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Initial assessment of multi-scale measures of CO_2 and H_2O flux in the Siberian taiga

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Abstract. We measured CO_2 and H_2O fluxes between undisturbed *Larix gmelinii* forest and the atmosphere at a remote Eastern Siberian site in July 1993. Scaled-up leaf-level porometer measurements agreed with those derived from the eddy correlation technique for the canopy fluxes of CO_2 and H_2O. Patch-scale measurements of ecosystem CO_2 exchange agreed in turn with regional CO_2 exchange rates derived from aircraft measurements made throughout the convective boundary layer. At all scales, midsummer CO_2 fluxes for this vast, dry boreal forest were low, with maximum C uptake rates of only about 5 μmol m^{-2} s^{-1}.

Key words. CO_2, eddy correlation, *Larix*, convective boundary layer, boreal forest.

INTRODUCTION

The world's boreal forests contain about 50% of the total carbon stored in vegetation and soils, and the majority of this boreal carbon, approximately 320 Pg, lies in the Russian taiga (Dixon *et al.*, 1994). The northern boreal zone is an area likely to experience larger greenhouse gas-driven temperature increases than other parts of the globe (Manabe & Wetherald, 1980). A general climate warming could have drastic effects on northern ecosystem carbon uptake and storage by directly affecting the physiology of important boreal species and by indirect effects on permafrost depth, nutrient cycling, site water balance or fire regime.

The majority of the Siberian taiga is dominated by *Larix* species which occupy a natural range of 7.8×10^6 km^2, about twice that of the North American boreal forest (Gower & Richards, 1990). *Larix russica* (Endl.) Sab. ex Trautv. (formerly *L. sibirica* Ledeb.) occurs primarily in the west and *L. gmelinii* (Rupr.) Rupr. (formerly *L. dahurica* Laws) in the east (Abaimov, Karpel & Koropachinskii, 1980; Silba, 1986, 1990). In these vast regions larch forms pure stands, regenerated by recurrent fire (Kupriyanov, Veretennikov & Zinin, 1987; Kurbatskii and Tsykalov, 1988).

We measured forest-atmosphere carbon and water fluxes at several scales in *L. gmelinii* forests of the eastern taiga, a little-studied region. Our goal was to test the integration of various-scale measurements from shoots up to the forest and region. Small-scale measurements provide valuable temporal and spatial variability data, and allow for more control over measurement or experimental conditions than inherently larger-scale measures. However, direct patch-scale measurements (i.e. including several ha and thousands of trees) have revealed the emergence of new ecosystem properties such as the importance of diffuse radiation transfer and the corresponding lack of proportionality between above-forest total irradiance and daily CO_2 uptake (Hollinger *et al.*, 1994). This introduces uncertainty in scaling up shoot-level measurements when investigating patch- or regional-scale (i.e. tens to thousands of square kilometres) phenomena. In this paper, we provide a preliminary synopsis of shoot-, patch- and regional-scale measures of forest-atmosphere CO_2 exchange during the Eastern Siberian growing season. We use detailed measurements of tree biomass and leaf area index (LAI) to scale shoot-level cuvette data up to the canopy level. These results are then compared with patch-scale canopy fluxes determined by the eddy correlation technique. Finally, we compare whole ecosystem fluxes measured at the patch-scale with regional-scale estimates based on aircraft measurements.

TABLE 1. Characteristics of *Larix* stand surrounding our eddy flux measurement tower in eastern Siberia (after Schulze *et al.*, 1995).

Basal area (m^2/ha)	Density (stems/ha)	Above-ground biomass (t/ha)	Below-ground biomass (t/ha)
23.5	1760	92.6	83.8

TABLE 2. Criteria for rejecting half-hour flux data.

Quality	Criteria	Values excluded[1]
Wind direction	$> 90°$ to array	145
Wind direction (θ)	$240 < \theta < 270$	61
Windspeed	< 0.5 m s^{-1}	75
Air temperature variance	$> 1°C$	12
H_2O concentration variance[2]	> 3 g m^{-3}	183
CO_2 concentration variance	> 100 p.p.m.	185
Data collection period	< 28 min	94

[1]Data was collected over a total of 697 half-hour periods; [2]includes 45 half-hour periods when rain fell.

METHODS

This work took place at a remote site in the Siberian taiga (lat. 60° 51.59424′ N, 128° 16.04004′ E; 348 m a.s.l.), approximately 155 km south west of Yakutsk and 50 km from the nearest settlement. The forest was dominated by *Larix gmelinii* with scattered *Betula platyphylla*, and had regenerated from fire approximately 130 years ago. Tree density was relatively high, but stand basal area and biomass were low (Table 1). The forest understorey was dominated by *Vaccinium vitis-idaea* and *Vaccinium uliginosum.*

Shoot level CO_2 and H_2O exchange were determined with a LiCor 6200 photosynthesis system (LiCor, Inc., Lincoln, NB, U.S.A.) on a total leaf area basis (conversion to a one-sided leaf area basis by multiplying by the total:projected area ratio of 2.6). We gained access to the canopy via wooden ladders and platforms constructed in the forest. Measurements of sun and shade foliage were made at 1–2 h intervals throughout the day at heights ranging from approximately 10–16 m. Values from between two and twenty-five separate samples were averaged for each measurement period. These values were then scaled up to the tree canopy level, on a per unit ground area basis, by multiplication by the one-sided leaf area index of 1.5 (Schulze *et al.*, 1995).

We measured patch-level CO_2, H_2O and sensible heat exchange rates with the eddy correlation technique on a half-hourly basis (Baldocchi *et al.*, 1988; McMillen, 1988) using the system described in Hollinger *et al.* (1994). Instrumentation was located atop a 22.5 m tower erected in the forest. The CO_2 exchange data were corrected for density and spectral effects (Webb, Pearman & Leuning, 1980; Moore, 1986; Businger & Delany, 1990). The ecosystem energy balance was examined for 'closure' by checking the equality of the sum of the latent heat (λE, H_2O) and sensible heat (H) fluxes ($\lambda E + H$) to the available energy (R_a)($R_a = \lambda E + H$). Half-hourly values of R_a were determined by the difference between measurements of above-forest net all-wave radiation (R_n), canopy and air column heat storage (S) and soil heat flux (G)($R_a = R_n - S - G$) according to Kelliher *et al.* (1992).

We calculated half-hourly changes in CO_2 storage in the forest air column below our 22.5 m flux measurement height by measuring the CO_2 concentration at heights of 1, 5, 9, 13, 17 and 21 m with a system consisting of a BINOS (Leybold-Heraeus, Hanau, Germany) non-dispersive infrared gas analyser, pumps, switching manifold, PTFE inlet tubes (i.d. = 4 mm) and data logger (model DL2, Delta-T Devices, Cambridge, U.K.). Additional eddy flux measurements of CO_2 and sensible heat exchange were made at a height of 1.8 m above the forest floor. These data were obtained with a single-axis sonic anemometer and fine-wire thermocouple (model CA-27, Campbell Scientific) and by ducting a sample of air from near the anemometer to a third infrared gas analyser (model LI-6252, Licor, Lincoln, Nebraska, U.S.A.). The combination of all measurements allowed calculation of the tree canopy CO_2 flux as the sum of the eddy flux at 22.5 m and the change in canopy air CO_2 storage minus the eddy flux at 1.8 m.

We followed stringent editing criteria to insure the quality of the eddy flux data. Data were rejected when sensor variance was high, when the wind direction differed by $> 90°$ from the direction of the instrument array, or when the wind was blowing from the area of our camp (Table 2). The need for this editing is shown by the influence of a small lake and wetlands near our camp on values of ecosystem surface conductance (Kelliher *et al.*, 1994) when the wind was from the west-south-west (Fig. 1).

Regional estimates of CO_2 flux were made using the convective boundary layer (CBL) approach (Raupach *et al.*, 1992). This involved measuring the profile of CO_2 concentration from ~30 m above the surface to well beyond the top of the mixed layer (~2500 m) and integrating with height to determine total column CO_2. To assess the morning and afternoon draw-down in CBL CO_2, measurements were made three times each day (~0600, ~1200 and ~1800 h) utilizing a Russian AN-2 biplane aircraft. The 1000 hp radial engine of this plane exhausts to the starboard side of the aircraft so our air inlet was located near the port wing tip. Air temperature was measured by a copper–constantan thermocouple placed directly in the airstream. Ambient CO_2 concentration was measured with an infrared gas analyser (model LI-6252, Licor, Lincoln, Nebraska, U.S.A.) with compensation for barometric (altitude) changes during each flight. The analyser was calibrated at ~15-min intervals with two bottles of reference CO_2 in air. Data was logged at 0.5 Hz with a datalogger (model 21X, Campbell Scientific, Inc., Logan, UT, U.S.A.) and laptop computer combination. A global positioning system (model Basic Plus, Trimble Navigation, Sunnyvale, CA, U.S.A.) was used to geo-reference the measurements.

RESULTS AND DISCUSSION

Agreement of the turbulent fluxes H and λE with the available energy R_a was generally good such that $R_a = 1.14 (H + \lambda E) + 6\ W\ m^{-2}$ ($r^2 = 0.90$) for 239 half-hourly periods (Kelliher *et al.*, 1994). Using the same instrumentation and techniques, a similar tendency of $(H + \lambda E) < R_a$, but smaller disparity of about 5–10%, was observed earlier above a New Zealand broadleaved forest (Kelliher *et al.*, 1992). At least part of the energy balance disparity in Siberia may be attributable to differences in sampling areas for the eddy flux and available energy measurements. Footprint analysis suggested that about 90% of the eddy flux source area was typically located in the first 650 m upwind of the tower. By contrast, for a 90% view factor, the above-forest net radiometer sampled an areal diameter (centred at the tower) of only 30 m and the ten forest floor heat flux plates were located next to the tower within an area of similar size.

Maximum values of CO_2 exchange and water vapour conductance were very low for both leaf and patch-scale measurements of Siberian *Larix*. Maximum values of canopy photosynthesis based on shoot-level measurements were ~ 5–$6\ \mu mol \times m^{-2} \times s^{-1}$ (Fig. 2). Similar maximum values were obtained by the eddy flux technique. There was generally good agreement between the daily pattern of shoot and patch-scale measurements of canopy CO_2 exchange (Fig. 2). The somewhat high early morning values based on measurements of shoot photosynthesis may reflect a bias towards stems located on the east side of the tree canopies. The general similarity of leaf and whole-canopy values suggests that, at least during the daytime, non-leaf canopy tissues (e.g. stems) had an approximate carbon balance whereby refixation rate ≈ respiration rate.

For water vapour, the daily pattern of flux at the patch scale is also similar for values scaled from shoots or the eddy correlation technique (Fig. 3). The sum of understorey evaporation (measured by five small lysimeters) and canopy transpiration (scaled-up from measurements of shoots) was identical at 1.4 mm to the total evapotranspiration measured with the eddy correlation technique. Typically,

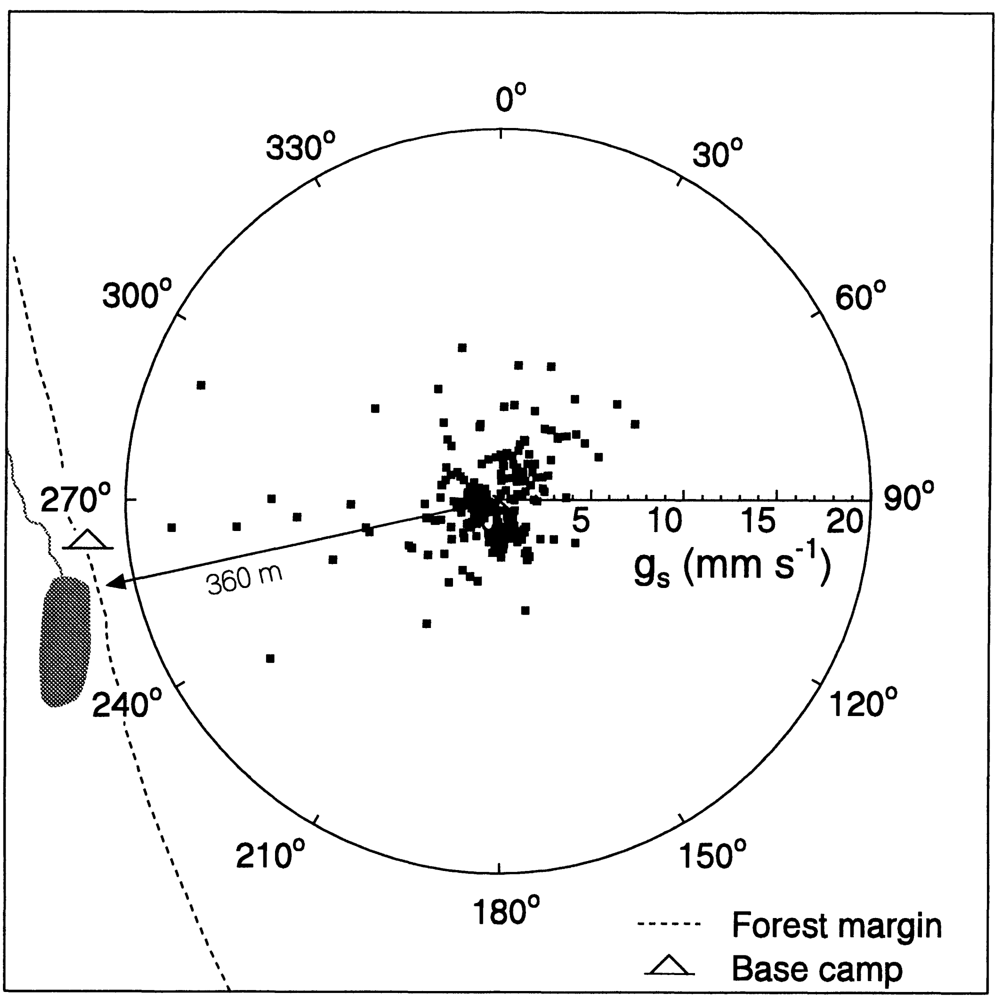

FIG. 1. Daytime surface conductance (g_s) (13–27 August 1993) as a function of wind direction. The distance of each point from the centre indicates the magnitude of g_s and the bearing the mean wind direction during the half-hour measurement period. High values of g_s when the wind is from the west-south-west result from the presence of a small lake and marshy ground in the 'footprint' zone.

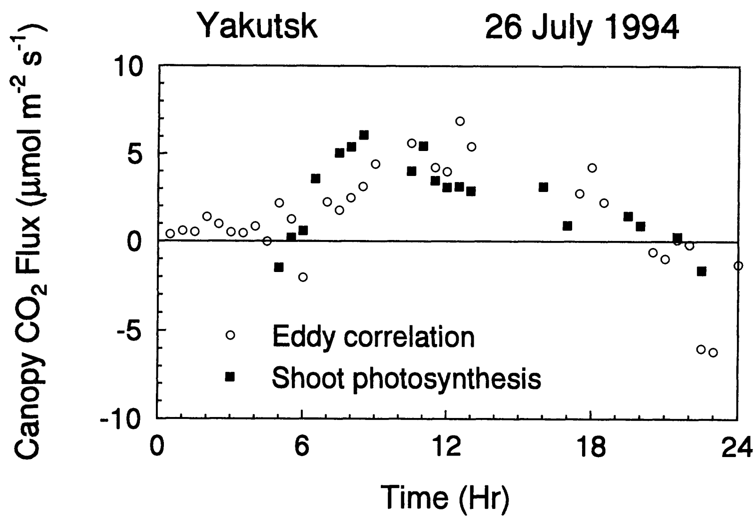

FIG. 2. Tree canopy carbon dioxide exchange rate in a Siberian *Larix* forest as the difference between fluxes measured above the forest and at 1.8 m above the forest floor (open circles) and by scaling-up leaf-level photosynthesis measurements (solid squares).

over 40% of total ecosystem evaporation came from the *Vaccinium* understorey.

Moving from shoot level measurements to the eddy correlation patch represents an increase in scale of $\sim 10^5$. The similarity of results when integrating from a small number of leaf measurements to the patch average (representing the mean exchange of several thousand trees) clearly indicates the exceptional uniformity of canopy environment and physiology in the *Larix* taiga. For example, during the middle of clear days, virtually all foliage in *L. gmelinni* canopies receives a saturating ($>$ 300 μmol photosynthetically active photons $m^{-2} \times s^{-1}$) light intensity. In other ecosystems, measurements would have to be stratified among species with more detail devoted to sampling within canopy variation. The resources needed to carry out such a sampling scheme would almost certainly exceed those needed for direct patch-scale measurements via eddy correlation.

Scaling to the region

Profiles of atmospheric potential (lapse rate corrected) temperature, $\Theta(\Theta = T + \Gamma \times z$, where T is the actual temperature, z is height and Γ is the dry adiabatic lapse rate) measured at different times of a sunny fine day show the evolution of the convective boundary layer (*CBL*) (Fig. 4A). In the early morning there is a shallow surface layer of relatively cool air up to $\sim$200 m above the forest. Above this layer the atmosphere is stably stratified. The corresponding CO_2 profile (Fig. 4B) shows that CO_2 is trapped in the surface layer, below a height of about 80 m.

As the surface warms during the day, convection (sensible heat) rapidly mixes the *CBL* to a height of $\sim$1200 m

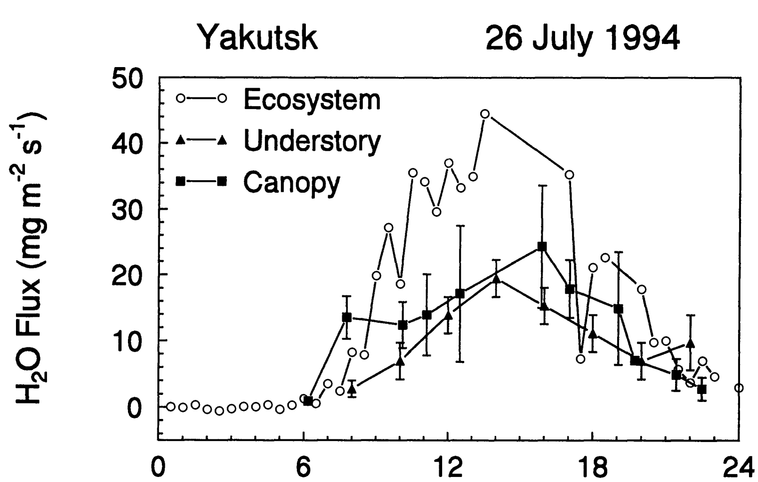

FIG. 3. Daily course of water flux in a Siberian *Larix* forest. The sum of understorey evaporation ($\pm$95% confidence limits) and scaled-up shoot transpiration ($\pm$95% confidence limits) is equivalent to the total ecosystem flux measured by eddy correlation (open circles).

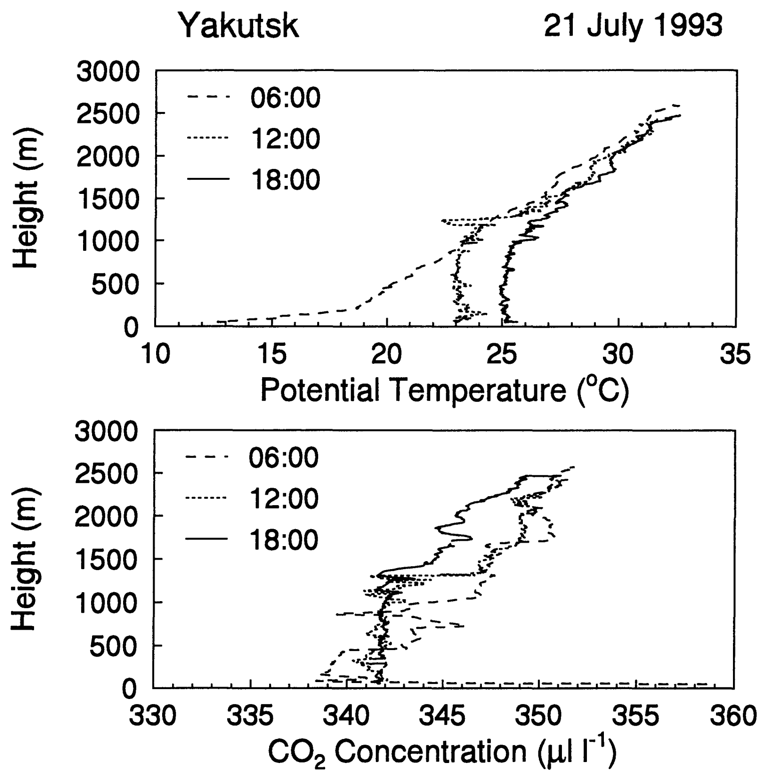

FIG. 4. Profiles of potential temperature (A) and CO_2 concentration (B) over *Larix* forest in eastern Siberia. During the day convective mixing minimizes gradients of these quantities in the *CBL*.

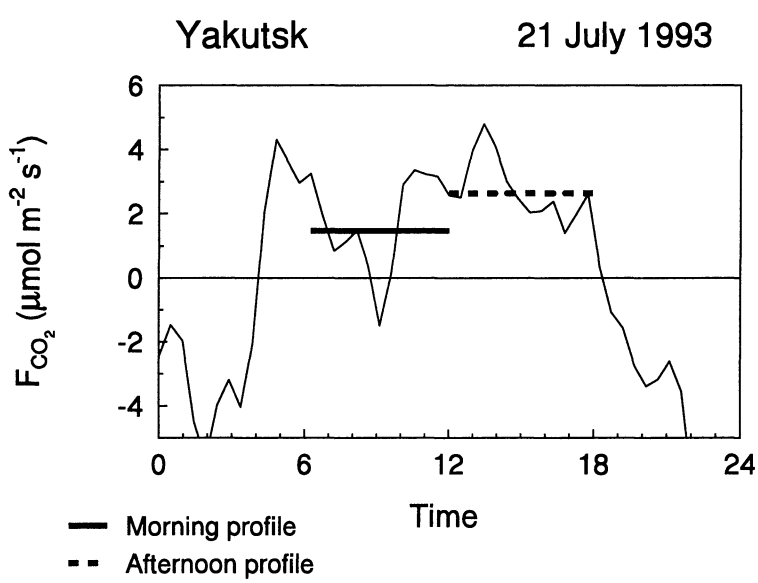

FIG. 5. Daily course of net ecosystem CO_2 exchange between a Siberian *Larix* forest and the atmosphere on a clear day in the middle of summer. The thin line connects smoothed, half-hourly measurements made from a tower with the eddy correlation technique. The horizontal solid and dashed bars represent mean regional CO_2 fluxes, estimated from aircraft measurements (see Fig. 4) using a convective boundary layer budget method, over the two time periods.

by noon. The gradients of Θ and CO_2 concentration through the *CBL* at this time and later in the day are minimal (Fig. 4). Above ~1300 m, the morning and noon CO_2 profiles coincide but noon and evening profiles do not coincide until ~2300 m, suggesting that air is being entrained from above into the *CBL* during the afternoon. Large entrainment fluxes across the top of the mixed layer have been observed over other forests (Martin *et al.*, 1988).

Integrating the concentration profile differences (to 2500 m) yields mean morning and afternoon regional CO_2 fluxes of ~ 1.5 and ~ 2.6 $\mu mol \times m^{-2} \times s^{-1}$ (Fig. 5). These CO_2 fluxes are comparable to the corresponding average patch-scale ecosystem eddy fluxes of 1.7 and 2.8 $\mu mol \times m^{-2} \times s^{-1}$, respectively, measured at the tower site. However, they were considerably less than earlier regional CO_2 fluxes estimated by the *CBL* technique over tropical forest (Wofsy, Harris & Kaplan, 1988) and Australian farmland (Raupach *et al.*, 1992), emphasizing the importance of vegetation physiological activity on larger-scale processes.

Raupach *et al.* (1992) showed that the along-wind length scale for regional flux estimates was related to the product of the mean wind speed in the *CBL* and the *CBL* height divided by a convective velocity scale. Accordingly, the midday regional along-wind length scale in Siberia was ~ 20 km with an averaging (source or footprint) area of ~ 50 km^2. This is nearly four orders of magnitude larger than the tower-based eddy flux footprint. However, during the night and early morning when *CBL* height and windspeeds are low, the regional along-wind length scale and averaging area may be < 1 km and < 2.5 km^2.

The speed, large-scale integration and relatively modest equipment requirements (excluding aircraft) of the *CBL* budget method suggest that this technique should be used more widely for assessing regional CO_2 fluxes. Another advantage of the method is that airmasses can be followed for repeated sampling throughout the day. However, the *CBL* profile method is limited to high pressure and fair weather conditions, meaning that flux estimates may not be indicative of values during other weather conditions. In addition, the draw-down of atmospheric CO_2 during the day is low, placing high demands on analytical precision. A net exchange of 5 $\mu mol \times m^{-2} \times s^{-1}$ between the surface and the atmosphere, for example, changes the CO_2 concentration in the *CBL* by only ~ 0.5 p.p.m. h^{-1}. Nevertheless, our successful test of the *CBL* budget method using tower-based eddy flux measurements in a uniform region bodes well for future applications, especially in regions with a mosaic of vegetation patches where a multitude of tower-based measurements might not be possible.

CONCLUSIONS

CO_2 and water vapour fluxes between the Siberian *Larix* canopy or whole ecosystem and the atmosphere are very low. The small magnitude of these fluxes contributes to their measurement uncertainty but also reduces feedbacks between the forest and atmosphere (e.g. McNaughton & Jarvis, 1983).

Cuvette measurements of CO_2 and H_2O exchange in this simple, homogeneous and low LAI forest were scaled by LAI and approximated measurements made at a higher scale by eddy correlation techniques. In turn, tower-based measurements of carbon dioxide exchange agreed with convective boundary layer budget estimates in this region of uniform forest. The natural integration inherent in the eddy flux and *CBL* techniques and the relative constancy of effort required with these techniques argues strongly for the adoption of the measurement technique closest in scale to the problem of interest.

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