito Ichii of

Fukushima University, for their suggestions concerning the satellite and climate data, two anonymous reviewers for their beneficial comments, Mr. Tohru Saito of IARC for his contributions to field observations, and Mr. Ned Rozell of IARC for his support.

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人工衛星データを用いたアラスカ域のクロトウヒ林における長期的な二酸化炭素フラックスの解析

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要 約

人工衛星から得られた正規化植生指数 (NDVI) と全球を対象に整備された気象データ (気温, 日射量) を入力として, アラスカ域のクロトウヒ林における二酸化炭素収支量を評価するモデル (Kitamoto *et al.*, 2007) を改良した。新しいモデルには, 様々な環境要因による光合成の抑制を再現するスキームが導入され, このモデルにより推定された総一次生産量 (GPP), 生態系呼吸量 (RE), 純生態系交換量 (NEE) は以前のモデルの推定結果と比べて, より精度良く地上の観測結果を再現できていた。また, 季節変動も地上観測結果をよく再現した。

アラスカ域のクロトウヒ林における 1982 年から 2003 年までの GPP, RE, NEE を評価した。これらの値の 22 年平均値は, それぞれ 2,172, 2,008, -164 g CO₂ m⁻² y⁻¹ となった。モデルの計算結果から, GPP は春の気温に感度が高く, RE は夏の気温に感度が高い事が示唆された。したがって, アラスカ地域のクロトウヒ林では, 春に昇温する場合は二酸化炭素吸収が増加し, 夏に昇温する場合は二酸化炭素吸収が減少する事が示唆された。
キーワード: アラスカ, AVHRR, クロトウヒ林, 二酸化炭素フラックス, 高緯度温暖化