한국농림기상학회지, 제5권 제2호(2003)
Korean Journal of Agricultural and Forest Meteorology, Vol. 5, No. 2, (2003), pp. 138~149

Inferring Regional Scale Surface Heat Flux around FK KoFlux Site: From One Point Tower Measurement to MM5 Mesoscale Model

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FK KoFlux 관측지에서의 지역 규모 열 플럭스의 추정: 타워 관측에서 MM5 중규모 모형까지

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ABSTRACT

Korean regional network of tower flux sites, KoFlux, has been initiated to better understand CO_2, water and energy exchange between ecosystems and the atmosphere, and to contribute to regional, continental, and global observation networks such as FLUXNET and CEOP. Due to heterogeneous surface characteristics, most of KoFlux towers are located in non-ideal sites. In order to quantify carbon and energy exchange and to scale them up from plot scales to a region scale, applications of various methods combining measurement and modeling are needed. In an attempt to infer regional-scale flux, four methods (i.e., tower flux, convective boundary layer (CBL) budget method, MM5 mesoscale model, and NCAR/NCEP reanalysis data) were employed to estimate sensible heat flux representing different surface areas. Our preliminary results showed that (1) sensible heat flux from the tower in Haenam farmland revealed heterogeneous surface characteristics of the site; (2) sensible heat flux from CBL method was sensitive to the estimation of advection; and (3) MM5 mesoscale model produced regional fluxes that were comparable to tower fluxes. In view of the spatial heterogeneity of the site and inherent differences in spatial scale between the methods, however, the spatial representativeness of tower flux need to be quantified based on footprint climatology, geographic information system, and the patch scale analysis of satellite images of the study site.

***Key words* : tower flux, regional-scale flux, CBL budget, MM5 mesoscale modeling**

I. INTRODUCTION

Korean regional network of tower flux sites, KoFlux, has been established to improve our understanding of CO_2, water and energy exchange mechanisms between ecosystems and the atmosphere; and to contribute to

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the regional, continental, and global networks such as FLUXNET and CEOP (Kim *et al.*, 2002; http://koflux.org). Eddy covariance method is employed to measure surface energy and CO_2 fluxes in all KoFlux sites. Most of flux towers are, however, located in non-ideal sites due to inhomogeneous patch-scale vegetation and complex topography. This complicates the application of eddy flux measurement due to additional terms (e.g., horizontal and vertical advection) to consider (Lee, 1998; Finnigan, 1999; Paw U *et al.*, 2000; Massman and Lee, 2002). However, it is practically difficult to quantify these effects using only tower-based micrometeorological observation. Three-dimensional observations or incorporations of appropriate models become necessary for quantifying these advection effects over complex, heterogeneous terrains (Massman and Lee, 2002).

While tower-based eddy covariance measurements cover relatively small region (1-10 km^2), current demands for understanding carbon and energy cycles on regional and continental scales have grown in the science community and societies. As a result, numerous large scale experiments and long-term observations have been formed on the basis of networking the flux towers. Convective boundary layer (CBL) budget method is one of the recent tools to infer regional surface fluxes and has been used to estimate surface fluxes of heat, water, CO_2, and NH_4 (e.g., Wofsy *et al.*, 1988; Munley and Hipps, 1991; Raupach *et al.*, 1992; Denmead *et al.*, 1996; Levy *et al.*, 1999; Gryning and Batchvarova, 1999; Cleugh and Grimmond, 2001; Laubach and Fritsch, 2002). In this approach, CBL is considered as a natural mixing chamber for estimating surface fluxes on regional scale ($10^2 \sim 10^4$ km^2). Strong mixing by turbulence in CBL naturally averages out small scale surface heterogeneities (Raupach and Finnigan, 1995).

Recently, Laubach and Fritsch (2002) re-examined the CBL budget method theoretically and suggested new concept of CBL budget method. The overall objective of this study was to infer the regional scale surface heat fluxes around FK site. To accomplish this goal, we employed CBL budget method and quantified the effect of horizontal advection on surface flux using radiosonde data collected at the site following Laubach and Fritsch (2002). We compared the tower-based heat fluxes with those obtained from different approaches such as NCEP/NCAR Reanalysis data (NNRD) and the output of Penn State-NCAR mesoscale model MM5 near this tower site. Through this comparison, we explored whether single tower of eddy covariance measurements can provide a representative flux over heterogeneous surfaces.

II. MATERIALS AND METHODS

2.1. Site description

FK KoFlux site is located at Haenam-gun, Jeollanamdo, Korea (34.55° N, 126.57° E, 13.74 m m.s.l.) (Fig. 1). Typical land cover types around the study site are typical farmland vegetation mixed with scattered rice paddies. Also found around the tower are the roads, small hills, residential areas, and scattered small forests with occasional biomass burnings. In a regional sense, there are small towns, water reservoirs, and rivers. Topography around FK site is relatively flat on a regional scale, except Wolch'ul Mountain (809 m m.s.l.) and Duryun Mountain (703 m.s.l.) which are located about

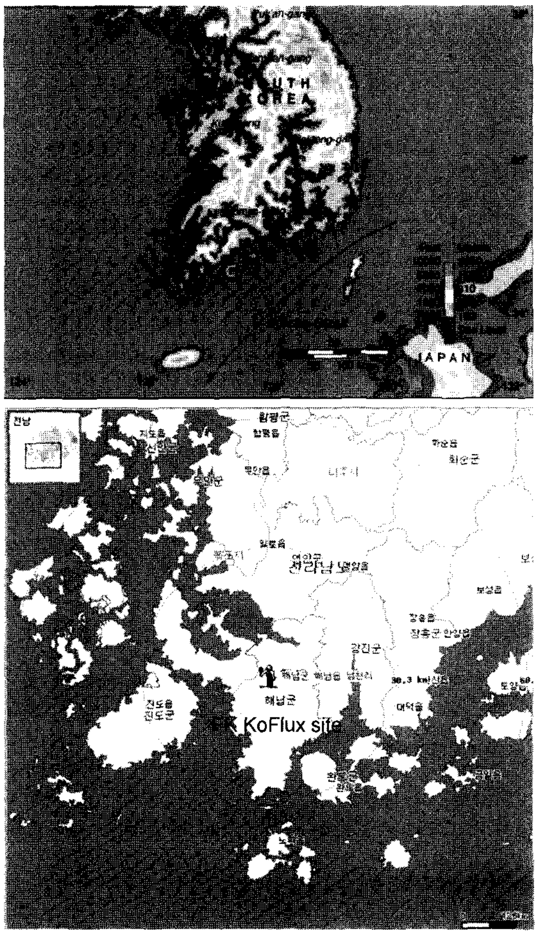


Fig. 1. Map of FK KoFlux site.

30 km north and 20 km south of the flux tower, respectively. It is also worth noting that the FK flux tower was within 30 km of the ocean (Fig. 1).

2.2. Field observation

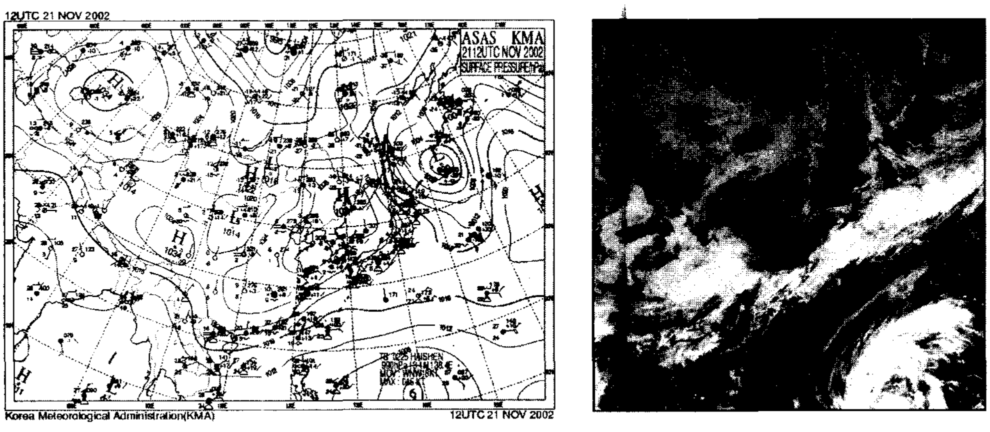
The surface flux measurements on a 25 m tower have been made since June 2002, and occasional radiosonde measurements have been performed by Meteorological Research Institute of Korea Meteorological Administration (KMA). The radiosonde data used in this paper were collected from 21 to 23 November 2002 and the profile measurements were made every three hours each day during this period. Eddy covariance system at FK site consists of three-dimensional sonic anemometer (CSAT3, Campbell Scientific, USA) and open-path H_2O/CO_2 gas analyser (LI7500, LICOR, USA) at 21 m above the ground (Fig. 2). CNR1 (Kipp & Zonnen, Germany) net radiometer was also installed at 20 m above the ground, and two sets of soil temperature probes (TCAV, Campbell Scientific, USA), soil moisture probes (CS615, Campbellsci, USA), and soil heat flux plates (HFP01SC, Hukseflux, The Netherlands) were buried at 0.1 m under the ground. Pan evaporation was also measured at the tower site. The meteorological variables measured in radiosonde observations were atmospheric pressure, geopotential height (gpm), relative humidity, wind speed, and wind direction. More detail information on micrometeorological and soil measurements at FK site can be found in Lee *et al.* (this issue) and in KoFlux website (http://koflux.org).

Fig. 2. Eddy covariance sensors including 3-d sonic anemometer and H_2O/CO_2 open-path gas analyser.

Sampling rate and averaging time for eddy covariance flux measurements are 10 Hz and 30 minutes, respectively. All the data were saved and processed on a real time basis in a data logger (CR5000, Campbell Scientifci, USA). Then the data were transferred to 1 Terra byte Linux file server at the Laboratiry for Atmospheric Modeling Research (LAMOR) at Yonsei University through KMA intranet using FTP. Post-processing of the field data were executed in COMPAQ DEC workstation using data processing program developed in Biometeorology Laboratory at Yonsei University (see, Hong and Kim, 2002; Technical note, http://koflux.org/biome/hong/technote.htm).

2.3. Weather conditions

Examination of synoptic weather conditions is a



(a) (b)

Fig. 3. (a) Surface pressure pattern on 12 UTC, 21 November 2002 and (b) visible satellite image on 03 UTC, 22 November 2002.

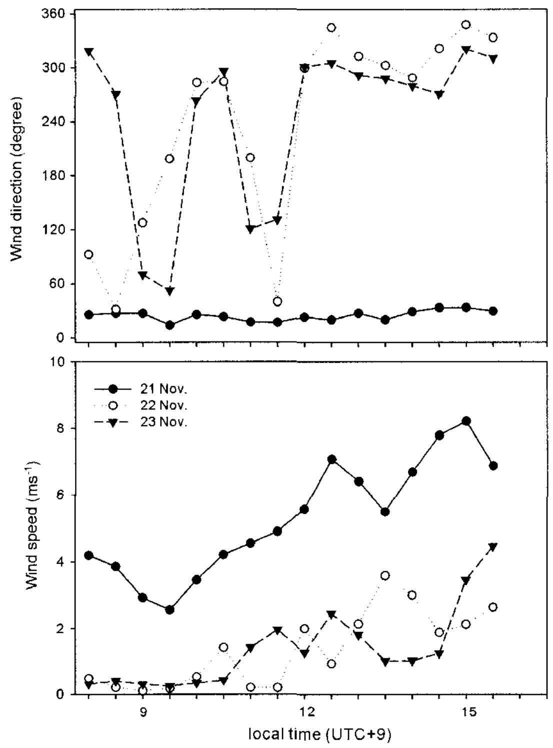


Fig. 4. The diurnal variation of wind direction and wind speed at a flux tower during 21~23 November 2002. Time is local time (UTC+9).

prerequisite in an application of convective boundary layer (CBL) column approach which can be used only under fair weather conditions. During the study period, the Peninsular was under the influence of high pressure system over northwest Manchuria (Fig. 3). Maximum and minimum air temperatures (at 20 m above ground) were 15.9°C and -2.4°C. Wind was mainly from north (from 315° to 45°) and the daytime mean wind speed (at 20 m) was generally >1 ms^{-1} (Fig. 4). There was no precipitation during this period, except the morning fog on 22 November 2002. It was partly cloudy on 21 November, but became fairly clear for the remaining period. As the Typhoon, "Haishen", moved northward, the atmospheric pressure at the flux site began falling.

2.4. CBL budget method

Theoretical background of CBL budget method is well documented in the literature (e.g., Raupach *et al.*, 1992; Laubach and Fritsch, 2002). Laubach and Fritsch (2002) suggested two approaches in CBL budget method. One, so-called "CBL column approach", is a traditional method based on Lagrangian concept. The other, "fixed column approach", is based on Eulerian concept. In our study, we applied the former approach, following Laubach and Fritsch (2002). In the case of heat, cumulative surface heat flux, I_θ^G, can be described as (Laubach and Fritsch, 2002):

$$\frac{I_\theta^G}{c_p\rho} = \underbrace{z_{i2}(\langle\theta\rangle_{i2}-\theta_{+2})}_{(I)} - \underbrace{z_{i1}(\langle\theta\rangle_{i1}-\theta_{+1})}_{(II)} + \underbrace{\frac{\gamma_\theta}{2}(z_{i2}^2-z_{i1}^2)}_{(III)} + \underbrace{\int_{t_1}^{t_2} w_+(\theta_+-\langle\theta\rangle_i)dt}_{(IV)} + \underbrace{\frac{I_\theta^H}{c_p\rho}}_{(V)} \quad (1)$$

where z_i is CBL height, t time, w vertical wind speed, c_p specific heat capacity, ρ air density, θ potential temperature, and γ_θ vertical gradient of potential temperature. z_{i1} indicates z_i at t_1 and subscript "+" implies the potential temperature at z_i. $\langle\ \rangle$ indicates the averaging with whole CBL depth. I_θ^G and I_θ^H are given as time integration of heat flux at the ground, F_θ and horizontal advective flux, F_θ^H:

$$I_\theta^G = \int_{t_1}^{t_2} F_\theta dt \quad (2\text{-}1)$$

$$I_\theta^H = \int_{t_1}^{t_2} F_\theta^H dt \quad (2\text{-}2)$$

Also, if we assume height-independent gradient of potential temperature, the integrated subsidence flux, fourth term in righthand side of Equation (1), can be parameterized (Laubach and Fritsch, 2002):

$$\int_{t_1}^{t_2} w_+(\theta_+-\langle\theta\rangle_i)dt = -\overline{w_+}\,\overline{\theta_+} - \frac{1}{2}(\langle\theta\rangle_{i1}+\langle\theta\rangle_{i2})\,(t_2-t_1) \quad (3)$$

where overbar means the time averaging between t_1 and t_2. Laubach and Fritsch (2002) also formulated the cumulative maximalistic horizontal advection for the CBL column approach as:

$$I_\theta^B = \frac{1}{2}(z_{i2}+z_{i1})(t_2-t_1)\frac{\partial\theta^A}{\partial t} \quad (4\text{-}1)$$

Moreover, cumulative minimalistic horizontal is given as:

$$I_\theta^A = \frac{1}{2}(z_{i2}-z_{i1})(t_2-t_1)\frac{\partial\theta^A}{\partial t} \quad (4\text{-}2)$$

$(\partial\theta/\partial t)^A$ is the potential temperature change with time due to only horizontal advection, was estimated following Laubach and Fritsch (2002). We constructed θ profile at t_2 from θ at t. when there was nothing but subsidence motion. This process was obtained by shifting θ profile at t_1 along z-axis by $\Delta z=\gamma_\theta z(t_2-t_1)$ and changing air density with dry adiabatic lapse rate.

Equation (1) explains that total column changes in CBL depend on the surface heat fluxes, entrainment processes, subsidence motion, and horizontal advection. In equation (1), each term has own physical meaning. (I)+(II) can be interpreted as the mean drawdown effect due to the jump of ρ_s across the CBL top. (III) is the deviation from this mean drawdown. (IV) can be considered as the subsidence fluxes and (V) be horizontal advective fluxes. The sum of (I), (II), and (III) accounts for the change of total column potential temperature and entrainment processes together. See Laubach and Fritsch (2002) for detail.

For inferring regional heat fluxes near FK KoFlux site using CBL column approach, CBL height was evaluated visually from the potential temperature profile from radiosonde measurements. Air density and potential temperature averaged in the entire CBL depth were calculated numerically using trapezoidal rule. Vertical wind speed at CBL height was computed in two different ways. First, vertical wind speed was calculated using the linear interpolation from NNRD at the nearest point from FK site. The horizontal resolution of NNRD was 2.5°. Second, vertical wind speed was estimated from the gradient of potential temperature at CBL top, θ_+ and γ_θ (Stull, 1988).

Table 1. Vertical wind speed ($cm \cdot s^{-1}$) from (a) potential temperature profile of sonde measurements and (b) from NCEP/NCAR Reanalysis data

Case number	Date	Time	z_i (m)	w_+ from eqn. (5)	w_+ from NNRD
21b	21 Nov.	05 UTC	934.5	0.76	1.24
21c	21 Nov.	08 UTC	841	0.55	1.22
22a	22 Nov.	02 UTC	632	4.17	
22b	22 Nov.	05 UTC	1352	1.38	1.83
22c	22 Nov.	08 UTC	1528.5	0.57	
23a	23 Nov.	02 UTC	1130	2.18	
23b	23 Nov.	05 UTC	1388	2.25	0.42

$$w_+ = -\frac{1}{\gamma_\theta}\frac{\partial\theta_+}{\partial t} \quad (5)$$

Table 1 shows the retrieved vertical wind speeds from two different data sources. The inferred vertical wind speed at CBL top, w_+ was about from 0.55 cm s^{-1} to 4.17 cm s^{-1}. The magnitude of w_+ is relatively larger compared with the results from Laubach and Fritsch (2002). It implies that the subsidence motion was important in CBL budget around FK KoFlux site, which is confirmed with the relatively large contribution of (IV) term in equation (1). Generally, the vertical wind speed did not show consistent variation with different data sources. In our study, we compared the regional heat fluxes using two independent data sources as mentioned above.

We can approximately deduce the horizontal source area (A) of the CBL budget method by following Raupach *et al.* (1992):

$$A = L_x \cdot L_y = [U(t_2-t_1)] \cdot [\sigma_v \cdot (t_2-t_1)] \quad (6)$$

With U=~4 ms^{-1}, σ_v=~1 ms^{-1}, and (t_2-t_1)=~3 to 6 hours, we obtain A of roughly 500 to 1000 km^2.

2.5. Simulation of MM5 mesoscale model

The nonhydrostatic MM5 model (version 3) was used in our simulation from 18 UTC on 20 November to 18 UTC on 23 November 2002. NCEP/DOE Reanalysis 6 hourly data were used for initial and boundary conditions, and two horizontal domains nested with grid sizes of 45 km and 15 km. The model physics used in this study included simple ice microphysics (Dudhia, 1989), Kain-Fritsch convection scheme (Kain and Fritsch, 1993), and Medium-Range Forecast (MRF) planetary boundary layer (PBL) model (Hong and Pan, 1996). The land cover classification was from U.S. Geological Survey 1 km data sets. The number of vertical layer was 23 and integration time step was 120 seconds. Numerical integration was conducted using COMPAQ FORTRAN compiler in COMPAQ DEC workstation (TRU 64 UNIX). Detailed information on MM5 mesoscale model is available at http://www.mmm.ucar.edu/mm5.

III. RESULTS AND DISCUSSION

3.1. Potential temperature profiles from radiosonde observations

In general, during the studied period, CBL heights, z_i

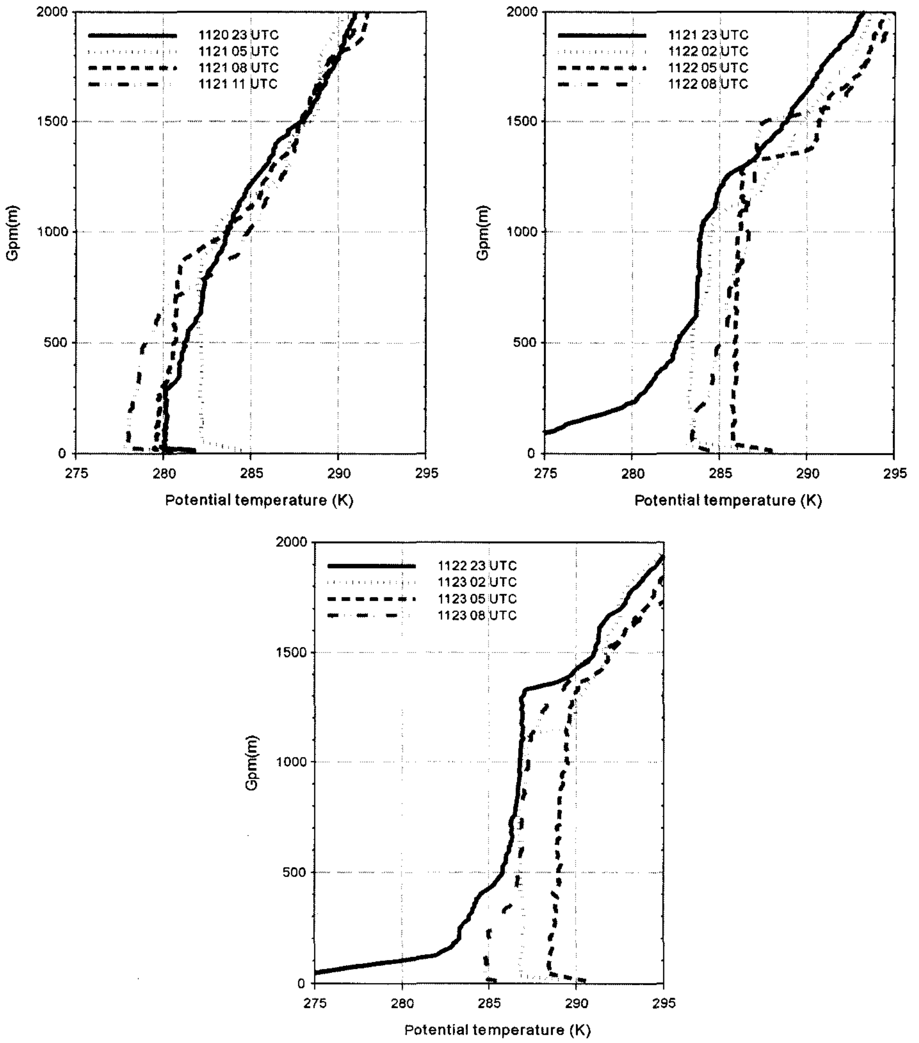


Fig. 5. The evolutions of the potential temperature profiles.

grew up to about 1600 m, but showed some variability from day to day (Table 1). The potential temperature averaged for the whole column of CBL was different each day. For example, it was 283 K on 21 November but was 288 K on 23 November although magnitudes of surface heat fluxes measured at the tower were similar on these two days.

In the morning of 21 November, the atmospheric stability became unstable near the surface while the residual layer still remained above (Fig. 5). The maximum $\bar{\theta}$ was relatively lower (~282 K), compared to those on the next two days. Potential temperatures showed no significant changes above the CBL height. Wind was steady from north all day. The shape and evolution of θ profiles might have been affected by clouds on this day, causing possible problems in interpreting the results of CBL budget approach. In the middle of this day, CBL depth was contracted during the period of 0500-0800 UTC, possibly due to strong subsidence and/or horizontal advection. Careful examination of the magnitude of each term in Eq. (1) suggested that the latter was likely the main cause (see Section 3.3 below).

On both 22 and 23 November, wind direction suddenly changed and then fluctuated between easterly and northwesterly. On both days, strongly stable surface layer prevailed in the morning. The potential temperatures averaged for the whole CBL column, $\langle\theta\rangle$, increased by approximately 2.5 K during 0200-0500 UTC. Maximum $\langle\theta\rangle$ was about 286 K and 289 K on 22 and 23 November, respectively. Above the CBL height in the free atmosphere, the potential temperature increased by about 1° per every three hours during daytime.

3.2. Sensible heat flux from eddy covariance tower

Sensible heat flux varied from near zero during nighttime to about 150 Wm^{-2} during the day. Its diurnal pattern generally followed that of net radiation, but showed more short-term fluctuations (when compared to relatively smooth changes in net radiation), likely due to scattered anthropogenic activities around the tower such as passing cars and biomass burning. Corresponding to the diurnal variation of sensible heat flux at the surface, PBL height grew up to about 1600 m (Table 1 and Fig. 6). Such positive relation between diurnal changes in sensible heat flux and PBL evolution has been well documented in the literature (e.g., Stull, 1988; Arya, 2001; Laubach and Fritsch, 2002). Precisely speaking, as pointed out in Section 2.4, CBL height depends on the magnitude of surface heat flux, entrainment, subsidence motion, and horizontal advection. The relative contribution of each term to CBL evolution are discussed in Section 3.3.

We examined the diurnal variation of the Bowen ratio (β, ratio of sensible heat to latent heat flux) during the study period to check whether the enegy partitioning reflected any spatial heterogeneity in the surface characteristics around the flux tower (Fig. 7). The variations in β are controlled by a suite of parameters associated with, among other things, meteorology, biophysics and ecophysiology of the site. However, in a relatively homogeneous area, β is nearly constant during the day. Therefore, the variation of β with different wind direction and footprint (which is a function of measurement height, atmospheric stability and surface roughness) may be used as an indirect measure of surface heterogeneity.

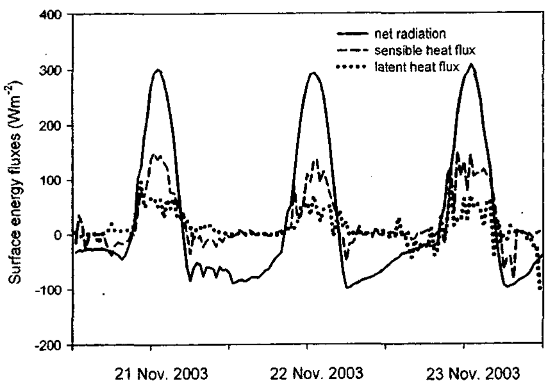


Fig. 6. Surface energy fluxes observed by eddy covariance method at FK KoFlux site.

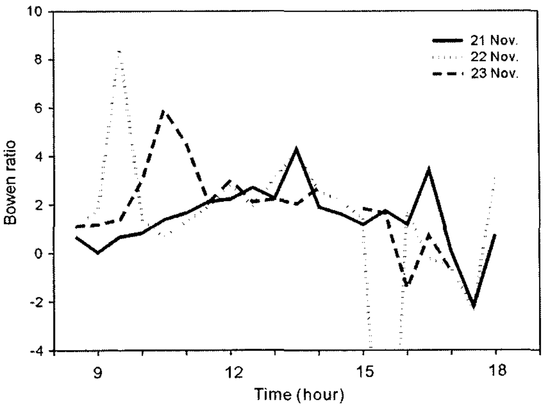


Fig. 7. The diurnal variations of Bowen ratio for 21~23 November 2002. Time is local time (UTC+9).

On 21 November, wind was predominantly from north throughout the day. The Bowen ratio varied from 0 to 4 and showed positive (0.45) with wind speed and negative (-0.52) correlation with z/L (z is the measurement height and L is Obukhov length), respectively. In other words, as the flux footprint stretched out with decreasing atmospheric stability, more warmer and drier areas were included in the tower flux measurements, resulting in higher Bowen ratio. On the other hand, the differences in β in the mornings of 22 and 23 November seemed to be caused by the shift in wind direction. In addition, there was indirect evidence of horizontal advection of sensible heat (i.e. oasis effects) in late afternoon hours near sunset. Although the tower flux was a result of direct measurement, interpretation of the observed flux is complicated by the temporally changing flux footprint and the subsequent underlying, spatially varying surface properties due to site heterogeneity. This challenge naturally leads our attention to the use of tower flux in CBL budget method to infer regional scale flux, as discussed below.

3.3. Comparison of fluxes from tower, CBL budget, MM5 and NNRD

3.3.1. Tower flux and CBL budget method

We summarized the results of measured, estimated, and modeled surface heat fluxes from various methods in Table 2. The horizontal advection was not considered in CBL budget method. It should be noted that the direct comparison of heat flux from these two approaches is not valid unless the area covered by the CBL budget method is perfectly uniform. In fact, the advantage of CBL budget method is to naturally integrate the surface heterogeneity by using the well mixed atmospheric CBL chamber with tower measurement of representative surface flux from the bottom of the chamber. Therefore, the flux difference between the two estimates represents the averaging effect of heterogeniety in FK site, provided no errors are involved in flux estimations.

In the cases 22ab and 22ac in Table 2, the heat flux from CBL budget method was relatively larger than the tower flux; whereas both were comparable in the case 22bc. Unfortunately, the observed difference or no difference in heat flux could be related to either averaging effect of the surface heterogeneity by CBL method or simply the artifact of ignoring advection in CBL method.

In section 3.2, we reported the increase of the Bowen ratio with increasing footprint from the tower. In the case of 22ac, the horizontal source area was larger than those of other cases (because time difference was 6 hours). Heat flux estimate from 22ac was greater than the averaged estimate of 22ab and 22bc, suggesting that spatial gradients in heat flux existed on a regional scale. Therefore, it was likely that the regional heat fluxes from CBL budget method included greater land surface which was warmer and drier, resulting in greater heat flux.

Table 2. Surface heat fluxes, F_θ(Wm^{-2}) with various horizontal source areas. Superscript 'T', 'MM5', and 'NNRD' is the surface heat fluxes from a tower, MM5 mesoscale model, and NCEP Reanalysis data respectively. Superscript 'CBL' and 'CBL$_N$' imply the surface heat fluxes from CBL budget method using eqn.(5) and NNRD for calculation of vertical wind speed. Horizontal advection was not considered

Data Set	F_θ^T	F_θ^{MM5}	F_θ^{CBL}	$F_\theta^{CBL_N}$	F_θ^{NNRD}
Source Area	<1 km^2	~10^2 km^2	10^2~10^3 km^2	10^2~10^3 km^2	~10^4 km^2
21bc	59	36	-209	-210	-18
22ab	106	95	223	195	51
22bc	51	40	34	58	-23
22ac	79	68	174	167	32
23ab	75	50	317	297	56

For the case of 21bc with cloudiness on 21 November, unrealistic heat flux of -200 W m^{-2} was obtained with CBL budget method during daytime. Laubach and Fritsch (2002) stated that the heat sink due to dissipation of clouds was not included in Eq. (1) and thereby offsetting sensible heat flux to be negative. For the case of 23ab, the heat flux from CBL budget method was 4 times larger than the tower flux. Such large heat flux might have resulted from changes in wind direction on 23 November. Indeed, different air mass affected the study region on this day, and it was confirmed with unreasonable magnitude of horizontal advection.

The relative contribution of individual terms in Eq. (1) to total sensible heat flux was also examined. The magnitude of subsidence motion ranged from 0 to 75 Wm^{-2}, which seemed larger than those of Laubach and Fritsch (2002). The sum of terms (I) and (II) tended to cancel out with positive value of term (III), except the case 21bc when the term (III) was negative (-130 Wm^{-2}) due to contraction of CBL depth. Because the term (IV) was near zero, the large horizontal advective flux (-217 Wm^{-2}) probably caused the contraction of CBL depth.

3.3.2. Tower flux and MM5 modeled flux

There was a good agreement between tower-based sensible heat fluxes and those simulated with MM5 mesoscale model except the periods around sunset. During this period, MM5 outputs showed no sign of sensible heat advection, which was observed in the tower flux measurement (Fig. 6). Oncley and Dudhia (1995) also reported that surface sensible heat flux from MM5 showed a good agreement with those from eddy covariance tower. With the known mismatch of footprint and site heterogeneity, however, such an agreement indicates neither that MM5 realistically simulated surface heat flux nor that tower flux well represented the regional flux. To accurately address this scaling issue, careful considerations must be given to temporal, spatial, and process matching between the two different scales (i.e., from 1-10 km^2 to 100-1000 km^2). Nevertheless, we noted that MM5 simulated the diurnal pattern of surface flux reasonably well without the coupling of more realistic land surface model. We suspect that the negative feedback in mesoscale model between PBL and the land surface could be dominant around this study region. For example, an overestimation of sensible heat flux causes the PBL temperature increase which, in turn, results in decreasing sensible heat exchange at the next time step in the mesoscale model (S. Y. Hong, personal communication). Alternatively, Raupach and Finnigan (1995) pointed out that regionally averaged energy balances over land surfaces were insensitive to the scale of heterogeneity. More thorough comparisons of all the energy balance components from MM5 and tower observations are currently underway.

3.3.3. Tower flux and NNRD

NNRD estimates of sensible heat flux were relatively

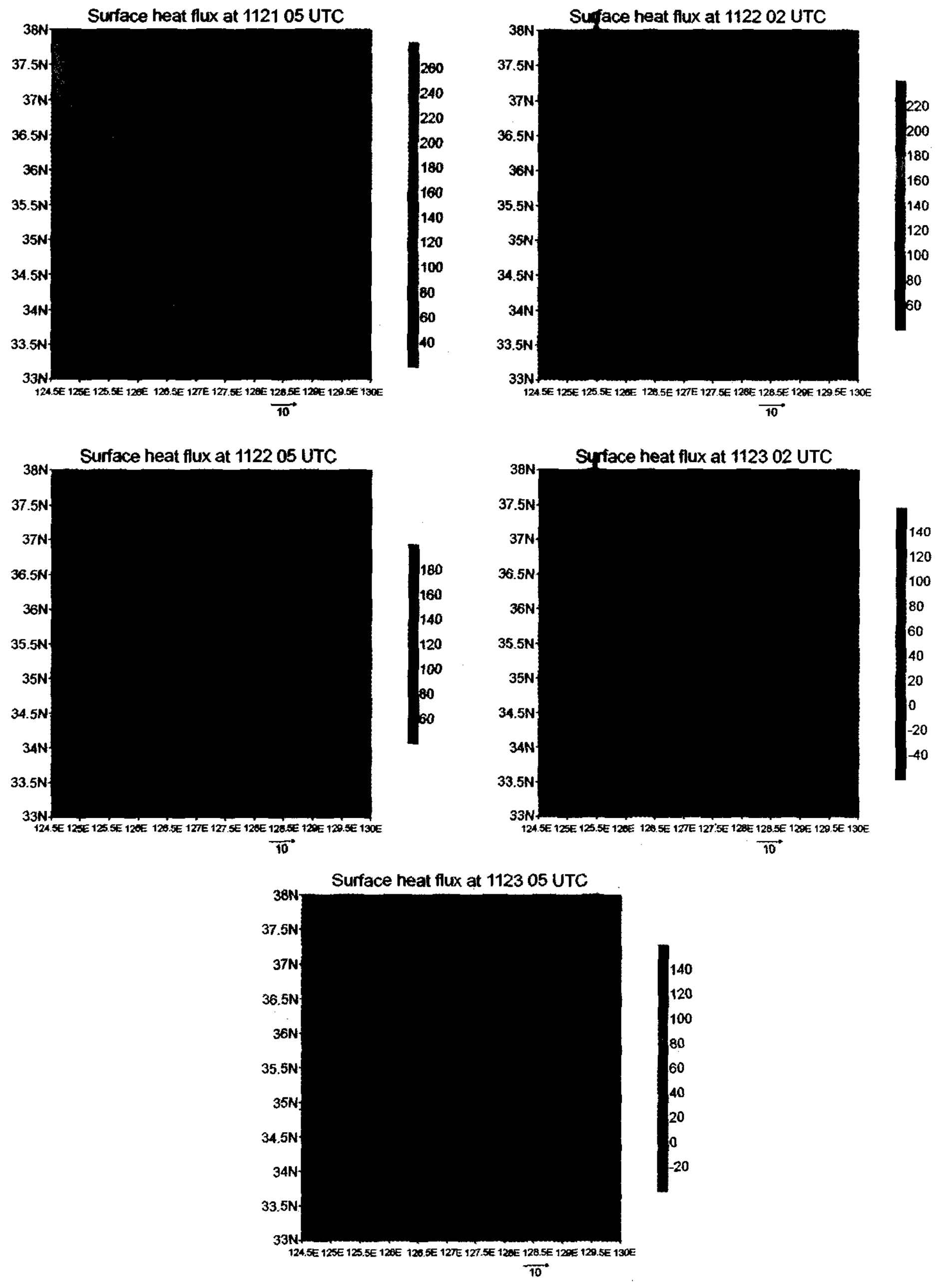


Fig. 8. Surface heat fluxes simulated by MM5 mesoscale model. Arrows are wind vector at 1000 hPa.

smaller than those from other data sets. Considering the coarse resolution (and therefore extensive spatial coverage) of NNRD, smaller fluxes may reflect relatively cooler areas on the north of study site (Fig. 8). This interpretation is valid only if the output of lumped model for given averaged inputs is same with the aggregated output of more detailed model using detailed inputs. Wood (1995) emphasized the importance of establishing the relationship between spatial variability in the inputs and model parameters, the scale being modeled and the proper representation of the hydrological processes at that scale. At present, adequate information on nonlinear interactions at different scales is not available and more research is needed on scaling of tower flux to larger scale based on footprint climatology, geographic information system, and the patch scale analysis of satellite images of the study site.

3.4. Effects of horizontal advection on CBL budget method

Results on the estimates of horizontal advection are summarized in Table 3. Following Laubach and Fritsch (2002), we included the advective flux in two different approaches: (1) horizontal advection exists only above z_i ($F_s^H = F_\theta^A$) and (2) horizontal advection is the same in all CBL depth ($F_s^H = F_\theta^A + F_\theta^B$).

F_θ^A was not negligible in magnitude and, if included, CBL budget estimates of heat flux approached tower-based estimates except the case 21bc. In the cases of 22ab and 22bc, the differences between the tower flux and the CBL budget method were within the measurement and computation errors. On the contrary, values of F_θ^B were unrealistic except for the case 21bc (in which large scale advective flux may have to be considered).

The background potential temperature changed substantially with a strong subsidence motion, yielding unrealistic magnitude of F_θ^B. It is also likely that large scale advection above CBL height may not represent the horizontal advection within CBL. The former is related with land-ocean differences but the latter due to patch scale heterogeneity may be dominant within the CBL. Garrat (1990) and Raupach and Finnigan (1995) pointed out the microscale and mesoscale advection by surface heterogeneity could be different. Laubach and Fritsch (2002) commented that the estimated advection would be inaccurate in heterogeneous terrain, where advection below z_i would be affected by local circulation patterns and internal boundary layers. Based on one-dimensional PBL model and MM5 mesoscale model, attempts are being made to quantify and constraint the horizontal advection at this site.

Table 3. Surface heat flux (Wm^{-2}) from CBL budget method considering horizontal advection. F_θ^A and F_θ^B are calculated from eqn. (4)

Data Set	F_θ^T	F_θ^A	$F_\theta^A+F_\theta^B$	F_θ^{CBL} (using F_θ^A)	F_θ^{CBL} (using $F_\theta^A+F_\theta^B$)
21bc	59	8	-151	-217	-58
22ab	106	67	252	155	-30
22bc	51	34	585	0	-550
23ab	75	-30	-321	347	639

IV. SUMMARY

In terms of inferring regional sensible heat flux from various measurement and modeling approaches, it was difficult to draw a general conclusion due to the limitation in the data and the assumptions used in the computations. Nevertheless, tower flux measurement has proven to be the practical backbone in bridging the scaling gaps between the different methods to estimate regional fluxes. Spatial heterogeneity of the site complicated the interpretation of the observed tower fluxes. The CBL budget method, based on the concurrent observations of radiosonde and tower flux, provides effective averaging scheme to overcome the issue of surface inhomogeneity. Yet, the uncertainty associated with estimating advection in the budget method still remains to be further investigated. Quantification of flux footprint must precede any further comparison of tower fluxes against regional fluxes simulated from models such as MM5.

적 요

KoFlux는 생태계와 대기 사이에 교환되는 이산화탄소, 수증기 및 에너지에 대한 우리의 이해를 높이고, FLUXNET과 CEOP 등의 지역, 대륙 및 전구 규모의 관측망에 기여하기 위해서 시작되었다. 그러나 한반도의 지형적 특성 때문에 KoFlux의 대부분의 플럭스 타워는 관측에 이상적이지 못한 장소에 위치하고 있다. 탄소 및 에너지 교환의 정량화를 위해서 뿐만 아니라 군락 규모에서 지역 규모로 확장하기 위해서는 관측과 모델링을 병용한 다양한 접근 방법의 적용이 필요하다. 본 연구에서는 지역 규모의 현열 플럭스를 추정하기 위해 타워 플럭스 관측, 대류 경계층(CBL) 수지 방법,

MM5 중규모 모형, 그리고 NCAR/NCEP 재분석 자료의 네 가지의 방법을 사용하여 다양한 면적을 대표하는 현열 플럭스를 산출하여 비교하였다. 비록 제한된 짧은 기간의 자료를 사용하였으나, 예비 분석을 통하여 (1) 해남 농경지 플럭스 타워에서 관측된 현열 플럭스가 지표의 불균질성을 보였고, (2) CBL 수지 방법으로 얻어진 지역 규모의 현열 플럭스는 수평 이류 효과의 계산 방법에 따라 다른 결과를 보였으며, (3) MM5 중규모 모형은 타워 플럭스 관측 값과 아주 유사한 현열 값을 수치 모사하였다. 그러나 관측지의 불균질성과 두 방법이 대표하는 면적의 근본적인 차이를 고려할 때, 플럭스 발자국 분석, 지리정보 시스템 및 관측지의 위성 영상 분석에 근거한 타워 플럭스의 공간 대표성을 정량화하는 것이 시급한 것으로 나타났다.

ACKNOWLEDGMENT

The financial supports for KoFlux were made by the Ministry of Environment of Korea through "The Eco-Technopia 21 Project" and The Ministry of Science and Technology (NRL Program). NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA. Special thanks go to sincere works of Hyuntak Kim and Byungkwan Moon at FK KoFlux site.

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