Estimating Regional Distribution of Sensible Heat Flux over Vegetation using Satellite Infrared Temperature with Viewing Angle Correction

By Dai Matsushima

Geophysical Institute, Tohoku University, Sendai, Japan

and

Junsei Kondo

Emeritus Professor of Tohoku University, Hiratsuka, Japan

(Manuscript received 16 December 1999, in revised form 14 August 2000)

Abstract

The spatial distribution of sensible heat flux over rice paddies is estimated on a several tens kilometer scale, together with possible error estimation using satellite infrared data. It is found that three types of correction of satellite infrared temperature (correction for atmospheric absorption, satellite viewing angle, and the surface emissivity) over rice paddy yield estimation errors of 25 Wm^{-2} for sensible heat flux on a half-hourly basis as root mean squares errors (RMSEs). These errors are sufficiently small compared with general observational errors. In particular, the viewing angle correction is so significant that the RMSE is 46 Wm^{-2} without the correction. Atmospheric and emissivity corrections using the LOWTRAN7 with radio sounding data yield a good estimation of surface infrared temperature, with RMSE being 1.0°C . An empirical and linear parameterization proposed by Troufseau et al. (1997) is applied for the viewing angle correction. In the approach, parameters are refitted based on the surface infrared temperature data. The Troufseau et al. (1997) parameterization is applied over a wide range of leaf area index (LAI) from 0.01 through 5. This parameterization efficiently corrects the temperature deficit by the viewing angle effect caused by canopy geometry. However, this parameterization is insufficient when the sensible heat flux is large because the temperature deficit is essentially nonlinear with regards to the difference between surface infrared temperature and air temperature.

1. Introduction

Infrared surface temperature has often been used for estimating surface heat fluxes, and many estimation methods have been developed especially for vegetation (Norman et al. 1995; Sun and Mahrt 1995; Sugita and Brutsaert 1996; Qualls and Brutsaert 1996; Humes et al. 1997; Bussières et al. 1997; Kustas and Humes 1997; Matsushima and Kondo 1997). However, there are some difficulties in the flux estimation. First, satellites are usually at an extremely high altitude of several hundred kilometers or more, and absorption of the surface

signals by atmospheric gas components is significant. Second, the vegetation canopy has a vertical structure, so the infrared surface temperature varies with the measurement viewing angle (Brutsaert and Sugita 1996). Some optimal viewing angles for estimating sensible heat flux above horizontal-homogeneous vegetation have been proposed (Huband and Monteith 1986; Vining and Blad 1992; Matsushima and Kondo 1997). Matsushima and Kondo (1997) found that the root mean squares error of estimated sensible heat flux is within 30 Wm^{-2} over a wide leaf area index (LAI) range provided the viewing angle is 70° from nadir. Third, the emissivity of the surface is not exactly unity but slightly less, and this significantly influences the infrared surface temperature, especially under clear

Corresponding author: Dai Matsushima, Geophysical Institute, Tohoku University, Sendai, 980-8578, Japan. E-mail: matsu@wind.geophys.tohoku.ac.jp
©2000, Meteorological Society of Japan

sky conditions. In addition to the above, the quality of satellite sensors can deteriorate over time, and the spatial resolution of the sensor is limited to the scale of kilometers.

The objective of this paper is to propose an optimal method for estimating sensible heat flux using satellite infrared surface temperatures combined with surface meteorological data. The error range of estimates is also investigated. The distribution of roughness and wetness parameters on a subgrid scale is not considered in the present analysis because the present method is applied in horizontal-homogeneous vegetation (rice paddy), but not in a field with complex elements. In this paper, we describe a method for estimating sensible heat flux using satellite infrared temperature over a vegetation surface, surface meteorological data, and the physical parameters of the vegetation canopy. The estimated flux is validated by observational flux values which were obtained by the Bowen ratio method. Advanced Very High Resolution Radiometer (AVHRR) channel 4 ($10.3\text{--}11.3\ \mu\text{m}$) of NOAA is used for infrared surface temperature, and data from routine meteorological and environmental stations are used for the surface meteorological data. An empirical parameterization proposed by Troufleau et al. (1997) is applied for estimating the viewing angle correction. This parameterization is tested over a wide range of LAI (0.01 through 5). When the canopy is sparse ($\text{LAI} \sim 1$), and the magnitude of sensible heat flux is large, this linear parameterization might be insufficient and a nonlinear term should be added. Maps of the sensible heat flux distribution on a regional scale are then illustrated.

2. Infrared and meteorological data

2.1 Infrared and flux data for validation

Infrared and flux data for validating the estimation were acquired by field experiments in a rice paddy located in Kogota-town, Miyagi Prefecture, Japan ($38^{\circ}33'\text{N}$, $141^{\circ}02'\text{E}$, Flux site (A) in Fig. 1). Ground-based measurements investigating the angular distribution of the directional infrared temperature over a rice paddy were carried out during the planting period (from May through September) of 1993 and 1994. The LAI and the surface heat fluxes at this site were also obtained. The experimental field is located in an almost horizontal-homogeneous rice paddy with sufficient fetch (at least 2 km) in the prevailing wind direction (west-north-west, south-east, and southwest). Flux data used in the present analysis were derived by the Bowen ratio technique on a half-hourly basis. Details of the infrared and the flux experiment are described in Matsushima and Kondo (1997) and Ishida et al. (1997). Some supplemental measurements of the directional infrared temperature and the LAI as what was done in 1993 and 1994 were performed in June and July of

1997, and the data acquired in the experiments are also used for parameterization of the viewing angle correction.

Infrared and flux data obtained from another field campaign to detect heat transfer under sea breeze conditions in the Sendai Plain are also used for the validation, and the heat budget over a rice paddy and vertical profiles of wind, temperature, and humidity were obtained by radio soundings in the campaign. Flux data at this site (Flux site [B]) were also derived by the Bowen ratio technique on a half-hourly basis. At the flux site (B), the angular distribution of the directional infrared temperature was not obtained (nadir view only). Details of this field campaign are given by Kuwagata et al. (1994).

The directional infrared temperature data obtained in the ground-based measurements are representative data of 10–20 m scales of the paddy surface. The standard deviations of average infrared temperatures of 10–20 m scales over 500 m scale rice paddies are found to be $0.5\text{--}1^{\circ}\text{C}$ according to airborne observations which the authors performed (unpublished results). Therefore, the spatial representation of the directional infrared temperature data is considered to be sufficient for the present satellite data (1.1 km grid).

2.2 Satellite data

The Japan Image Database (JAIDAS) archived by Tohoku University is used as satellite infrared data. JAIDAS (<http://noaa.cc.tohoku.ac.jp/>) has daily NOAA-AVHRR images in and around Japan from 1990 to the present. These images are geometrically adjusted by universal transverse Mercator projection (1.1 km grid). In the present analysis, channel 4 data of NOAA-10, 11, and 12 are used as the infrared temperature, and their wavelength band widths are 10.6 to $11.5(\mu\text{m})$, 10.3 to $11.3(\mu\text{m})$, and 10.5 to $11.4(\mu\text{m})$. Twenty-six images are chosen for the present analysis based on the following reasons:

1. During the planting period (May through September).
2. Images acquired in daytime.
3. Few clouds (even some cirrus is critical).
4. Surface heat flux data for validation exist.
5. Satellite zenith angle is within 50° from nadir.

The ground-based infrared data was not always obtained for each selected image (11 of 26 images). LOWTRAN7, the calculation code for atmospheric radiative transfer (Kneizys et al. 1988), is employed to estimate the atmospheric correction with observed vertical profiles of temperature and humidity.

Fig. 1. Target area of the present analysis (squares). Also indicated are the locations of the surface meteorological stations and the flux sites. Triangle denotes station observing wind. Diamond denotes station observing wind and air temperature. Circle denotes station with wind, air temperature, and relative humidity, except for Sendai Meteorological Observatory where the routine radio sounding is performed, which is denoted by a solid circle. Double circle denotes flux site.

Profiles of temperature and humidity data were obtained from routine radio soundings at Sendai Meteorological Observatory, and special radio soundings performed at the flux site (B) (Ku wagata et al. 1994). Information of the 26 satellite images is listed in Table 1.

2.3 Surface meteorological data

Surface meteorological data covering temperature, wind direction and speed, were acquired by Automated Meteorological Data Acquisition System (AMeDAS) managed by the Japan Meteorological Agency (JMA) and used in the present analysis. Surface meteorological data were also acquired by atmospheric environmental stations managed by the Miyagi prefectural government and used for the present analysis. Data from the special field campaign obtained at flux site (A) in 1993 through 1994, and at flux site (B) in 1989 are also used for the analysis. The numbers of meteorological stations corresponding with the variety of data elements are shown in Table 2, and their locations are illustrated in Fig. 1. The density of meteorological stations is between $1/5 \sim 1/100 \text{ km}^{-2}$, and they are concentrated in Sendai City and along the coast.

3. Scheme for estimation of sensible heat flux

The presently proposed method for estimating sensible heat flux is illustrated by a flow chart in Fig. 2. The bulk method is applied to calculate sensible heat flux H formulated as

$$H = c_p \rho g_a (T_s - T_a), \quad (1)$$

where c_p is the specific heat of air at constant pressure, ρ the density of air, and g_a the aerodynamic conductance or reciprocal of the aerodynamic resistance (r_a). In addition, T_s is an effective or bulk surface temperature of vegetation canopy, and T_a the air temperature at a reference height. Definition of the effective surface temperature is referred to Kondo and Watanabe (1992), which is that the sensible heat flux is unchanged, even if the hypothetical condition $T_c(z) = T_g = T_s$ (constant) is imposed, where $T_c(z)$ is the vertical distribution of surface temperature inside the canopy, and T_g the ground surface temperature at the bottom of the canopy.

In the present analysis, sensible heat flux is estimated for every grid of surface infrared temperature data. The land-use of the target grids presently analyzed is only rice paddy, which are selected with the land-use maps published by Geographical Sur-

Table 1. Information of 26 satellite images. NOAA denotes the satellite number of NOAA, Ang. denotes the satellite zenith angle, Dir. denotes the satellite viewing direction, and GBM denotes whether the ground-based measurement is obtained (circles) or not (crosses).

Date & Time(JST)				NOAA	Ang.	Dir.	GBM
Jun.	4	1989	12:48	11	1	ENE	○
Jun.	13	1989	7:59	10	40	ESE	○
Aug.	29	1989	13:03	11	23	ENE	○
May	19	1993	7:12	12	26	W	×
May	27	1993	7:40	12	21	ESE	×
May	7	1994	7:13	12	16	W	×
May	7	1994	15:52	11	19	ENE	×
May	9	1994	15:28	11	21	WSW	×
May	9	1994	17:50	12	48	WSW	×
May	13	1994	6:43	12	48	W	×
May	31	1994	6:55	12	33	W	×
Jun.	2	1994	4:11	11	44	W	○
Jun.	2	1994	7:51	12	45	ESE	○
Jun.	15	1994	16:17	11	42	E	×
Jun.	15	1994	17:51	12	46	WSW	○
Jun.	16	1994	16:04	11	26	ENE	○
Jun.	22	1994	18:39	12	24	ENE	○
Jun.	23	1994	4:54	11	14	E	○
Jun.	23	1994	6:57	12	32	W	○
Jul.	3	1994	18:01	12	33	WSW	×
Sep.	2	1994	5:27	11	42	ESE	○
Sep.	3	1994	7:40	12	36	ESE	×
Sep.	4	1994	7:18	12	3	E	×
Sep.	4	1994	16:26	11	40	ENE	×
Sep.	5	1994	16:14	11	25	E	×
Sep.	26	1994	7:42	12	40	ESE	×

Table 2. The number of meteorological stations corresponding with the variety of data elements. U = wind speed, T = air temperature, H = relative humidity, F = heat flux

Elements	Number	Remarks
U	19	
U, T	20	
U, T, H	5	
U, T, H, F	2	Flux sites

vey Institute of Japan. The 365 target grids are shown in Fig. 1.

Variables in Eq. (1) (T_s , T_a , and g_a) are calculated as follows. The effective surface temperature T_s is given as corrected infrared temperature. The required corrections are the atmospheric correction ΔT_{ra} , the viewing angle correction ΔT_{rv} , and the emissivity correction ΔT_{re} . The observed satellite infrared temperature T_r is then transformed to the effective surface temperature T_s as

$$T_s = T_r + \Delta T_{ra} - \Delta T_{rv} + \Delta T_{re}. \quad (2)$$

The amount of the atmospheric and the emissivity correction is calculated by LOWTRAN7 with a vertical atmospheric profile and the satellite zenith angle. The emissivity over the rice paddy is assumed as 0.98 for $LAI < 2$ and 0.99 for $LAI \geq 2$. The satellite zenith angle is calculated based on orbit illustrations of quicklooks of NOAA-AVHRR database archived by the Institute of Industrial Science, University of Tokyo (<http://www.tkl.iis.u-tokyo.ac.jp/SatIAN/>). The viewing angle correction is required to correct the difference between a directional infrared temperature (corrected for atmospheric and the surface emissivity effects) and the effective surface temperature for sensible heat flux. In general, the difference between the two temperatures is dependent on LAI and radiation conditions (Matsushima and Kondo 1997). The viewing angle correction is provided by an empirical parameterization proposed by Troufleau et al. (1997). Parameters are refitted by the least squares method using observational data obtained from the ground-based observation of the

Fig. 2. Flow chart for estimating sensible heat flux.

surface infrared temperature over the rice paddy.

Surface meteorological data were not observed in every grid. Thus, they were interpolated subjectively considering meteorological phenomena (sea breeze front, etc.) and topography. An objective interpolation was not employed because the topography around the target area is complex, though the target area is almost flat, and the advection of the sea breeze is significant.

The LAI of the rice paddy is estimated by date using data obtained in 1993 and 1994, which is described in Matsushima and Kondo (1997).

The aerodynamic conductance of the rice paddy is calculated by a parameterization proposed by Matsushima and Kondo (1997). This parameterization is a function of wind speed at 10 m height, the LAI, and static stability over the surface layer, which is parameterized by the virtual temperature difference between 10 m height and the surface.

4. Parameterization of viewing angle correction

After correcting the original satellite infrared temperature for atmospheric and emissivity effects, a temperature error still remains, especially in sparse canopy cases, which may cause overestimation of sensible heat flux. This error is attributed to the vertical structure of the canopy geometry. If the

satellite infrared sensor views the paddy near nadir, a higher infrared temperature than the effective surface temperature T_s is observed in midday, which is the contribution of the underlying surface. The effective surface temperature is almost equivalent to the temperature of the upper layer of the canopy in which the heat and water exchanges are dominant (Brutsaert and Sugita 1996). This causes the deficit of the infrared temperature and the effective surface temperature, which requires viewing angle correction because the effective surface temperature is observed at a large oblique angle (70° from nadir) (Matsushima and Kondo 1997).

Troufleau et al. (1997) proposed a linear fitting given as

$$\Delta T_{rv} = \alpha x + \gamma \quad (3)$$

where $x = T_r(\phi) - T_a$, to reduce the temperature deficit and error of estimates of sensible heat flux. Here, $T_r(\phi)$ is the surface infrared temperature viewed at angle ϕ from nadir, and T_a is the air temperature at 10m height. The measurements of $\phi = 70^\circ$ are used for parameterization, except for the LAI = 0.04 case ($\phi = 50^\circ$), because the small emissivity of the water surface for measurements at $\phi = 70^\circ$ (0.90) significantly lowers the infrared temperature; this does not affect larger LAI cases. In the present study, this parameterization represents

Fig. 3. Illustration of the relationship between the viewing angle correction ΔT_{rv} and the difference between the surface infrared temperature and the air temperature (10 m) x under a LAI = 0.42 condition.

the viewing angle correction. The parameter α is fitted by the least squares method for individual LAI cases using the ground-based observational infrared temperature over the rice paddy, and $\gamma=0$ is assigned. Figure 3 illustrates the linear parameterization for LAI = 0.42 (sparse canopy). The amount of the correction ΔT_{rv} does not depend on the viewing angle itself provided the viewing angle is within 50° from nadir. The parameter α , which depends on the LAI, is listed in Table 3.

Another linear parameterization was proposed by Chehbouni et al. (1997) to find the difference between an effective surface temperature and the air temperature for a sparse canopy. It is given as

$$H = c_p \rho \beta \frac{T_r - T_a}{r_a}. \quad (4)$$

Here,

$$\beta = \frac{T_s - T_a}{T_r - T_a}. \quad (5)$$

In Fig. 3, the Troufleau et al. linear regression does not seem the best fit of observations where the distribution appears nonlinear. Therefore, a nonlinear term is added to the Troufleau et al. parameterization, which is formulated as

$$\Delta T_{rv} = a_1 + a_2 x + \sqrt{a_3 + a_4 x + a_5 x^2}, \quad (6)$$

where a_1 through a_5 are empirical parameters which depend on the LAI. The values of the parameters are listed in Table 3. The nonlinear parameterization for LAI = 0.42 is also shown in Fig. 3.

The nonlinear term is not zero when the canopy is sparse; it is not needed and the magnitude of correction is small when the canopy is dense (LAI > 3)

or nearly a bare surface (LAI < 0.1). The linear coefficients a_2 and α resemble each other according to the LAI.

The present analysis investigates the viewing angle correction by Eqs. (3), (4), and (6). The next section describes the difference of estimation errors in the resulting sensible heat flux among these methods including the case without the viewing angle correction.

5. Estimation error

Figure 4 shows the comparison of the surface infrared temperature obtained by satellite and ground-based measurements acquired at the flux sites A and B. The satellite infrared temperature is corrected for atmospheric absorption and the surface emissivity. The results are fairly good for the overall range of LAI, and the root mean squares error (RMSE) is 1.0°C . This shows that atmospheric correction using the LOWTRAN7 with radio sounding data yields good results. Figure 5 shows the amount of the viewing angle correction according to LAI. The magnitude is between 0 and 3°C because the satellite images analyzed were obtained mostly in the morning and early evening. However, about 6°C of ΔT_{rv} occurs in the LAI = 0.14 case which corresponds to midday. Temperature of the underground water surface can be much higher than leaf temperature of the upper canopy where the surface temperature is near the ambient air temperature because midday solar radiation is absorbed largely by the underground surface, while sensible heat exchange is efficient in the upper canopy not at the underground surface. In addition to the above, the longwave emissions from the underground surface are easily detected, especially over a near nadir viewing in case of canopy being sparse. Therefore, a large ΔT_{rv} can occur, especially in midday and sparse canopy condition cases. Figure 6 shows the estimated sensible heat flux on a half-hourly basis with the viewing angle correction by the linear parameterization of Troufleau et al. (1997) (a), without the viewing angle correction (b), with the viewing angle correction by the linear parameterization of Chehbouni et al. (1997) (c), and by the nonlinear parameterization (d). Atmospheric and emissivity corrections are considered in all four cases, and they are compared with estimates by the Bowen ratio method. Estimation error stands out in Fig. 6(b) when the magnitude of sensible heat flux is large. These correspond to cases that appeared in Fig. 5, namely, the canopy is sparse and temperature of the underlying surface (water surface) is much higher than the effective surface temperature which is almost equivalent to the temperature of upper layer of the canopy where active heat exchange occurs. Directional infrared temperature by satellites tends to be much higher than the effective temperature, because satellites view more

Table 3. Values of parameters appearing in Eqs. (3) and (6). Also listed are the roughness length for momentum z_0 and the zero-plain displacement d , which are estimated from wind profiles observed in flux site A.

LAI	z_0	d	α	a_1	a_2	a_3	a_4	a_5
0.04	0.005	0.0	0.03	0.2	0.01	0	0	0
0.14	0.01	0.01	0.37	-0.4	0.25	1.5	-0.7	0.10
0.42	0.02	0.05	0.57	-1.6	0.60	8.5	-3.1	0.30
0.68	0.02	0.10	0.47	-1.7	0.55	10.0	-3.1	0.25
1.01	0.03	0.13	0.52	-1.0	0.45	8.0	-2.5	0.25
1.8	0.05	0.2	0.41	-1.0	0.45	1.5	-1.1	0.25
3.8	0.07	0.3	0.09	0.09	0.05	0	0	0
5.4	0.13	0.4	0.05	0.11	0.07	0	0	0

Fig. 4. Comparison of the surface infrared temperature by satellite and ground-based measurements acquired at the flux sites A and B. The satellite infrared temperature is corrected for the atmospheric absorption and the surface emissivity.

of the underlying surface than the upper layer of canopy in their viewing angles which are apart from the optimal viewing angles. Therefore, the viewing angle correction ΔT_{rv} increases as sensible heat flux increases. The RMSE and average of estimation error of each method are listed in Table 4. It is found that the viewing angle correction is significant in the estimation. There is no noticeable difference in estimation error among (a), (c), and (d), thus, it appears that estimation error does not depend on parameterizations. Figure 7 shows the comparison of the linear and nonlinear estimates of the case of 12:48 JST 4 June 1989 ($LAI = 0.14$). A systematic bias occurs when the magnitude of sensible heat flux is more than about 100 Wm^{-2} . When sensible heat flux is large, the temperature difference ($T_r - T_a$)

Fig. 5. The amount of viewing angle correction according to the LAI.

can be also large in almost all cases, and the linear parameterization does not agree with observation as illustrated in Fig. 3. Namely, the amount of viewing angle correction ΔT_{rv} by the linear parameterization is much smaller than that of the nonlinear parameterization. The nonlinear parameterization is found to be effective to the flux estimation when sensible heat flux is large.

A sensitivity test was performed to investigate the error of sensible heat flux caused by input data errors. Probable data fluctuations given to the test are listed in Table 5. Figure 8 shows the standard errors due to these six elements according to the stability, the LAI, and the wind speed. Strength of stability is assumed as absolute values of the Obukhov length being between 30 and 50 m. The range of assumed sensible heat flux is between -150 and 400 Wm^{-2} . The error increases as the LAI and the wind speed increase, and is larger under unstable and neutral conditions than under stable conditions except when the wind speed is small. When a rice paddy is in the grown stage ($LAI \sim 5$), the magnitude of sensible heat flux is small seasonally (September). Input data error could cause significant errors of sensible

Fig. 6. Estimated sensible heat flux on a half-hourly basis with the viewing angle correction by the linear parameterization of Troufleur et al. (1997) (a), without the viewing angle correction (b), with the viewing angle correction by the linear parameterization of Chehbouni et al. (1997) (c), and by the nonlinear parameterization (d). They are compared with estimates by the Bowen ratio method.

heat flux, especially in this season.

6. Spatial distribution of sensible heat flux

Figure 9 shows examples of the spatial distribution of sensible heat flux in a rice paddy. The rice paddy analyzed here is located on a flat plain, and there is little subgrid heterogeneity with LAI being 0.14 for (a), and 0.55 for (b). Flux over the other land-use areas is not calculated because their viewing angle correction has not been investigated yet, and the possible error is obscure, especially for forests with complex topography. In Fig. 9(a), there is a south-easterly sea breeze blowing inland until around the air temperature contour of 28°C indicated by the wind arrows and contours of the air

Table 4. Root mean squares errors and averages of error of sensible heat flux (Wm^{-2}) by estimation methods of linear regression of Troufleur et al. (1997) (a), without the viewing angle correction (b), linear regression of Chehbouni et al. (1997) (c), nonlinear regression (d), and without all corrections (e).

Method	(a)	(b)	(c)	(d)	(e)
RMSE	24	46	24	25	47
Avg.	+2	+18	+3	-4	-35

temperature. The large magnitude of sensible heat flux and the large gradient of the air temperature

Fig. 7. Comparison of the linear and the nonlinear estimates for the case of 12:48 JST 4 June 1989.

Table 5. Probable input data fluctuation to estimate sensible heat flux by the present method.

atmospheric correction	$\pm 0.5^{\circ}\text{C}$
viewing angle correction	$\pm 1^{\circ}\text{C}$
LAI	$\pm 20\%$
air temperature	$\pm 1^{\circ}\text{C}$
wind speed	$\pm 1\text{ ms}^{-1}$
emissivity	± 0.01

just inside the coast suggest that the cold advection from over the sea is immediately warmed over the land. Sea surface temperature near the coast on the day is about 17°C. In Fig. 9(b), however, the sea breeze is blowing in only near the coast of the southern part of the map, and a downslope westerly wind is blowing (The west part of the map contains 500 to 1000 m high mountains). The contrast of sensible heat flux is remarkable (The signals are opposite). The sea surface temperature near the coast is around 18 to 21°C. Other examples are of the same nature as that described above.

7. Conclusion

Sensible heat flux over horizontal-homogeneous rice paddies on a several tens kilometer scale was estimated using satellite infrared temperature combined with surface meteorological and canopy data, and maps of sensible heat flux were made. The RMSEs of sensible heat flux estimations with three corrections for satellite infrared temperature are about 25 Wm⁻² on a half-hourly basis, and 46 Wm⁻² without the viewing angle correction. This shows

Fig. 8. Standard errors due to the possible data fluctuations listed in Table 5 according to the LAI and the wind speed for neutral case (a), unstable case (b), and stable case (c). Indicated numerals denote the wind speed in ms⁻¹.

Fig. 9. Examples of the spatial distribution of sensible heat flux in a rice paddy on 12:48 JST 4 June 1989 (a), and 17:51 JST 15 June 1994 (b). Contours are of the air temperature and figures are in degrees Celsius. Wind speed is indicated by arrows (full length: 2 ms^{-1} , half length: 1 ms^{-1}). Sea surface temperature near the coast is 17°C for (a) and 18 to 21°C for (b).

that the viewing angle correction is critical to estimate sensible heat flux over vegetation. The amount of the viewing angle correction does not appear to depend on parameterizations. However, a systematic bias could cause errors and a nonlinear parameterization should be used when the magnitude of sensible heat flux is large. Sensitivity to input data fluctuations was tested, and it was found that relatively large errors could occur when the wind speed was large and the LAI was large. Errors are relatively limited under stable conditions. Finally, maps of sensible heat flux distribution were illustrated. The estimates are quantitatively valid within some distinct errors.

Acknowledgments

The authors thank Prof. Kawamura of Tohoku University for providing satellite images. Thanks are extended to Dr. Kuwagata of Tohoku National Agricultural Experiment Station, and Mr. Ishida of Hirosaki University for their surface heat flux data in rice paddies. The authors appreciate valuable comments of two anonymous reviewers which helped improvement of the manuscript. Surface meteorological data except for the flux sites were offered by the Japan Meteorological Agency and the Miyagi Prefectural Government.

References

- Brutsaert, W. and M. Sugita, 1996: Sensible heat transfer parameterization for surfaces with anisothermal dense vegetation. *J. Atmos. Sci.*, **53**, 209–216.
- Bussières, N., R.J. Granger and G.S. Strong, 1997: Estimates of regional evapotranspiration using GOES-7 satellite data: saskatchewan case study, July 1991. *Canadian J. Remote Sens.*, **23**, 3–14.
- Chehbouni, A., D.L. Seen, E.G. Njoku, J.P. Lhomme, B. Monteny and Y.H. Kerr, 1997: Estimation of sensible heat flux over sparsely vegetated surfaces. *J. Hydro.*, **188–189**, 855–868.
- Huband, N.D.S. and J.L. Monteith, 1986: Radiative surface temperature and energy balance of a wheat canopy, I: Comparison of radiative and aerodynamic canopy temperature. *Boundary-layer Meteor.*, **36**, 1–17.
- Humes, K.S., W.P. Kustas and D.C. Goodrich, 1997: Spatially distributed sensible heat flux over a semi-arid watershed. part I: use of radiometric surface temperatures and a spatially uniform resistance. *J. Appl. Meteor.*, **36**, 281–292.
- Ishida, S., T. Ishida and J. Kondo, 1997: The seasonal variation of heat balance on a paddy field. *J. Japan Soc. Hydrology & Water Resources*, **10**, 123–132 (in Japanese with English abstract).
- Kneizys, F.X., E.P. Shettle, L.W. Abreu, J.H. Chetwynd, G.P. Anderson, W.O. Gallery, J.E.A. Selby and S.A. Clough, 1988: *Users Guide to LOW-TRAN7*. AFGL-TR-88-0177, Air Force Geophysical Laboratory, 1–137pp.

- Kondo, J. and T. Watanabe, 1992: Studies on the bulk transfer coefficients over a vegetated surface with a multilayer energy budget model. *J. Atmos. Sci.*, **49**, 2183–2199.
- Kustas, W.P. and K.S. Humes, 1997: Spatially distributed sensible heat flux over a semiarid watershed. part II: use of a variable resistance approach with radiometric surface temperatures. *J. Appl. Meteor.*, **36**, 293–301.
- Kuwagata, T., J. Kondo and M. Sumioka, 1994: Thermal effect of the sea breeze on the structure of the boundary layer and the heat budget over land. *Boundary-layer Meteor.*, **67**, 119–144.
- Matsushima, D. and J. Kondo, 1997: A proper method for estimating sensible heat flux above a horizontal-homogeneous vegetation canopy using radiometric surface observations. *J. Appl. Meteor.*, **36**, 1696–1711.
- Norman, J.M., W.P. Kustas and K.S. Humes, 1995: A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. *Agric. For. Meteorol.*, **77**, 263–293.
- Qualls, R.J. and W. Brutsaert, 1996: Effect of vegetation density on the parameterization of scalar roughness to estimate spatially distributed sensible heat fluxes. *Water Resour. Res.*, **32**, 645–652.
- Sugita, M. and W. Brutsaert, 1996: Optimal measurement strategy for surface temperature to determine sensible heat flux from anisothermal vegetation. *Water Resour. Res.*, **32**, 2129–2134.
- Sun, J. and L. Mahrt, 1995: Determination of surface fluxes from the surface radiative temperature. *J. Atmos. Sci.*, **52**, 1096–1106.
- Troufleau, D., J.P. Lhomme, B. Monteny and A. Vidal, 1997: Sensible heat flux and radiometric surface temperature over sparse Sahelian vegetation. I An experimental analysis of the kB^{-1} parameter. *J. Hydro.*, **188–189**, 815–838.
- Vining, R.C. and B.L. Blad, 1992: Estimation of sensible heat flux from remotely sensed canopy temperatures. *J. Geophys. Res.*, **97**, 18951–18954.

測定角補正を施した衛星赤外放射温度による植生地に対する 顕熱フラックス分布の推定

松島 大

(東北大学大学院理学研究科地球物理学専攻)

近藤純正

(東北大学名誉教授)

数十 km 程度の水平スケールにおける顕熱フラックス分布を、衛星赤外データを用い、水田を対象として、その誤差とともに推定した。衛星赤外放射温度に 3 種類の補正 (大気中の吸収物質、衛星の測定角、および地表面の射出率に関する補正) を施すことによって 30 分間平均値で二乗平均誤差 (RMSE) が 25 Wm^{-2} という一般的な観測誤差に対して十分小さい誤差で水田上の顕熱フラックスを推定できることが分かった。このうち特に測定角補正が重要であり、測定角補正を行わない場合の RMSE は 46 Wm^{-2} になった。大気補正と射出率補正は LOWTRAN7 にラジオゾンデによるデータを用いることで行われ、補正後の値を地上での観測値と比較した RMSE は 1.0°C であった。測定角補正のパラメタリゼーションのために Troufleau et al. (1997) の提案による経験的な線形式を用いた。この線形式のパラメータは広範囲の葉面積指数 (0.01 から 5) に対して地上観測値に基づいて再決定された。このパラメタリゼーションによって、植生キャノピーの幾何学的構造に起因し、放射温度の測定角によって表れる植被面温度の誤差を十分に補正できることが分かった。しかし、このパラメタリゼーションも顕熱フラックスが大きいときにはその補正が十分ではない。これは植被面温度の誤差が植被面の放射温度と気温との差に対して非線形であることによる。