An Experiment for the Evaluation of the CO₂ Budget on a Regional Scale in Hokkaido, JAPAN

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Abstract

The accurate assessment of the global CO₂ budget largely depends on the regional observations and estimations of the regional CO₂ fluxes. For understanding the CO₂ budget on a regional scale, comprehensive experimental research was made at Ishikari plain in Hokkaido, the northernmost island in Japan. The CO₂ source data were collected from the public statistical data, and CO₂ sink data for typical forests in Hokkaido were based on the results at Tomakomai Flux Research Site and Teshio CC-LaG site. The regional carbon budget was also estimated inversely using an atmospheric transport model with an experimental observation mainly by airplane in the summer and winter of 2003. The estimated regional carbon budgets during the observation period were estimated as $-20.7 \mu\text{mol m}^{-2} \text{s}^{-1}$ within the Ishikari plain in summer, and $18.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ within the Sapporo urban area in winter. Both the CO₂ absorption in summer and the CO₂ emission in winter were overestimated as compared with the integrated CO₂ sink and source data. The overestimation resulted from complex regional airflow, inadequate distance between the aerial observation lines and large-scale CO₂ source, and the problem in temporal and spatial division of CO₂ inventory.

Key words: Carbon dioxide, CO₂ budget, Kyoto protocol, Regional scale

1. Introduction

Global warming resulting from the increase in atmospheric CO₂ is a severe environmental problem. Thus, the regional CO₂ exchange between the surface and the atmosphere are needed to assess the global CO₂ budget.

In Japan, the national government collects CO₂ source data mainly from public statistics in reports in compliance with United Nations Framework Convention on Climate Change (UNFCCC). The CO₂ sink of the terrestrial ecosystem is measured mainly on by ecological and micrometeorological methods. On a regional- and global-scale, the CO₂ budget is controlled by the anthropogenic CO₂ emission and the natural CO₂ absorption on the supposition that there is no exchange through the atmospheric boundary layer. Because of the possibility of large errors in estimating the regional CO₂ budget based on a limited number of source and sink data, there is an urgent need to establish a more accurate validation procedure for estimating regional CO₂ exchange.

The CO₂ budget on the regional scale can be estimated directly by measuring the transport of CO₂ in air. The changes of CO₂ concentration through the land area should be the same as CO₂ exchange at the same area.

This paper compares the estimated regional CO₂ budget by experimental observation using an airplane with that by an integrated method using public statistical data

2. Materials and Methods

This study focuses on the carbon budget in the western area of Hokkaido where urban regions distribute patchily in a 100 km scale. It is assumed that fossil fuel is consumed heavily by industries and by

Fig.1. Location in Ishikari plain, west of Hokkaido

large cities while carbon dioxide can be absorbed by large-scale croplands and forests. Within the studied region, Sapporo is the largest city in Hokkaido with a population of about 2 million, and Tomakomai is an industrial area. It is relatively easy to measure the absorption and emission of CO₂ in this area by measuring the transport of CO₂ into and off the area because it faces the sea and is surrounded by mountains. (Fig. 1)

The regional CO₂ budget in this area can be estimated by the following procedures:

- a) Collection of the inventory data of CO₂ source, CO₂ flux measurement over the archetypal forest, and GIS mapping;
- b) Experimental observation using airplane for direct measurements of horizontal and vertical profiles of the atmospheric CO₂ concentrations;
- c) Estimation of the distribution of CO₂ concentration using an atmospheric transport model and GIS data under typical climate conditions;
- d) Comparison between experimental observations and modeling results;

2.1 Data collection and GIS mapping

We used public statistical data for the anthropogenic CO₂ source because of their accessibility. Data quality was enhanced by weighting with CO₂ emission ratio in Hokkaido: manufacturing industries (31%), residential sectors (18%), road transportation (18%), and commercial and institutional sectors (12%). These CO₂ source data were classified into seasonal and hourly categories and mapped to the geographical grid of 1 km by 1 km resolution.

The CO₂ sink data were measured using the eddy covariance method at Tomakomai Flux Research Site (40-years-old larch plantation; 42-44°N 141-31°E, Tomakomai, Hokkaido, Japan) and Teshio CC-LaG (Carbon Cycle and Larch Growth Experiment) Site (natural conifer-hardwood mixed forest; 45-03°N 142-07°E, Horonobe, Hokkaido, Japan) which were established by the National Institute for Environmental Studies with the cooperation of Hokkaido University and Hokkaido Electric Power Co., Inc. CO₂ flux measurements in the Teshio Experimental Forest of Hokkaido University started in August 2001. The capacity of CO₂ fixation was 293 to 389 gC m⁻² year⁻¹ in the larch plantation at the Tomakomai site (Hirano et al., 2003), and less than 100 gC m⁻² year⁻¹ in the natural forest at the Teshio site. This difference may be attributed to the more mature forest and heavier snow cover in winter at Teshio. These results were GIS-mapped using a vegetation map and the same method for the CO₂ source data.

2.2 Experimental Observation

Measurements of 2-dimensional distribution and vertical profiles of CO₂ concentrations in upwind and downwind are necessary for the estimation of the CO₂

budget. If measured for a different condition, the results cannot be used for budget calculation.

Experimental observations using an airplane and airborne CO₂ analyzer developed by CGER/NIES were conducted once in summer and once in winter, 2003. Both a CO₂ source and sink exist within Ishikari Plain in summer, so we chose the flight course to observe the vertical profiles of the CO₂ concentrations both upwind and downwind. In contrast, only CO₂ source exists within the plain in winter because of snow cover and defoliated trees, thus we circled over Sapporo to observe CO₂ emissions from the commercial and residential regions. Figure 2 shows the flight courses on February 24 and July 23, 2003. The altitudes of horizontal flights were decided according to atmospheric conditions, and there were 4-5 horizontal flights within both observations.

Fig.2. Flight courses on February 24 (solid line) and on July 23 (dotted line) 2003, respectively.

2.3 Simulation of the CO₂ distribution

The atmospheric model used was AIST-MM (Gambo, 1978, Kondo et al., 2001, Saigusa et al., 2002), which is based on the dynamic equation with hydrostatic and Boussinesq approximations. CO₂ was treated as a non-reactive material, and CO₂ advection and diffusion were calculated from wind-fields and potential temperature (Brummage, 1968, Schulze et al., 1994).

$$\frac{\partial(DC)}{\partial t} + \frac{\partial(DCu)}{\partial x} + \frac{\partial(DCv)}{\partial y} + \frac{\partial(DCs)}{\partial z} = K_{cx}D \frac{\partial^2 C}{\partial x^2} + K_{cy}D \frac{\partial^2 C}{\partial y^2} + \frac{1}{D} \left(\frac{\partial}{\partial z} K_H \frac{\partial C}{\partial z} \right) + Q_c \quad (1)$$

$$s = \frac{z - z_G}{z_T - z_G} \quad (2)$$

$$D = z_T - z_G \quad (3)$$

$$\dot{s} = \left[w - u \left(\frac{\partial z}{\partial x} \right) - v \left(\frac{\partial z}{\partial y} \right) \right] \frac{\partial}{\partial z} \quad (4)$$

where u , v and w are west-east, south-north, and vertical components of wind velocity; C is CO₂ concentration, and Q_c is the source and sink of CO₂;

K_H and K_C are the vertical diffusion coefficient of potential temperature and the horizontal diffusion coefficient of CO₂ respectively; z_T and z_G are altitude of the upper limit and ground surface within the calculation region respectively.

3. Results and Discussion

3.1 CO₂ budget in winter

The altitudes of horizontal flights were 900, 1300, 2000 and 6000 feet on February 24, 2003. Fig. 3 shows the horizontal CO₂ distributions at 1000ft and 6000ft. The wind direction was NW above an altitude of 300m and SE below that as the consequence of radiational cooling. The horizontal flight course at 1000ft was not circular in order to keep away from mountains, and an air mass of the high CO₂ concentration was observed at the leeward side of the Sapporo commercial area. This peak decreased with altitude; and there were hardly any peaks at 6000ft.

Fig.3. CO₂ concentration around Sapporo by aerial observation at 1000ft (a) and 6000ft (b).

The CO₂ emission rate within the circular flight course was estimated as $18.8 \mu\text{mol m}^{-2}\text{s}^{-1}$ based on the experimental observation, whereas using CO₂ source data yields a rate of $12.5 \mu\text{mol m}^{-2}\text{s}^{-1}$.

The distribution of CO₂ concentration at 900ft was compared the simulated results using an atmospheric transport model and CO₂ inventory data to find the cause of the difference. According to the simulation, the CO₂ concentration difference from background level at leeward side was 12ppm, which was less than the aerial result of 20-30ppm. The most probable reason

was that the high CO₂ concentration near the ground surface below the 900ft significant vertical zone could not be detected due to the prohibition by law of low level flight. There are several possible causes for the difference: complex regional urban airflow, inadequate distance between the aerial observation lines and large-scale CO₂ sources in Sapporo. Additionally, the spatial and temporal repartitioning of the statistical data also included the errors.

3.1 CO₂ budget in summer

To find suitable wind conditions for aerial observation, distribution of air CO₂ concentration was simulated using an atmospheric transport model for geostrophic winds (10 m s^{-1}) from all directions. Figure 4 shows the simulated CO₂ distribution at the ground level for a southern wind with total cloud amount of 3. The high CO₂ concentration area in the center of the Ishikari plain (inside dash line) appeared in the Tomakomai Industrial Area.

Fig.4. simulated spatial CO₂ distribution (ppm) at ground level with a southern wind of 10 m s^{-1} .

The simulation with an east-west geostrophic wind in summer produces unsuitable atmospheric conditions for observation, but a feasible condition with a south-north wind.

An aerial observation using an airborne CO₂ analyzer was made on July 23, 2003, when the southeast wind within the atmospheric boundary layer of about 7000ft was 6 to 10 m s^{-1} and 2 to 4 m s^{-1} above that. Figure 5 and Figure 6 show horizontal CO₂ distribution at the windward side and lee side of Ishikari plain respectively. Figure 5 shows that CO₂ concentrations within every horizontal flight at windward side were nearly the same, indicating that the background CO₂ was almost homogenous. In contrast, Fig.6 shows a decrease of CO₂ concentrations at the east- and westends of every horizontal flight. Because there are extended CO₂ sink areas, such as forest and cropland on both sides of the Ishikari plain, the decrease should be caused by photosynthetic CO₂ absorption. However, the effect of the CO₂ source,

especially by the Sapporo commercial area, was not detected by aerial observation.

Fig.5. Horizontal CO₂ distribution at the windward side of the Ishikari plain on July 23, 2003.

Fig.6. Horizontal CO₂ distribution at the leeward side of the Ishikari plain on July 23, 2003.

The CO₂ flux rate estimated by aerial observation and an atmospheric transport model was $-18.8 \mu\text{mol m}^{-2} \text{s}^{-1}$, which was similar to the CO₂ absorption rate by terrestrial ecosystem and crop land within this region in the daylight. Thus, CO₂ emission in this region was hardly detected by this aerial observation. It was caused by the weak source footprint because the flight course was very close to the ground CO₂ source area of Sapporo.

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