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Field Intercomparison and Calibration of Net Radiometers

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순복사계의 야외 상호 비교 및 보정

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ABSTRACT

Net radiation (*Rn*) is one of the most fundamental components in surface energy budget. For an accurate measurement of *Rn*, periodic and consistent calibrations of net radiometers are required. With a 4-month time interval, two field experiments were conducted to inter-compare and calibrate two types of net radiometers (the Q-7.1 and the CNR1), widely used in flux measurements. Differences between the Q-7.1 and the CNR1 net radiometers were within 7.7%, and the errors after calibration against the standard net radiometer were <3.2%. Radiometric responses and calibration factors appeared to have changed with sky conditions, especially temperature difference with season's progress. We concluded that the periodically calibrated Q-7.1 can replace more expensive, more accurate CNR1 net radiometer for long-term field measurements, providing that field calibrations of net radiometers are performed every 4 - 6 months interval.

Key words : **net radiation, field calibration, intercomparison, net radiometer**

I. INTRODUCTION

Net Radiation (*Rn*) is one of the most fundamental components in surface energy exchanges. It causes the diurnal variation of the sensible heat, latent heat and soil heat fluxes during daytime, and cools the ground surface, resulting in stabilization of the surface layer by radiative cooling during nighttime. For an accurate measurement of *Rn*, periodic and consistent calibration of net radiometers is required. Manufacturers usually recommend that net radiometers be recalibrated every 1 or 2 years. However, factory calibrations are costly and time consuming as well. Therefore, practical field calibration and field inter-comparisons have been conducted with different net radiometers.

Two types of net radiometers widely used in flux measurements were used in this study. One is the Q-7.1 net radiometer (Campbell Sci. Inc., USA, hereafter, Q-7.1), which is a polyethylene-dome net radiometer. The other is the CNR1 net radiometer (Kipp & Zonen, Holland, hereafter, CNR1) which is a four-way component system providing more comprehensive

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Corresponding Author: Joon Kim(joon-kim@yonsei.ac.kr) information. The Q-7.1 is relatively inexpensive and requires no power for operation, whereas the CNR1 requires power. In general, the accuracy of a net radiometer increases with cost and power requirements. The accuracy of old or inexpensive radiometers can be improved by comparing their outputs with those of the high-performance instruments.

Field experiments were conducted twice to calibrate and inter-compare the above two net radiometers at 4-month intervals. These studies were initiated from the discussion during the Korea Monsoon Experiment Program (KORMEX) Observation/AsiaFlux Domestic Workshop (29-30 November 2000). From the experimental results, the difference of radiometric responses as well as the change of correction factors with atmospheric conditions will be shown. The purpose of this study was i) to introduce major net radiometers used in flux measurements in Korea, ii) to present the field calibration processes, and iii) to examine the results of the intercomparison and calibration of net radiometers.

II. INSTRUMENTS

2.1. Q-7.1 net radiometer

The Q-7.1 has 60 junction thermopiles. Thermopiles coated with black paint are set onto upper and lower wafers, and they are protected from the ambient air by polyethylene domes (Fig. 1). Incident radiation is converted to heat by the black paint, and then the temperature difference between the upper and lower surfaces is measured by thermopiles (Smith *et al.*, 1997).

The temperature difference developed across the plates is (Szeicz, 1975; Smith *et al.*, 1997) :

$$T_1 - T_2 \approx \frac{Rn}{4\, T_1^3 + 2k/d + h} \tag{1}$$

where T_1 and T_2 are temperatures of the upper and lower surfaces of the plate, respectively, σ is the Stephan-Boltzmann constant ($\approx 5.67 * 10^{-8}$ Wm^{-2}K^{-4}), d is the thickness of the plate, k is its thermal conductivity, and h is the heat transfer coefficient between the surface of plate and the air. Equation (1) shows that the temperature difference is in proportion to Rn. Here, the sign of Rn is positive when toward the ground surface.

In the Q-7.1, a 0.25 mm-thick polyethylene dome is used over both the upper and lower surface. Most sensors, which measure longwave radiation, are subject to some degree of error caused by convective cooling as air moves past the sensors (Campbell Scientific. Inc, 1996; Brotzge and Duchon, 2000). Such effects are experimentally determined. The decrease of net radiation by low-to-moderate wind speed (3 − 6 m s^{-1}) on a homogeneous field in a clear day is <6%.

2.2. CNR1 net radiometer

The CNR1 is an instrument using four radiometers. Two are CM3 radiometers (hereafter, CM3) measuring the shortwave radiation, and the others are CG3 radiometers (hereafter, CG3) measuring longwave radiation. It is designed such that CM3 and CG3 are positioned both upward and downward (Fig. 2). These four radiometers measure four components of radiation, and Rn can be calculated as:

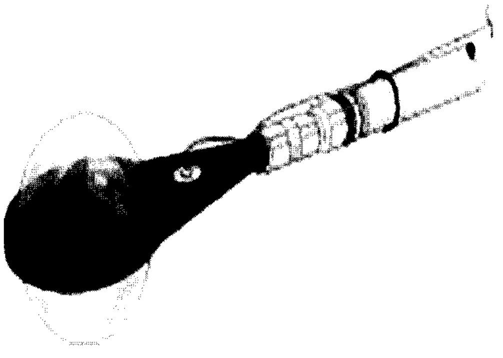

Fig. 1. Q-7.1 net radiometer (from http://www.campbellsci.com).

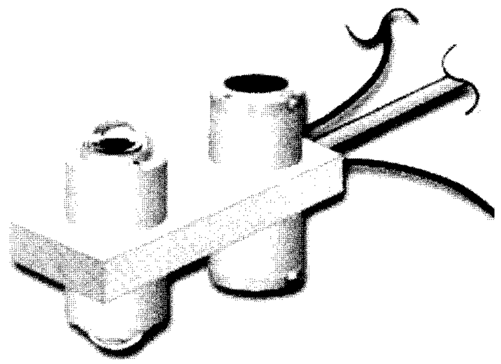

Fig. 2. CNR1 net radiometer (from http://www.campbellsci.com).

$$Rn=(Rsdn-Rsup)-(Rlup-Rldn) \qquad (2)$$

where *Rsdn* is downward shortwave, *Rsup* is upward shortwave, *Rldn* is downward longwave, and *Rlup* is upward longwave radiation.

The CNR1 has the advantage of gathering additional information such as albedo, net longwave radiation, and the effective radiative temperature of the atmosphere and the ground surface. Also, it can prevent dew or frost accumulation by a built-in heating element which can be turned on or off (Smith *et al.*, 1997). To operate the heater requires a 12V power source.

2.3. Wavelengths range of radiometer

Similar to Q-7.1, the CM3 and CG3 have inner thermopiles measuring quantity of radiation. However, their wavebands of radiation are different from one another because of the optical difference of the radiometric domes. The Q-7.1, CM3, and CG3 use polyethylene domes, glass domes, and silicon double-windows, respectively (Smith *et al.*, 1997). Polyethylene domes are optically transparent to all wavelengths of radiation, except narrow bands from 3 to 14 μm. Glass dome, however, transmit radiation with wavelengths ranging from 0.3 to 3.0 μm (Szeicz, 1975). The silicon windows act as filters that absorb radiative wavelengths longer than 5.0 μm (Kipp & Zonen, 1997). Hence, optical properties of the domes determine the range of the measured wavelengths. Table 1 shows the specifications of Q-7.1 and CNR1 provided by each manufacturer.

III. EXPERIMENTS

3.1. Experiment 1

The first experiment was conducted at the Korea Global Atmosphere Watch Observatory, Ahnmyun-do on 12-14 February 2001. The experimental site was located on a mountainside, and the ground surface was covered by short grasses and somewhat inclined toward the west (Fig. 3). Net radiometers were mounted 1.85 m above ground and a cup anemometer was mounted at 2.1 m. The distance between two CNR1s was about 0.65 m and others were separated by about 0.4 m.

Fig. 3. Ground surface of the site.

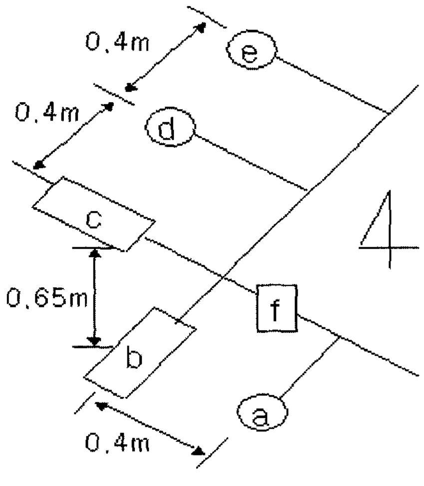

Fig. 4. A top-view diagram of the tower in experiment 1. (a: Q-7.1(1), b: CNR1(1), c: CNR1(2), d: Q-7.1(2), e: Q-7.1 (3), f: Anemometer)

Table 1. Specifications of Q-7.1 and CNR1

Net radiometer		Spectral range (μm)	Domes	Thermopile	Response time (s)	Length (m)	Weight (kg)
Q-7.1		0.25-60	Rigid polyethelene	60-junction	30	0.94	2.9
CNR1	CM3	0.3-2.8	Glass	64-junction	18	0.58	4.5
	CG3	5.0-50	Silicon				

Table 2. Net radiometers used in experiment 1

Radiometer	Quantity	Serial No.	Calibration Factor	Ownership
CNR1	2	(1) 000263	Sensitivity : 9.40 $\mu VW^{-1}m^2$	METRI
		(2) 980108	Sensitivity : 10.80 $\mu VW^{-1}m^2$	KFRI
Q-7.1	3	(1) Q98050	Cal. Fac.: Top 9.25, Bot. 11.42 $Wm^{-2}mV^{-1}$	METRI
		(2) Q97021	Cal. Fac.: Top 9.36, Bot. 11.51 $Wm^{-2}mV^{-1}$	YONU
		(3) Q97028	Cal. Fac.: Top 9.10, Bot. 11.19 $Wm^{-2}mV^{-1}$	

YONU: Yonsei unversity, METRI: Korean Meteorological Research Institute, KFRI: Korea Forest Research Institute

Determination of the distance among radiometers is described in the Appendix. Net radiometers are generally set up toward the south; however in this experiment, some were aligned toward the northwest and others toward the southwest due to installation difficulties (Fig. 4). Net radiometers were mounted to avoid being screened by the shadow of the tower with their sensors positioned as horizontally as possible. Outputs were sampled and stored every 30 seconds by two dataloggers (CR23X, Campbell Scientific Inc., USA), considering the response time of Q-7.1 (see Table 1). Table 2 summarized net radiometers used in Experiment 1.

3.2. Experiment 2 (with a new reference net radiometer)

The second experiment was conducted on the roof of the Science building, Yonsei University on 19-22 June 2001. The standard radiometer used in this second experiment was provided with a new calibration. The new standard is CNR1(#970067) (hereafter, CNR1(3)) which had been kept inside the laboratory after being calibrated in the factory. Q-7.1(2), Q-7.1(3), CNR1(2), and CNR1(3) were used in Experiment 2. The 3 m tower was used and net radiometers were generally set up in parallel and facing the south, 1.6 m high above the ground and separated 0.4 m from one another (Fig. 5). Outputs were sampled every 30 seconds and stored every 10 minutes by two dataloggers (21X, Campbell Scientific Inc., USA).

3.3. Calibration and intercomaprison

3.3.1. The standard net radiometer

CNR1(2) was chosen as the standard because net radiometers of the 4-way component system are known to be more accurate than polyethlene dome radiometers and are often used as the reference or standard in other studies (e.g., Halldin and Lindroth, 1992; Brotzge and Duchon, 2000).

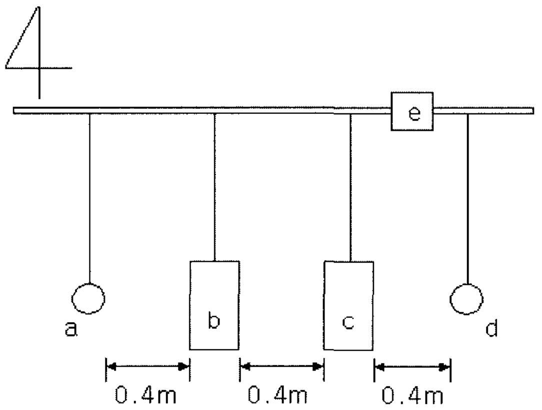

Fig. 5. A top-view diagram of the tower in experiment 2. (a: Q-7.1(2), b: CNR1(2), c: CNR1(3), d: Q-7.1(3), e: Anemometer).

3.3.2. Data quality

Some data were corrected or excluded in the data processing. First, the values of *Rsdn* and *Rsup* were fixed to zero if $Rsdn < 0$. Outputs during radiometer maintenance and when the angle of solar radiation is < 10 degrees (about 40 minutes) were excluded in the calibration processes because there were some errors in CNR1 due to deviations in the directional response of the CM3 (Kipp & Zonen, 1997). Data measured during precipitation in Experiment 2 were also removed in the analysis.

3.3.3. Atmospheric conditions

Radiant quantity is significantly affected by atmospheric conditions (e.g., air temperature, humidity, cloudiness, etc.). Unfortunately, in this study, we could not directly measure these meteorological variables. Instead, we adopted two variables to represent the sky conditions of the experimental periods. First, we used 'effective sky temperature' (T_{eff}) from *Rldn* of CNR1(2) replacing air temperature. It is calculated as $(Rldn/\sigma)^{1/4}$ (Kipp &

Zonen, 1997). Also, cloudiness is one of the most important factors representing sky condition. It causes the fluctuation of downward radiation. To represent cloudiness of the experimental period, we used clearness index, k_t which has been widely used by solar engineers (Gu *et al.*, 1999). It is calculated as the ratio of global horizontal to extraterrestrial radiation on an hourly, daily, and monthly average basis (Gonzalez and Calbo, 1999). In this study, k_t was computed on a daily average basis.

3.3.4. Calibration method

The simple regression method was used in calibrating Q-7.1 against the standard:

$$y = ax + b \tag{3}$$

where x is the output of Q-7.1, y is that of the standard instrument, a is the slope, and b is the intercept. Three facts are worth noting in this approach: (1) Field *et al.* (1992) pointed out that a and b might vary by season or sky conditions. Therefore, we examined the change of calibration coefficient of net radiometers in view of the changes in season and sky condition; (2) we determined the criterion of an allowable error as 6%. In the CNR1 manual (Campbell Scientific Inc., 2002), it is stated that deviations of more than 6% can be used to correct the calibration factors. Hence, we evaluated the agreement between net radiometers based on this criterion; and (3) the data were divided into two groups: $Rn > 0$ and < 0, since Q-7.1 has different calibration factors according to positive or negative Rn. The calibration was carried out for the Q-7.1s which were toward the same direction as the standard in order to remove the directional influence. Net radiometers, facing different direction from the standard, were then compared with one another.

3.3.5. Statistical analysis

The following statistics were calculated for comparison in this study: the average (Avg), coefficient of determination (r^2), root mean square error ($RMSE$), systematic $RMSE$ ($SRMSE$), and normalized standard error of the estimate ($NSEE$) (Willmott, 1981; Colello *et al.*, 1998);

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}} \tag{4}$$

$$SRMSE = \sqrt{\frac{\sum_{i=1}^{n}[\,y_i - (ax_i + b)\,]^2}{n}} \tag{5}$$

$$NSEE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n} y_i^2}} \tag{6}$$

where n is the total number of data points and $SRMSE$ is considered in this study as '$RMSE$ after calibration'.

IV. RESULTS AND DISCUSSION

4.1. Comparison of directional response

During the Experiment 1, it was partly cloudy on 13 February. The value of k_t was 0.56 and the averaged T_{eff} was -17.8°C. Fig. 6 shows diurnal variation of radiation components. Maximum values of $Rsdn$ and Rn were, respectively, 641 and 417 Wm^{-2} and averaged surface albedo was 0.18. The outputs of Q-7.1s were nearly identical with one another (Fig. 7(a)), whereas those of the two CNR1s differed appreciably from each other (Fig. 7(b)). Q-7.1(1) did not seem to be affected by spatial and directional difference, but CNR1(1) was affected likely because of the difference in $Rldn$ (Table 3).

It was interesting to note that the diurnal variation of $Rldn$ was similar to that of its difference from the

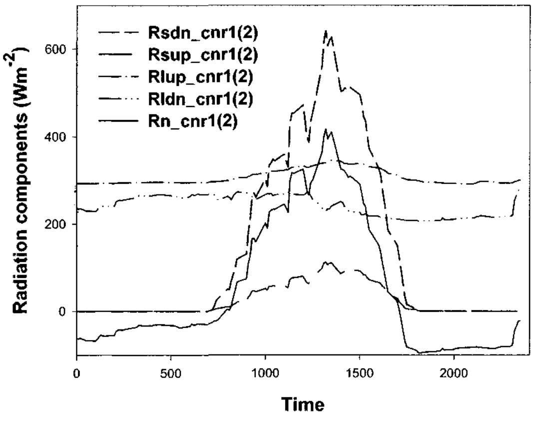

Fig. 6. Diurnal variations of radiation components on 13 February.

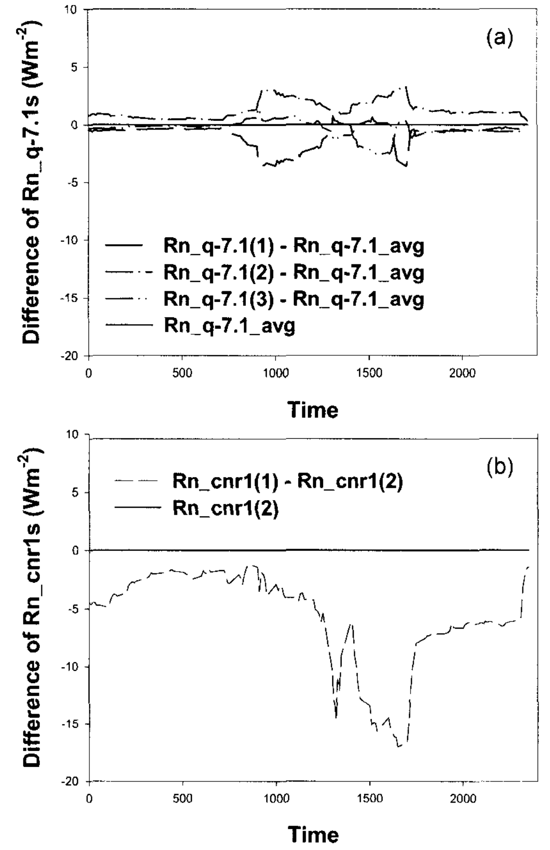

Fig. 7. Differences of net radiation due to the directional difference (a) Difference of Q-7.1s, (b) Difference of CNR1s.

Table 3. Daily averaged components and RMSE of CNR1s

	CNR1(1) (Wm^{-2})	CNR1(2) (Wm^{-2})	RMSE (Wm^{-2})
Rsdn	138.6	139.1	2.9
Rsup	26.9	26.0	2.1
Rlup	306.8	306.5	0.4
Rldn	237.9	242.0	4.7
Rn	42.8	48.6	7.2

standard radiometer (Fig. 8). In general, measurement bias between two instruments increases with the magnitude of the measurement. However, in this case, as *Rldn* became greater, its difference tended to decrease. To verify this difference of directional response, further investigation is required.

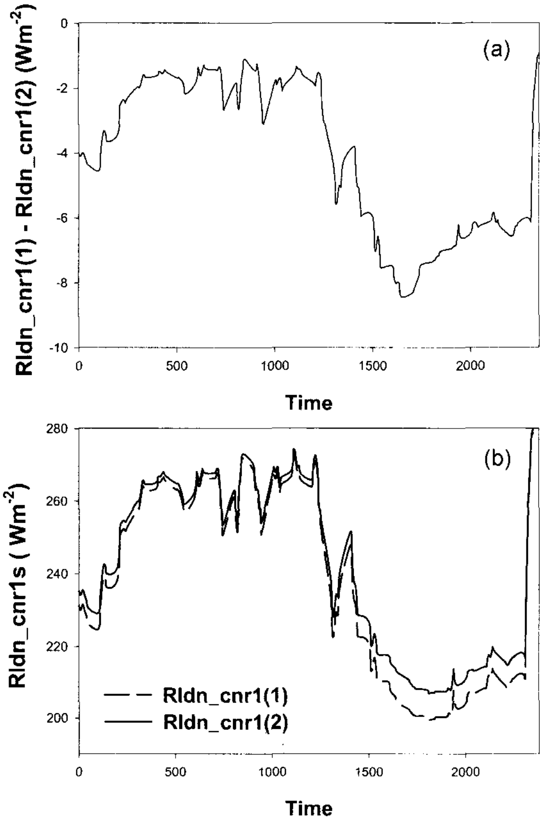

Fig. 8. Diurnal variation and difference of downward long-wave radiation of CNR1s (a) Difference of Rldn_cnr1s, (b) Diurnal variation of Rldn_cnr1s.

4.2. Intercomparison of two net radiometers in Experiment 1

Outputs of CNR1 were larger than those of Q-7.1s during daytime, and smaller during nighttime (Fig. 9). This difference in daytime and nighttime *Rn* was canceled out in the computation of daily-averaged *Rn*. *RMSE* and *%NSEE* of Q-7.1s against the standard instrument were within 10.9 Wm^{-2} and 6.8%, respectively. Here, *%NSEE* is equal to *NSEE* * 100 (%). In practice, relatively cheap Q-7.1 can be used in place of CNR1 with an uncertainty of about 7% in *Rn* measurement.

In order to reduce the error of Q-7.1 less than the criterion of 6%, we calibrated Q-7.1s against CNR1(2). The differences between Q-7.1s and the standard were much reduced after the calibration. The *RMSE* and *%NSEE* after calibration were within 2.1 Wm^{-2} and 1.3%, respectively (Table 4).

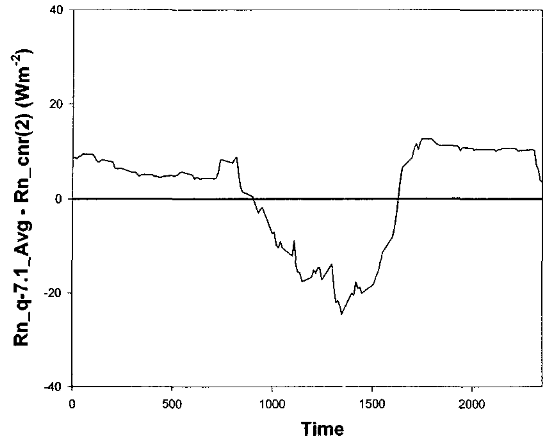

Fig. 9. Difference of Rn_q-7.1_avg and Rn_cnrl(2) on 13 February.

Table 4. Results of the calibration, RMSE and %NSEE in experiment 1

		Q-7.1(2)		Q-7.1(3)	
Average (Wm^{-2})		50.6		49.0	
Day/Night		day	night	day	Night
a_l		1.085	1.130	1.086	1.106
b_l		-9.35	-1.84	-6.88	-1.81
r^2		0.9995	0.9997	0.9992	0.9997
RMSE (Wm^{-2})	Before	10.6		10.9	
	After	2.0		2.1	
%NSEE (%)	Before	6.6		6.8	
	After	1.2		1.3	

4.3. Intercomparison of CNR1 in Experiment 2

In order to verify the accuracy of the standard, CNR1(2), we compared its outputs with those of CNR1(3) which was the newly calibrated reference. Intercomparison for each radiation component was conducted (Table 5). The *RMSE* and *%NSEE* between the two CNR1s were just 2.6 Wm^{-2} and 1.0%, respectively. We noted that the outputs of CNR1(2) was nearly identical with those of CNR1(3), and did not correct the calibration factor of CNR1(2).

4.4. Intercomparison and calibration in Experiment 2

In experiment 2, it was partly cloudy on 20 June and was mostly overcast on 21 June. The values of k_t and the averaged T_{eff} on these two days were 0.53 and 16.7°C, 0.19 and 21.2°C, respectively. Fig. 10 shows diurnal variation of individual radiation components. Maximum values of *Rsdn* and *Rn* were, respectively, 963.0 and 623.8 Wm^{-2} on 20 June, and averaged surface

Table 5. Daily-averaged components of CNR1s, RMSE and %NSEE

	CNR1(2) (Wm^{-2})	CNR1(3) (Wm^{-2})	RMSE (Wm^{-2})	%NSEE (%)
Rsdn	276.6	275.4	2.9	0.7
Rsup	62.9	62.3	1.4	1.4
Rlup	479.9	482.3	2.4	0.5
Rldn	400.7	403.1	2.5	0.6
Rn	132.6	131.9	2.6	1.0

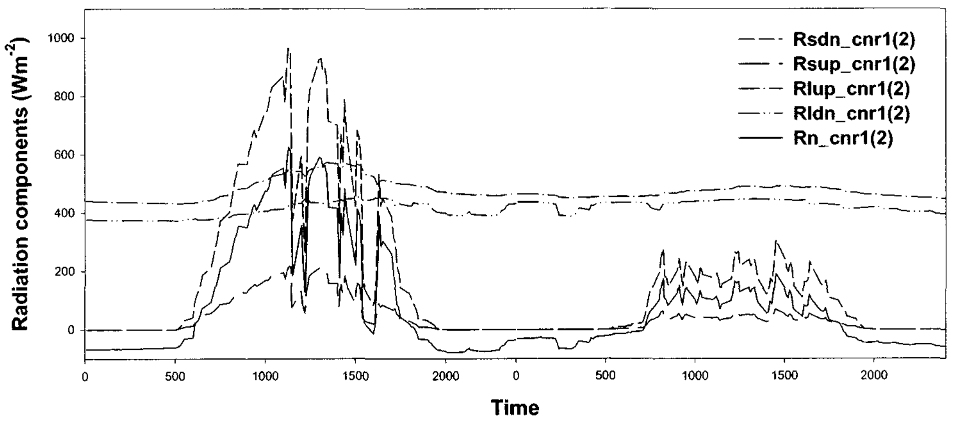

Fig. 10. Diurnal variation of radiation components on 20-21 June.

albedo was 0.23. It rained in the afternoon (1530-1750 hrs, LST) on 20 June when the outputs of shortwave radiation dropped accordingly. Outputs during this period were excluded from the analysis. CNR1 outputs were larger than those of Q-7.1s during daytime but were smaller during nighttime in Experiment 1. Again, outputs of Q-7.1s were consistently greater than those of CNR1 during nighttime. However, the differences during daytime were fluctuating significantly (Fig. 11). Such inconsistent differences during daytime caused the overall differences between *Rn*_q-7.1 and *Rn*_cnr1(2) to be greater in Experiment 2. We first applied the a_l and b_l to the measurements on 20 June, but the error of Q-7.1 exceeded 6% (Table 6). Because these net radiometers had not been used in the field after Experiment 1, it was difficult to suspect the changes in calibrations. We also speculate that the atmospheric conditions may have affected changes in calibration during the second experiment. We corrected the calibration factors again and noted that the errors after corrections were <3.2%.

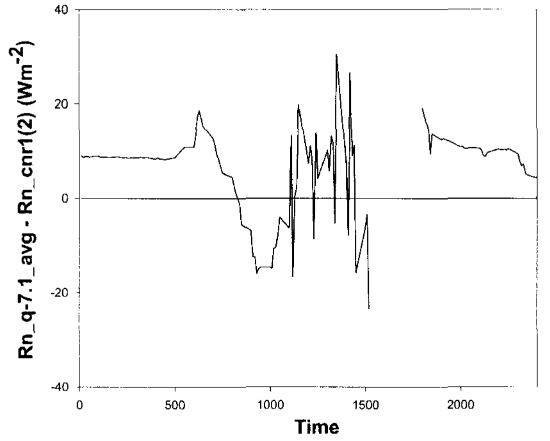

Fig. 11. Difference of Rn_q-7.1_avg and Rn_cnr1(2) on 20 June.

Table 6. Results of the calibration, RMSE and %NSEE in experiment 2

		Q-7.1(2)		Q-7.1(3)	
Average (Wm^{-2})		144.7		144.7	
Day/Night		Day	Night	Day	Night
a_l		1.016	0.987	1.030	1.013
b_l		-10.54	-9.10	-9.73	-9.32
r^2		0.9961	0.9866	0.9947	0.9880
RMSE (Wm^{-2})	Before	20.9		18.9	
	After	7.5		8.6	
%NSEE (%)	Before	7.7		7.0	
	After	2.8		3.2	

4.5. Changes in calibration coefficients of net radiometers

The fluctuating differences in net radiation during daytime on 20 June might have been caused by many factors such as optical properties of radiometric domes, response time, wind convection, temperature changes, and so on (Smith *et al.*, 1997). The atmospheric conditions, which might have induced these differences in calibration factors, could be changes in seasonal temperature, cloudiness by sudden alteration of weather and so on (Field *et al.*, 1992).

In order to examine the varying responses of net radiometers to changing atmospheric conditions, we summarized k_t, T_{eff}, daytime calibration factors of Q-7.1s and their changes in Table 7. Cloudiness on 20 June was similar to that on 13 February, and the temperatures on 20 June and 21 June were relatively similar. We think that the changes in temperature probably had played a role here but cloudiness must be also investigated more carefully in terms of responses of different wavebands. To minimize the potential

Table 7. Calibration factors and their changes against those in 20 June

Date	k_t	T_{eff} (°C)	Q-7.1(2)		Q-7.1(3)	
			Calibration factors	Changes in calibration factors (%)	Calibration factors	Changes in calibration factors (%)
13 Feb.	0.56	-17.8	m=10.16, o=-9.35	6.83%	m=9.88, o=-6.88	5.44%
20 June	0.53	16.7	m=9.51, o=-10.54	●	m=9.37, o=-9.73	●
21 June	0.19	21.2	m=9.57, o=-9.04	0.63%	m=9.60, o=-9.28	2.45%

(Rn = m*V + o, m: muliplier, o: offset, V: output voltage of Q-7.1) errors in the radiation measurements, calibration of Q-7.1 against the reference net radiometer (e.g., CNR1) should be performed every 4 - 6 months (preferably before and after the growing season or field experiment). The CNR 1 net radiometer can be well replaced by regularly calibrated Q-7.1 radiometers for long-term field experiments with <5% of measurement uncertainty.

V. SUMMARY AND CONCLUSION

One of the most difficult problems in the measurement and study of radiation is that there is no true radiometer (Kondratyev, 1970; Halldin and Lindroth, 1992). However, it is always possible to take more accurate measurements through careful and consistent calibration against a high-precision radiometer. We have conducted two short-term field experiments to inter-compare and calibrate two net radiometers (i.e., Q-7.1s and CNR1s), which are most widely used in flux measurements. Weather conditions during the two experiments were not the best but the comparisons and calibrations of the two net radiometers with a certain time interval and with different directional arrangements provided some insights to further investigate. Major findings were: (1) relatively inexpensive and easily manageable Q-7.1 net radiometer can replace CNR1 for *Rn* measurement with <5% error; (2) field calibration of net radiometers are recommended for every 4-6 months due to changes in calibration factors with time and environment; (3) differences in directional and temporal responses of the two net radiometers need further examination; and (4) considering the spatial variation of net radiation due to surface heterogeneity in many flux sites, several Q-7.1 net radiometers can be successfully employed in combination with more expensive net radiometers (e.g., CNR 1) to obtain a reasonable spatial coverage with a minimal cost.

적 요

순복사는 지표 에너지 수지의 가장 근본적인 요소 중 하나이다. 순복사의 정확한 관측을 위해, 주기적이고 지속적인 순복사계 보정이 요구된다. 플럭스 관측에 널리 사용되는, 두 가지 타입의 대표적인 순복사계 (Q-7.1과 CNR1)의 상호 비교 및 보정 실험이 약 4개월 간격으로 두 차례 시행되었다. Q-7.1과 CNR1 간의 차이는 7.7% 이내였고, 표준 기기와의 보정 후 오차는 3.2% 이내였다. 순복사계의 반응 차이와 보정계수는 대기 상태, 특히 계절 변화에 따른 온도 차이에 따라 다르게 나타났다. 결론적으로, 주기적으로 보정된 Q-7.1은 CNR1을 대체하여 장기 관측에 사용될 수 있고, 보정 주기로는 4-6개월이 권장된다.

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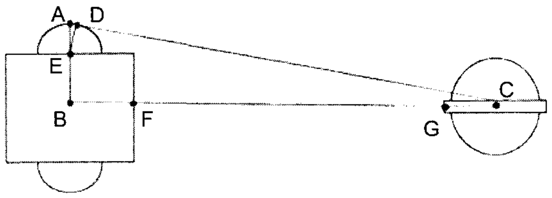

Fig. 12. Diagram of interval between CNR1 and Q-7.1. ∠ABC=∠ADE=90°, ∠ACB=∠AED=10°, △ABC ∽ △ADE, $\overline{AB}$=7.5, $\overline{AD}$=0.25, $\overline{DE}$=1.48, $\overline{BF}$=4.0, $\overline{GC}$=3.5(cm).

Appendix.

Determination of the Separation Distance of Net Radiometers

While net radiometers should be placed as closely as possible to minimize environmental bias, there should be also a sufficient separation distance from one another to minimize the shading effect. As mentioned above, there were errors in CNR1 due to deviations in the directional response of the CM3's when solar elevation was lower than 10 degree. This angle was the criterion for determining the minimum separation in this experiment. It is simply determined as (Fig. 12) :

$$\overline{DE} : \overline{AD} = \overline{BC} : \overline{AB}$$

$$1.48:0.26 = (4.0+\overline{FG}+3.5):7.5$$

$$\overline{FG} \approx 35.2(\mathrm{cm})$$

Therefore, the separation distance between net radiometers was set at 0.4 m in this experiment.