A bulk similarity approach in the atmospheric boundary layer to determine regional sensible heat fluxes

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ABSTRACT

Profiles of potential temperature measured by radiosoundings in the atmospheric boundary layer (ABL) were used with surface temperature measurements to determine regional sensible heat flux H by means of transfer parameterizations on the basis of bulk similarity. In the present study, the similarity function C was calibrated with the FIFE (First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment), NOPEX (Northern Hemisphere Climate Processes Land Surface Experiment, TABLE (Tsukuba Atmospheric Boundary Layer Experiment) and GAME-T data sets. Then the calibrated function was applied to the data set with the ABL bulk equation to derive H values which were compared well with reference fluxes of H_s with the rms error of the order of 20 Wm^{-2}.

1.Introduction

The knowledge of the amount of regional evapotranspiration is important for forecasting meteorological phenomena and estimating the water resources. One of the ways to determine the amount of evapotranspiration is through heat balance approach. In this approach the latent heat flux is calculated from the observation or estimation of the sensible heat flux (H), the net radiation (R_n) and the soil heat flux (G). In the present analysis, it is assumed that R_n and G are measured, and regional H values should be estimated from the ABL bulk similarity approach.

The surface sensible heat flux H can be written in the bulk similarity formulation as

$$H = \left(\theta_{s,r} - \theta_a\right) k u_* \rho c_p \Bigg/ \left[\ln\left(\frac{h_i - d}{z_{oh,r}}\right) - \mathrm{C}\left(\frac{h_i - d}{L}\right) \right] \qquad (1)$$

where $\theta_{s,r}$ is the surface potential temperature, θ_a the mean potential temperature of the mixed layer, k(= 0.4) von Karman's constant, u_* the momentum flux, ρ the density of the air, c_p the specific heat at constant pressure, d the displacement height, $z_{oh,\,r}$ the scalar roughness for sensible heat, h_i the top of the ABL and L the Obukhov length. The symbol C( ) denotes function of the stability parameter $(h_i - d)/L$.

In the present study, the function C of the bulk similarity formation was calibrated with the FIFE (First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment) (Sugita and Brutseaert, 1992), NOPEX (Northern Hemisphere Climate Processes Land Surface Experiment), TABLE (Tsukuba Atmospheric Boundary Layer Experiment) and GAME-T (GEWEX Asian Monsoon Experiment-Tropics).

2. Method

2-1. Experimentations and Data sets

2-1-1. TABLE

One data set was obtained during the TABLE project, which took place in the summer of 1992 in and around Tsukuba city in Japan. The area of 16 by 16 km can be characterized by its flat topography and its complex land usages. Surfaces are covered with forests, agricultural sites, grass fields, rice paddies and urban structures. Details of the area and experimentations can be found in by Sugita et al. (1993).

2-1-2. NOPEX

Another set of data was obtained during NOPEX Concentrated Field Effort 2, which took place in the spring and summer of 1995. The area of 40 by 70 km is flat and its surfaces were covered with dense boreal forest with clearings used for agriculture. Details of the area and experimentations can be found in Halldin et al. (1995).

2-1-3. FIFE

The data set was obtained during FIFE Intensive Field Campaigns (IFC) 1-4 in 1987 and IFC 5 in 1989 in northeastern Kansas. The area of 15 by 15 km is covered with tall grass prairie, with the height around 40 cm over a strongly dissected terrain. Details of the area and experimentations can be found in Sellers et al. (1988) and Murphy et al. (1991).

2-1-4. GAME-T

The other data set was obtained during a field campaign within the framework of the GAME-T project, which took place in February and March of 1999 in the central part of Thailand. The topography is generally flat except for a 100-m high hill some 1.5 km away from the site. Surface are covered with evergreen and deciduous forests whose height is variable in the range of 5 to 20 m, paddy fields, grasslands and farmlands, bare soil, water reservoirs and small villages (Toda and Sugita, 2003).

2-2. data sets

2-2-1. Radiosondinds

For the measurements of the ABL temperature, humidity and wind speed in daytime, radiosonde was used in all experiments. The details of the measurementations can be found in by Sugita and Brutsaert (1990a) for FIFE, Sugita et al. (1999) for TABLE and Hiyama et al. (1999) for NOPEX.

2-2-2. Surface fluxes

In all experiments, surface flux stations were deployed, where sensible heat flux were obtained and used as reference values H_s in the following analysis.

In the FIFE data sets, H_s is the averages of 6 stations in 1987 and is calculated by surface-layer analysis of temperature profile in 1989 because of difficulties of flux aggregation due to non-uniform nature of surface soil moisture. In both experiments of NOPEX and TABLE, H_s was evaluated by the following way; the stations in two experiments were deployed on all major surface types (5 stations in TABLE [Hiyama et al., 1995] and 2 in NOPEX [Mölder et al., 1998]. First, the time-averaged flux of each station was interpolated in time to produce the flux at the time of the radiosonde launch. The fraction a_i by which the particular surface type that occupies the footprint area was used as weighting factors to produce the area-averaged flux H_s as

$$H_s = \sum_{i=1}^{n} a_i H_i \tag{2}$$

where H_i represents the flux of the ith surface types of n major surface types in footprint area. For the size of the footprint area, a fan-shaped area with a 30° central angle extending 8 km for TABLE (Sugita et al., 1997) and 10 km for NOPEX (Hiyama et al., 1999) in the general upwind direction was employed.

In GAME-T, the turbulence measurements of wind velocity and temperature were carried out with a sonic anemometers mounted at 60 m on the tower. The measured values are treated as H_s.

2-3. The function C for sensible heat

The function form studied with the FIFE data set in Brutsaert and Sugita (1990) and Sugita and Brutsaert (1992) can be given as

$$\mathrm{C} = a \ln\left[-\frac{hi-d}{L}\right] + b \tag{3}$$

$$\mathrm{C} = a \ln\left[1-\frac{hi-d}{L}\right] + b \tag{4}$$

$$\mathrm{C} = a\left[-\frac{hi-d}{L}\right]^{b} \tag{5}$$

$$\mathrm{C} = \ln\left\{1+\left[-\frac{hi-d}{L}\right]^{a} \Big/ b\right\} \tag{6}$$

$$\mathrm{C} = \Psi_h\left(\frac{az_0}{L}\right) + \ln\left(\frac{h_i-d}{z_0}\right) - b \tag{7}$$

where a and b are the constants to be determined for and Ψ_h is the stability correction function for sensible heat for the surface layer profile equation.

The value of a and b are determined in the local calibration mode by a trial-and-error method. First, the H values are determined from (1) and (3)-(7) with arbitrarily selected a and b constants. The resulting fluxes are compared with independently determined reference H_s values, and such statistics as the correlation coefficient r, the ratio of means $[H_s]/[H]$, the regression coefficient c and e in a linear equation $H_s = cH + e$, and the root mean square (rms) error are evaluated. This process is repeated by changing *a* and *b* constants in a small step, and *a* and *b* values that produced the best agreement between H_s and H were finally selected as the calibrated constants.

3.Results

For all data sets, the result of *r*, *c*, *e*, $[H_s]/[H]$ and the rms error between H_s and H calculated with the calibrated C function is listed in Table 1, and the result for (1) with (7) is shown graphically in Figure 1.

They indicate that all of the combined data set calibrated work well with all data sets. However, the result for the NOPEX data is slightly worse than the others. $\Delta\theta$ ($\theta_{s,r}$ - θ_a) value of NOPEX data sets is generally very small, and as such the maximum δH (the probable error of H) value, contributed by the error of u_*, $z_{oh,\,r}$ and $\Delta\theta$ (Sugita et al., 1996), is as large as around 14Wm^{-2}. The - $(h_i$ - $d)/L$ values of the NOPEX data set also is closer to zero, and the value of C changes more for the same $-(h_i$ - $d)/L$ change near $-(h_i$ - $d)/L = 0$. This also contributes large error of this data set.

Table 1. Statistics in the comparision of H_s and H

	equation	r	c	e	$[H_s]/[H]$	rms error
FIFE	(4)	0.973	1.01	14.2	1.23	24.8
	(5)	0.971	1.01	14.3	1.24	25.1
	(6)	0.968	1.02	12.9	1.22	24.2
	(7)	0.972	1.01	14.1	1.23	24.6
	(8)	0.981	0.991	12.4	1.18	20.6
TABLE	(4)	0.989	0.992	0.535	1.00	3.55
	(5)	0.990	1.00	0.376	1.00	3.43
	(6)	0.988	1.01	-0.563	1.00	3.84
	(7)	0.990	0.994	0.408	1.00	3.47
	(8)	0.984	1.02	-1.15	0.998	4.37
NOPEX	(4)	0.839	0.701	34.2	0.922	30.1
	(5)	0.812	0.681	36.5	0.916	32.3
	(6)	0.737	0.567	49.0	0.864	43.4
	(7)	0.818	0.679	35.9	0.907	32.7
	(8)	0.678	0.565	54.4	0.913	40.5
GAME-T	(4)	0.994	1.16	-0.521	1.16	23.0
	(5)	0.996	1.16	-1.55	1.14	21.3
	(6)	0.993	1.17	-2.56	1.15	22.6
	(7)	0.995	1.16	-1.16	1.15	21.8
	(8)	0.995	1.08	1.82	1.10	15.7
combined data set	(4)	0.963	1.02	8.10	1.10	21.8
	(5)	0.961	0.989	8.14	1.09	22.2
	(6)	0.947	0.998	9.50	1.08	24.4
	(7)	0.961	1.02	8.25	1.09	22.1
	(8)	0.964	0.989	8.30	1.06	19.9

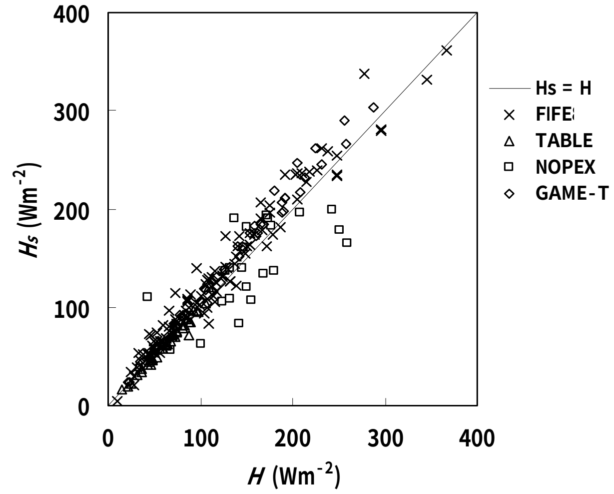

Figure 1. Comparison between H values calculated for combined data set with (1) and (7) with $a = 5.13$ and reference value H_s.

4.Conclusion

The stability functions C are determined for four data sets (FIFE, TABLE NOPEX and GAME-T) in which the surface usages are different, and it appears that the bulk similarity with those functions is capable of producing regional surface fluxes. However, the result also shows that depending the data set, the resulting H values tend to overestimate or underestimate the reference values. This might be due to the C-function which includes only the stability effect and which might need additional parameters to reflect other ABL physics.

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