

VERTICAL DISTRIBUTION OF NOCTURNAL NET RADIATION IN THE LOWEST FEW HUNDRED METERS OF THE ATMOSPHERE*

Takuro SEO, Nobuyuki YAMAGUCHI** and Eiji OHTAKI

INTRODUCTION

Vertical distributions of nocturnal net radiation were measured in November 4—6, 1966; these measurements were made as a part of an extended observation of the nocturnal inversion in the period of March 1966 to March 1967 at Mizushima, Okayama Prefecture. A C.S.I.R.O.-type net radiometer was used. The radiometer was carried aloft with use of a moored balloon to a maximum level of 300 m. The results, supplemented by the observations during August and October 1967, are presented. The purpose of the measurements was to learn the characteristics of the net radiation profile in the occurrence of nocturnal inversion and to understand the role of the radiational process in the formation of the surface inversion.

It is accepted that the temperature change in the atmospheric boundary layer is governed by the vertical divergence of turbulent heat transfer and that of net radiation, provided advection is negligible. The radiative divergence can be calculated by several semi-empirical methods based on the radiative transfer equation. Robinson (1950), Möller (1955) and Azuma (1957) applied the methods to the air layer near the ground and found that the calculated radiative temperature change is far greater than the actual change. Direct measurements have been made possible by the development of a net radiometer of high sensitivity by Funk (1960). His measurements confirmed the results of Robinson and others, but were limited to several meters above the ground. For higher levels in the boundary layer, only accessible data are those of six ascents in the Arctic Alaska recently published by Lieske and Stroschein (1967). They found that the magnitudes of radiative divergence deduced from balloon data for the levels up to 250 m were usually small compared with those from tower data for the layer 2—5 m. Our data are similar to their balloon data in the height range covered. The surface condition of our location is not sufficiently homogeneous for this kind of observation; nevertheless, our results indicate some consistent features and may contribute to the understanding of the process of heat exchange in the boundary layer.

OBSERVATIONS

General Observations were made in the following three periods: November

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** Present affiliation: Kochi University.

4—5 1966, August 16—18 1967 and October 14—15 1967.

The site was located on an unoccupied area of a reclaimed foreshore ($34^{\circ}31'N$ $133^{\circ}41'E$), 1000 m wide in east-west direction and 500 m wide in north-south direction (see Fig. 1). The ground of sandy soil was sparsely covered with grass. Ascents of the balloon were made near the center of the site.

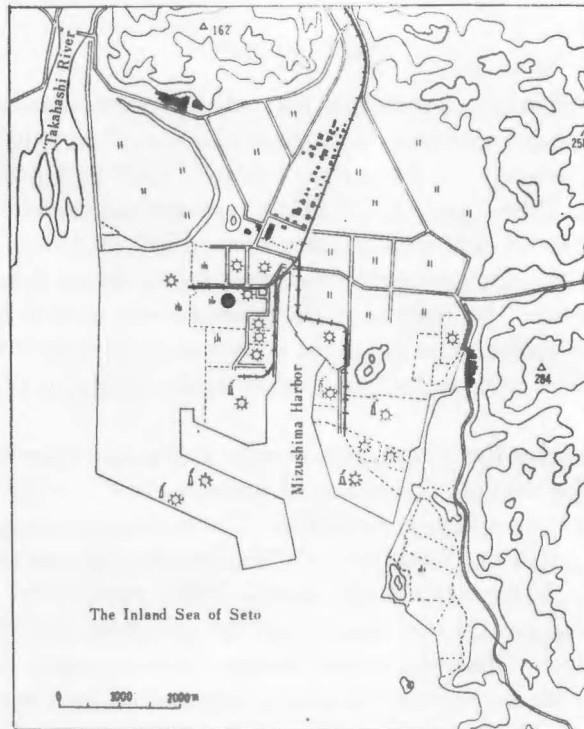


Fig. 1. Schematic topographical map around the site, which is marked by ●.

- | | |
|-------------|-----------------------|
| paddy field | ⊗ thermal power plant |
| waste land | ⌒ stack |
| ⊗ factory | |

Net Radiometer Measurements of net radiation were made with C.S.I.R.O.-type net radiometers manufactured by Eiko Co. Ltd.. The radiometers were standardized by field comparison with a net radiometer of the same type of known calibration constants (MIDDLETON No. 467). The results showed that the radiometers employed had the sensitivity of about $25 \text{ mV/cal cm}^{-2} \text{ min}^{-1}$ in the infrared region. The output of the radiometer was recorded by a self-balancing potentiometer with a 5 mV span. The nominal precision with this sensor-recorder system was $1/2 \text{ mcal cm}^{-2} \text{ min}^{-1}$.

The temperature coefficient of the sensitivity of the original net radiometer is stated to be $0.001/^{\circ}\text{C}$ (Funk 1961); our data were corrected for this temperature coefficient. The time constant of the instrument is about one minute (Funk 1960).

Moored Balloon Technique Two vinyl balloons of kytöon type, filled with 40 m^3 and 15 m^3 of hydrogen respectively, were used to carry the radiometer.

The radiometer was mounted to the mooring cable 20 m below the balloon, and its output was led to the recording potentiometer at the ground through leads temporarily fixed at 50 m intervals to the mooring cable. To gimbalize the radiometer a universal joint was used in the last observation (Fig. 2). In the earlier two observations in which no universal joint was employed, the radiometer was mounted as follows (Fig. 3): a plastic pipe (15 cm in length and 4 cm in diameter) jointed at right angle to the stem of the radiometer was fastened to the cable by metal bands; the position of the pipe was adjusted so as to level the instrument. This simple mounting ensures an approximate levelling of the radiometer, provided the cable is stretched along the vertical. The possible error involved is considered later.

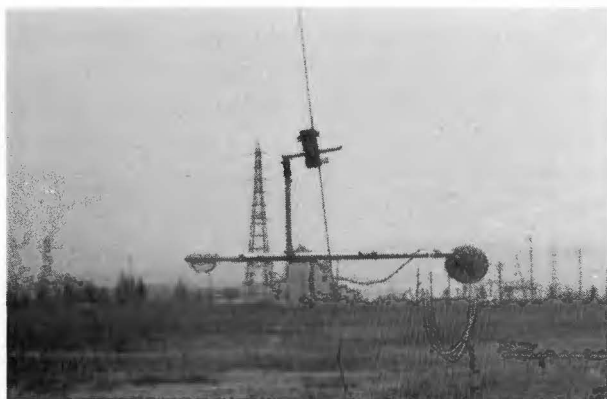


Fig. 2. Radiometer mounting in the observation in October 1967.



Fig. 3. Net radiometer and thermistor thermometer in ventilation tube.

A winch was used to reel the cable. Operation of the winch was stopped at each 50 m in cable length, and the measurement was taken at each level for at least one minute. Altitude of the balloon was determined from (i) the cable length

and (ii) the clinometer observations of the elevation angle of the balloon and the inclination angle of the cable at the ground. The accuracy of the height determination is estimated to be within 10 per cent (Takasu *et al.* To be published.).

Measurements were repeated in both ways of ascent and descent of the balloon. The duration of one run was 20 to 60 minutes, depending on the highest altitude reached by the balloon.

The vertical profile of air temperature was measured in a similar procedure to that for net radiation. The temperature measurement was made with a ventilated thermistor thermometer fixed to the cable beneath the radiometer (Fig. 3).

For further details of the balloon technique, refer to a paper to be published (Takasu *et al.*).

Errors in the Measurements The radiometer was fixed rigidly to the flexible cable in the first two observations as mentioned above. It was unavoidable that the radiometer dipped as the cable inclined from the vertical. The effect of the inclination of the radiometer on its output was examined at the height of 1.5 m above the ground for various inclinations given to the sensing element. From the results shown in Fig. 4 the error due to the inclination is estimated to be within 2 per cent for the inclination angles less than 20 degrees. Most of our measurements were taken under light wind conditions, and the balloon was found to ascend almost directly overhead; even with moderate winds the cable was never found to deviate appreciably from the vertical near the position of the radiometer. It is improbable that the error due to the inclination could be important under these circumstances

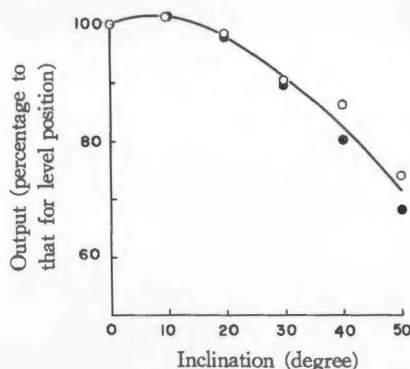


Fig. 4. Variation of output of the net radiometer with inclination of its sensing element. Feb. 13, 1968 (○ 1800–1830; ● 1831–1855). Net radiation: 120–124 $\text{mcal cm}^{-2} \text{ min}^{-1}$.

The captive balloon screens the sky near the zenith from the view of the radiometer. The sky around the zenith is at lower effective temperatures than the balloon. The situation causes an overestimation of the downward flux. The effect is estimated on the following assumptions appropriate for our case: (i) the balloon of 2 m in diameter is located directly over the radiometer at the distance of 20 m;

(ii) the temperature of the balloon is 0°C and the effective radiative temperature of the sky is -20°C . The calculation gives a value of about $2 \text{ mcal cm}^{-2} \text{ min}^{-1}$ for the overestimation.

The two factors above mentioned—the dip of the radiometer and the shading by the balloon—lead to underestimation of the net radiation. However, they could not have any significant effect on the observed profile of net radiation, because it is unlikely that the errors due to them were subject to any systematic variation with height.

It seems that the inhomogeneities of the surface around our site are more critical for the interpretation of the profile from the balloon data. The surface condition to the west of the site is similar to that around the site at least to a distance of about 2 km; in the remaining sectors there exist towns, factories and water surfaces, though most of them are 500 m or more away from the point of ascent (see Fig. 1). The radiative temperatures of these outside areas may be assumed to be somewhat higher than that of the sandy ground in the neighborhood of the site. The situation must effect an apparent increase of the terrestrial radiation with increasing height, because the radiometer scans a wider area as it ascends. The quantitative estimate of the effect is difficult. However, it can be shown that the instrument at the height of 200 m receives 90 per cent of its upward flux from the surface area of 600 m in radius and with the center right under the balloon. It is therefore probably safe to assume that the profile below the height of 200 m was approximately representative of the surface condition near the site.

It is to be noted that our measurements, except one evening measurement, were taken in the periods of northerly winds and hence were not subject to the direct influence of the effluents of the stacks of high discharge (see Fig. 1). However, it must be admitted that the possible presence of haze particles, though unrecognizable to the eye, could have had some effect in the present observations.

RESULTS AND DISCUSSIONS

An example of the record of net radiation is reproduced in Fig. 5. The recorded trace shows a regular variation with height notwithstanding the disturbing effects mentioned above.

The observational data of 17 runs in total are given in Appendix A. These data on the net radiation are plotted against height. Three examples are given in Fig. 6 with the temperature profiles measured at the same time. It is found that the plotted values of net radiation are somewhat scattered; however, a smooth curve can be fitted reasonably to the plotted points as shown in the figure. From this curve, which may be regarded as a mean profile for the duration of one measurement, the net radiation values for specified heights (2, 50, 100 m and so on) are read and given in Appendix B. The net radiation in run 9 was too variable to be analysed by the method mentioned above. The data of this run is specially discussed in the last section. The values of air temperature at the specified

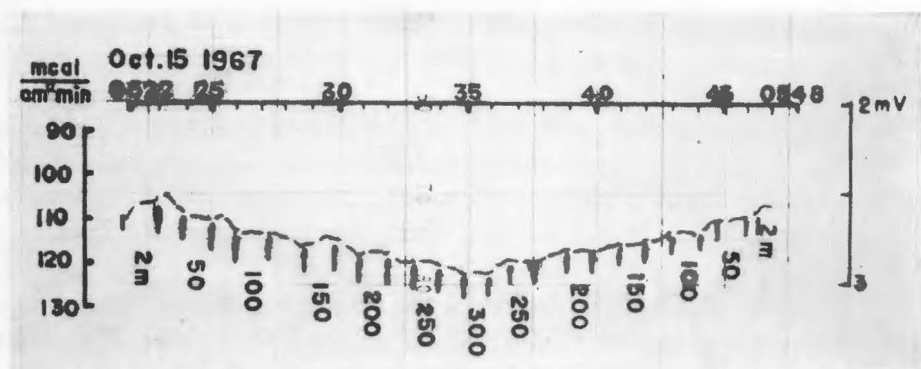


Fig. 5. Example of record of net radiation.

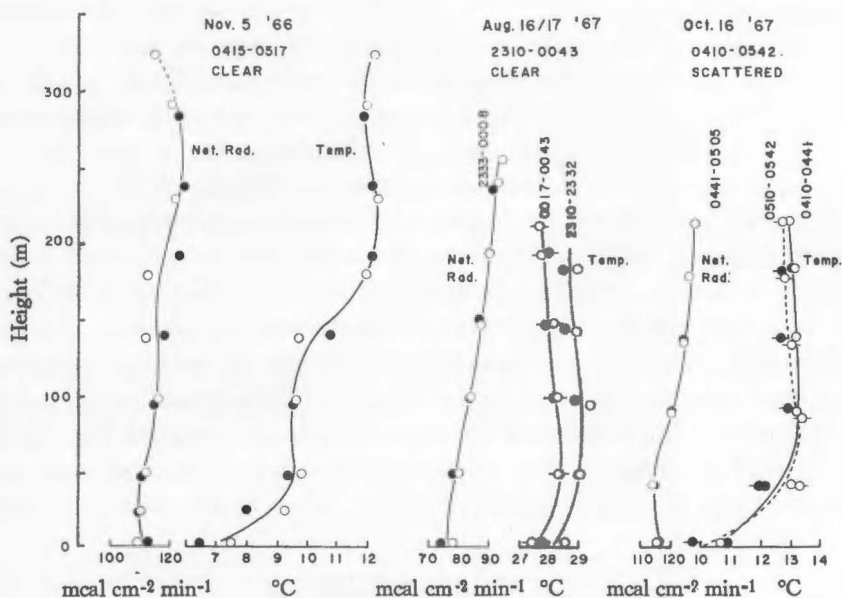


Fig. 6. Examples of profiles of net radiation and air temperature, illustrating the method of reduction of data.

○ measurement in ascending stage

● measurement in descending stage

heights, obtained in a similar manner, are given in Appendix C.

Profile of the Net Radiation in the Occurrence of Inversion Selecting the measurements under "clear" or "high scattered" sky, including one measurement under "high broken" (run 2), the differences of net radiation between successive specified levels are taken from Appendix B and shown in Fig. 7. They are averaged for each observation and summed upward from the lowest 2m level to give the average profiles of net radiation as shown in Fig. 8. The average profiles of air temperature constructed in a similar manner are also shown in Fig. 8.

We see from Fig. 7 and Fig. 8 the following characteristics of the vertical profiles of net radiation, though the individual profiles rather deviate from the

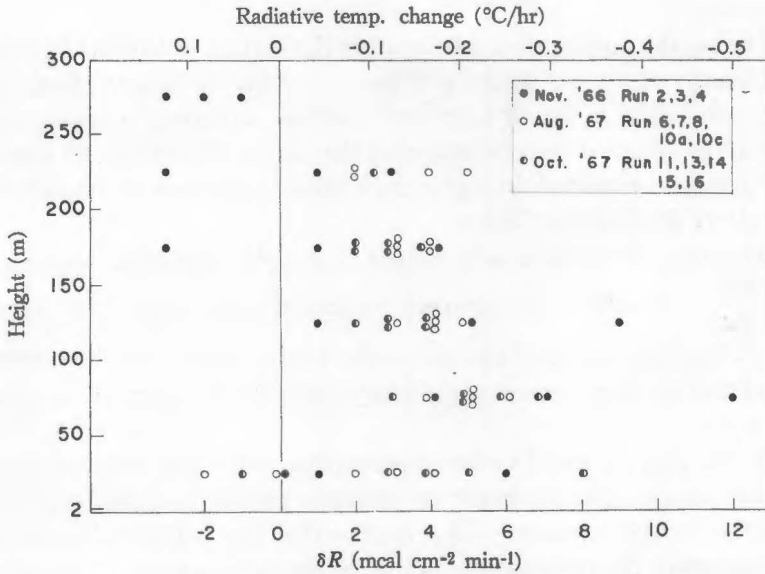


Fig. 7. Difference of net radiation δR ($\text{mcal cm}^{-2} \text{ min}^{-1}$) between specified heights. Selected runs are as follows:

(2), (3), (4) from November '66 observation marked by $\bullet$; (6), (7), (8), (10a), (10c) from August '67 observation marked by $\circ$; (11), (13), (14), (15), (16) from October '67 observation marked by $\odot$. Only run (2) is measurement under "high broken" sky, all others under "clear" or "scattered" sky.

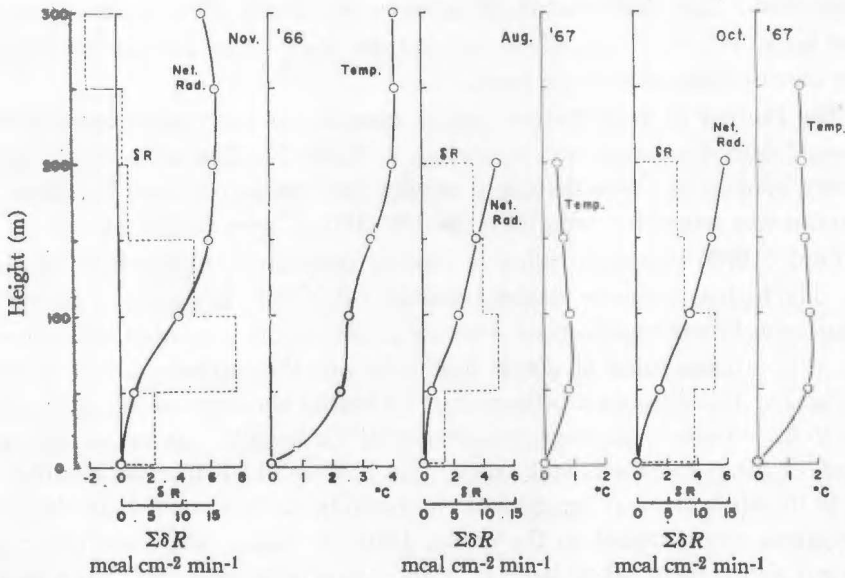


Fig. 8. Average profiles of net radiation and air temperature at night of fair weather. δR ($\text{mcal cm}^{-2} \text{ min}^{-1}$) is difference of net radiation over the indicated height interval averaged for each of three observations (dotted line). $\Sigma \delta R$ ($\text{mcal cm}^{-2} \text{ min}^{-1}$) is scale for average profile obtained by adding the differences.

average profile.

(1) During the nighttime of fair weather the surface inversion of temperature was established and the net radiation R (taken positive for upward flux) generally increased with height in the air layer up to 250 m, indicating a radiative cooling prevalent in the layer. It is to be remarked that in the November '66 observation, when the inversion extended through a thick layer, a decrease of net radiation was observed above the height of 250 m.

(2) The rate of increase with height, i.e., the vertical divergence of net radiation $\frac{\partial R}{\partial z}$, showed a characteristic variation with height. In general, the radiative divergence increased upward in the lowest layers to a maximum near the level of 100 m, then decreased gradually upward. It was most variable in the 2–50 m layer.

(3) In the August and October observations, with the temperature profiles being rather simple, the maximum of radiative cooling occurred directly above the top of the surface inversion. This implies that the radiational process tended to make monotonic the temperature profile in the surface layer. The same effect was recognized in the lower parts of the ascents of the November '67 observation. The above relation between the profile of net radiation and that of air temperature has been noted by Lieske and Stroschein (1967).

Comparison of the Radiative Cooling Rate with the Actual Rate of Cooling The radiative cooling rate is defined as $\frac{1}{c_p \rho} \frac{\partial R}{\partial z}$. (The symbols used are standard.) The difference of R between two levels 50 m apart (48 m in the lowest layer) is used in the calculation and the result is assumed as representative of the mean cooling rate of the layer.

The average of the radiative cooling rates for the layer from 2 m to 200 m is compared with the actual rate of cooling in Table 1. The table shows that the radiative cooling rate was definitely smaller than the actual rate of cooling. The difference was somewhat reduced in the 50–100 m layer (Table 2).

Funk (1960) observed radiative cooling rates much higher than the actual ones. The highest value he obtained exceeded 10°C/hr. In contrast, the radiative cooling rates in our observations were invariably small compared with the actual ones, with a mean value of about 0.2°C/hr and the highest value of 0.5°C/hr (see Fig. 7). The difference between Funk's results and ours can be attributed, in part, to the difference in range and interval of the height: our values refer to the interval of 50 m and the height range from 2 m up to 300 m, while Funk's data refer to the air layer near the ground. It should be further pointed out that Funk's observations were limited to the earlier hours at night, while our observations discussed above were taken later at night. It is to be remarked that a radiative cooling rate much higher than those above mentioned occurred in one of our measurements in the evening: November 5, 1966, 1548–1610 (run 5). In this measurement, the outgoing radiation already prevailed and a radiative cooling

TABLE 1
Comparison of radiative temperature change with actual one for 2—200 m layer

Run	Date	Time ⁽¹⁾	Actual ⁽²⁾ (°C/hr)	Radiative
(1)	Nov. 4 '66	1910—2002	−0.4	−0.2
(2)	Nov. 4	2207—2257	−0.4	−0.1
(3)	Nov. 5	0100—0200	−0.4	−0.25
(4)	Nov. 5	0415—0517	−0.3	−0.1
(6)	Aug. 16 '67	2210—2240	−0.35	−0.2
(7)	Aug. 16/17	2333—0008	−0.65	−0.15
(8)	Aug. 17	0203—0230	−0.3	−0.15
(10)	Aug. 18	0310—0454	−0.4 ⁽³⁾	−0.1
(13)	Oct. 15 '67	0301—0330	−0.45	−0.2
(15)	Oct. 15	2002—2223	−0.6	−0.1
(16)	Oct. 16	0105—0130	−0.3	−0.15
(17)	Oct. 16	0441—0505	−0.2	−0.1

(1) Time of measurement of net radiation.

(2) Change over 6 hours interval for November observation and about one hour interval for August and October observations.

(3) Mean from run (10a), (10b) and (10c).

TABLE 2
Comparison of radiative temperature change of specified air layer
with actual one in °C/hr

Height interval (m)	Average for November '66 observation		Average for August '67 observation		Average for October '67 observation	
	Actual	Radiative	Actual	Radiative	Actual	Radiative
2—50	−0.5	−0.1	−0.4	−0.1	−0.45	−0.1
50—100	−0.4	−0.3	−0.4	−0.2	−0.35	−0.2
100—150	−0.35	−0.2	−0.4	−0.15	−0.4	−0.15
150—200	−0.2	−0.1	−0.45	−0.1	−0.4	−0.1
200—250	−0.15	−0.05				
250—300	−0.2	+0.1				

rate of about 2°C/hr was observed for the air layer 2—50 m.

Calculation of the Radiative Divergence by the Deacon Chart Moisture data necessary for the calculation were obtained with a thermistor psychrometer in the October '67 observation. The results are given in Appendix D. The Deacon chart for water vapor pressure 10 mb has been adopted for the calculation (Deacon 1950). The temperature and moisture profiles above the height of 200 m have been assumed by reference to the radiosonde data at Yonago Weather Station*. The temperature indicated by a thermocouple (bare copper-constantan wire of 0.2 mm in diameter) placed on the ground was used as a "surface" temperature.

The comparison of the calculated and observed flux divergences is made in

* The air temperature at the height of 5 km was taken as −10°C and the precipitable water from surface to 5 km as 1.2 cm.

TABLE 3
Comparison of observed and calculated difference of net radiation
in $\text{mcal cm}^{-2} \text{ min}^{-1}$ between specified height interval

Run	Date	Time	Height interval:			
			2—100 m		100—200 m	
			Obs.	Cal.	Obs.	Cal.
(13)	Oct. 15 '67	0301—0330	13	8	7	5
(14)	Oct. 15	0522—0548	7	5	5	2
(15)	Oct. 15	2202—2223	8	8	5	3
(16)	Oct. 16	0105—0130	8	10	9	3
(17)	Oct. 16	0441—0505	5	6	6	4

Indicated time is time of measurement of net radiation. Calculated value is a mean of two values from temperature and humidity profiles about 1/2 hours before and after the indicated time.

Table 3. The calculated results show general agreement with the observed ones for the 2—100 m layer but they tend to give an underestimation for the 100—200 m layer. Thus, the calculation appears to support the observed result that the radiative cooling rate was lower than the actual rate of cooling.

The Role of Radiative Transfer in the Nocturnal Cooling Process
Robinson (1950) and Funk (1960) concluded that the surface inversion is primarily of radiational origin for the reason that the radiative cooling rate was found to be much higher than the actual one. They inferred further that the turbulent heat transfer acts as a brake to the radiational cooling process. In our observations the radiative cooling rate in inversion conditions was found to be consistently smaller than the actual one. It follows that other forms of heat transfer should contribute essentially to the cooling process so as to maintain the inversion.

The problem is considered in more detail for the case of run 11 (Table 4). The decrease in heat storage of the air layer of the thickness δz , $-c_p \rho \frac{\partial T}{\partial t} \delta z$ ($\delta z = 50$ m) calculated from the measured temperature change is given in column 2 of the table. The increase of net radiation through the layer $\frac{\partial R}{\partial z} \delta z$ is given in column 3. The difference $-c_p \rho \frac{\partial T}{\partial t} \delta z - \frac{\partial R}{\partial z} \delta z$ given in column 4 represents the effect of the vertical eddy transfer and advection by the heat balance relation for the layer:

$$-c_p \rho \frac{\partial T}{\partial t} \delta z = \frac{\partial R}{\partial z} \delta z + \frac{\partial H}{\partial z} \delta z + c_p \rho v_H \frac{\partial T}{\partial s} \delta z,$$

where H is the vertical eddy transfer of heat (positive for the upward flux), v_H the horizontal wind speed, and $\frac{\partial T}{\partial s}$ the horizontal temperature gradient in the direction of v_H .

We have no observed data on the vertical divergence of eddy transfer of heat $\frac{\partial H}{\partial z}$; however, it can be estimated as follows. The value of H may be assumed

TABLE 4
Components of heat balance for layer of thickness $\delta z \approx 50$ m

1	2	3	4	5	6	7	8	9	10
Height m	$-c_p \rho \frac{\partial T}{\partial t} \delta z$	$\frac{\partial R}{\partial z} \delta z$	Diff. (2)-(3)	$\frac{\partial H}{\partial z} \delta z$	$c_p \rho v_H \frac{\partial T}{\partial s} \delta z$	$\frac{\partial \theta}{\partial z} \delta z$	H	H'	A
		mcal cm ⁻² min ⁻¹				°C	mcal cm ⁻² min ⁻¹		cgs
2	7	5	2	3	-1	1.9	-10	-10	1
50	19	7	12	3	9	0.3	-7	-8	7
100	19	3	16	3	13	0.1	-4	4	7
150	19	3	16	1	15	0.0	-1	20	—
200							0	36	—

$-c_p \rho \frac{\partial T}{\partial t} \delta z$: decrease in heat content associated with measured cooling $\left(-\frac{\partial T}{\partial z}\right)$ of the layer

$\frac{\partial R}{\partial z} \delta z$: difference of net radiation R (positive for upward flux) between upper and lower boundary of the layer

$\frac{\partial H}{\partial z} \delta z$: difference of vertical eddy heat transfer between upper and lower boundary of the layer

$c_p \rho v_H \frac{\partial T}{\partial s} \delta z$: change in heat content of the layer due to advection

$\frac{\partial \theta}{\partial z} \delta z$: increase of potential temperature through the layer

H : vertical eddy transfer of heat estimated by the method described in the text

H' : vertical eddy transfer of heat obtained from heat balance relation with neglected advection

A : Austausch coefficient in g cm⁻¹ sec⁻¹

as -10 mcal cm⁻² min⁻¹ at the level of 2 m.* It may be taken nearly vanished in the 150–200 m layer, since the gradient of potential temperature (column 7) is negligible in this layer and the value of Austausch coefficient must remain within reasonable limits of the order of 10 g cm⁻¹ sec⁻¹. Moreover, H must be negative (downward flux) through the layer 2–150 m, corresponding to the positive sign of the gradient of potential temperature. With the above information on the upper and lower limits of the value of H and its sign between the limits, the values at intermediate levels can be reasonably approximated (column 8).

The difference of H between the upper and lower boundary of each layer are thus obtained $\left(\frac{\partial H}{\partial z} \delta z$ in column 5), and the advective term $c_p \rho v_H \frac{\partial T}{\partial s} \delta z$ is determined as the residual (column 6). This term assessed as the residual contains accumulated errors; however, it is apparent from the table values that the advective effect is significant except in the lowest 2–50 m layer. It is to be noted that the advective loss of heat found here, i. e., that of the order of 10 mcal cm⁻² min⁻¹ for the layer thickness $\delta z = 50$ m, is caused by the horizontal temperature gradient of about 0.1 °C/km for the wind speed of 1 m/s.

The Austausch coefficient for heat can be determined from the estimated

* This estimate is based on the two measurements by the eddy correlation method in the October observation which gave the values of 5 and 9 mcal cm⁻² min⁻¹ at the 1.5 m level for the duration of 3 minutes.

values of H and the measured gradient of potential temperature $\frac{\partial \theta}{\partial z}$. The results are given in column 10. These values are reasonable ones for light wind conditions at night; this suggests the general validity of the foregoing analysis.

If we neglect the advection and take the difference $-c_p \rho \frac{\partial T}{\partial t} \delta z - \frac{\partial R}{\partial z} \delta z$ equal to the divergence of eddy heat flux, we obtain for the eddy transfer of heat the values given in column 9 of Table 4. The procedure is to add successively the differences given in column 4 to the assumed value of eddy heat flux ($-10 \text{ mcal cm}^{-2} \text{ min}^{-1}$) at the 2 m level. It turns out that the sense of the flux reverses at the level of 100 m and is incompatible with the sign of $\frac{\partial \theta}{\partial z}$ in the upper levels. This difficulty can not be overcome, unless abnormally high values are assigned to the eddy heat flux at the 2 m level. Thus, it appears that the neglect of the advection is not justified at least for the layers above 100 m.

The arguments presented above for a specific case applies more or less to most of the present measurements. Their implication is not easy to comprehend; however, it may be concluded that the nocturnal cooling process in the atmospheric boundary layer is a complex phenomenon in which the radiational process is not necessarily the primary one.

Net Radiation under Variable Skies One measurement under variable skies (run 9) is described for comparison. When the state of the sky was variable, especially when the cloudiness by low or middle clouds varied, the time change of the net radiation was relatively large compared with its variation with height. The vertical profile under these circumstances was difficult to obtain by our single radiometer method. One of such cases (run 9) is illustrated in Fig. 9 in terms of

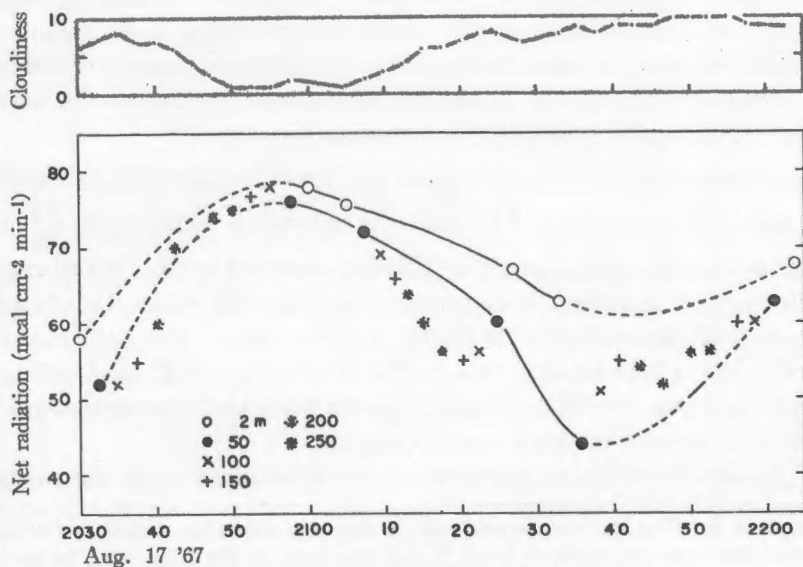


Fig. 9. Net radiation under variable cloudiness.

the time variation at approximately fixed heights. Three consecutive ascents were taken in this measurement. The temperature stratification was in lapse condition. Fig. 9 shows that radiative warming prevailed in the 2—50 m layer, in contrast to the radiative cooling prevalent in the occurrence of inversion.

CONCLUSION

It appears to be established from the observations that the net radiation generally increases with height in the lowest 200 meters on a calm, clear night when a surface inversion appears. The radiative cooling prevalent in the same layer showed the maximum at a level of about 100 m. The level approximately corresponded to the top of the inversion layer. The radiative cooling rate was in the order of $1/10^{\circ}\text{C/hr}$ in agreement with the similar measurement by Lieske and Stroschein (1967). It was found to be smaller than the actual cooling rate, in contrast to the results of Funk (1960) for the air layer near the ground. This indicates that other processes—turbulent and advective—than that of radiational origin were co-operative in the formation and maintenance of the nocturnal inversion in the boundary layer. It seems that the regime of heat exchange in the boundary layer is different from that in the air layer next to the ground.

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APPENDIX A

Net radiation R ($\text{mcal cm}^{-2} \text{ min}^{-1}$) at height z (m)

State of the sky, and wind direction and speed (m/s) at 2 m height are given at the bottom of the individual table.

(1) Nov. 4 '66 1910—2002				(2) Nov. 4 '66 2207—2257				(3) Nov. 5 '66 0100—0200			
z	R	z	R	z	R	z	R	z	R	z	R
2	115	2	79	2	102	2	90	2	95	2	109
25	116	25	81	23	103	25	92	24	100	23	108
50	119	50	86	49	95	50	100	46	108	45	109
100	122	100	93	100	103	100	112	91	113	93	112
150	123	150	101	149	106	149	119	143	122	145	124
200	126	200	112	198	106	197	113	193	125	191	125
247	127	249	120	246	107	242	108	239	125	234	124
294	126	296	124	291	107	290	102	278	123	284	130
344	124			334	94			320	122		
CLEAR to HIGH BROKEN NW : 0.5-1				HIGH BROKEN NW : 0.5-2				HIGH SCATTERED NE : 1.5-3			
(4) Nov. 5 '66 0415—0517				(5) Nov. 5 '66 1548—1610				(6) Aug. 16 '67 2210—2240			
z	R	z	R	z	R	z	R	z	R	z	R
2	109	2	112	2	60	2	50	2	81	2	81
24	110	24	109	25	60	25	105	49	85	49	85
49	112	47	110	50	95	50	90	97	90	95	90
98	116	95	115	98	110	98	87	144	94	130	95
138	112	140	118	142	90	142	113	189	99	185	98
180	113	193	123	176	120			215	101	215	102
230	122	239	125					250	107		
292	121	284	123								
324	115										
CLEAR N : 1-1.5				CLEAR S : 1.5-2				CLEAR W : 0			
(7) Aug. 16/17 '67 2333—0008				(8) Aug. 17 '67 0203—0230				(9a) Aug. 17 '67 2030—2100			
z	R	z	R	z	R	z	R	z	R	z	R
2	78	2	74	2	76	2	78	2	58	2	78
50	80	50	78	50	79	50	78	49	52	50	76
99	84	100	83	100	83	100	84	95	52	99	78
147	88	150	87	149	87	150	89	136	55	145	77
194	91	197	90	197	90	200	92	174	60	173	75
240	93	236	92	242	93			228	70	213	74
257	95							246	75		
CLEAR NW : 0				CLEAR N : 0				LOW BROKEN to LOW SCATTERED N : 2			
(9b) Aug. 17 '67 2105—2127				(9c) Aug. 17 '67 2133—2204				(10a) Aug. 18 '67 0310—0338			
z	R	z	R	z	R	z	R	z	R	z	R
2	76	2	67	2	58	2	68	2	76	2	76
49	72	49	60	49	44	50	63	49	77	49	75
99	69	97	56	95	51	100	60	97	81	97	79
141	66	143	55	143	55	141	59	143	84	145	83
174	64	180	56	183	54	178	56	180	87	182	87
207	60			212	52	204	56	203	88		
				252	55						
LOW SCATTERED to LOW BROKEN N : 2				MIDDLE OVERCAST or MIDDLE BROKEN NNE : 2				CLEAR NNE : 2			

(10b) Aug. 18 '67 0355—0425				(10c) Aug. 18 '67 0425—0454				(11) Oct. 14 '67 2020—2100			
z	R	z	R	z	R	z	R	z	R	z	R
2	75	2	71	2	71	2	75	2	110	2	115.5
50	75	50	66	50	70	50	73	41	113	41	120
99	76	100	68	99	75	99	76	91	122	90	126
149	80	149	74	149	78	149	80	132	126	136	129
195	83	197	81	199	82	197	82	173	129	171	131
235	86	239	85	246	84	244	85	210	131	214	132
251	88			260	87			228	133		
HIGH SCATTERED NNE : 1				MIDDLE SCATTERED NNE : 0.5				CLEAR NNW : 0			
(12) Oct. 14 '67 2251—2310				(13) Oct. 15 '67 0301—0330				(14) Oct. 15 '67 0522—0548			
z	R	z	R	z	R	z	R	z	R	z	R
2	83	2	82	2	110	2	111.5	2	107	2	108
41	82	40	84	42	117.5	42	116.5	42	111	42	111
89	84	90	86	90	122	90	121	91	114	92	114
132	81	130	86	136	127	136	124.5	138	115.5	139	117
172	69	170	84	172	129	176	128	173	119	186	118
194	72.5			212	130			210	121	215	121
LOW BROKEN NNW : 0				CLEAR CALM				CLEAR CALM			
(15) Oct. 15 '67 2202—2223				(16) Oct. 16 '67 0105—0130				(17) Oct. 16 '67 0441—0505			
z	R	z	R	z	R	z	R	z	R	z	R
2	111	2	114.5	2	101	2	105	2	116	2	117.5
42	115	42	116.5	42	104	42	107.5	41	115	41	115
90	120	92	120	91	106	91	112	89	121	91	121.5
133	124	137	122	138	115	138	118	136	125	138	125
179	125	180	125	186	118	184	121	179	127	180	127.5
210	126			220	121			214	129		
LOW SCATTERED NNE : 0				MIDDLE BROKEN NNE : 0				MIDDLE SCATTERED NNW : 0			

APPENDIX B

Net radiation (mcal cm⁻² min⁻¹) at specified height

Run	Date	Time	Height (m)						
			2	50	100	150	200	250	300
(1)	Nov. 4 '66	1910—2002	97	101	108	112	119	124	125
(2)	Nov. 4	2207—2257	96	96	108	113	110	107	104
(3)	Nov. 5	0100—0200	102	108	115	124	125	126	125
(4)	Nov. 5	0415—0517	110	111	115	116	120	123	121
(5)	Nov. 5	1548—1610	54	93	99	100			
(6)	Aug. 16 '67	2210—2240	81	85	91	96	100	105	
(7)	Aug. 16/17	2333—0008	76	79	84	88	91	93	
(8)	Aug. 17	0203—0230	77	79	84	88	91	93	
(10a)	Aug. 18	0310—0338	76	76	80	84	88		
(10b)	Aug. 18	0355—0425	74	71	73	78	82	87	
(10c)	Aug. 18	0425—0454	73	71	76	79	82	86	
(11)	Oct. 14 '67	2020—2100	113	118	125	128	132		
(12)	Oct. 14	2251—2310	82	83	83	81	(73)		
(13)	Oct. 15	0301—0330	110	118	123	127	130		
(14)	Oct. 15	0522—0548	108	112	115	117	120	123	
(15)	Oct. 15	2202—2223	113	116	121	124	126		
(16)	Oct. 16	0105—0130	103	106	111	117	120		
(17)	Oct. 16	0441—0505	117	116	122	126	128		

APPENDIX C

Air temperature ($^{\circ}\text{C}$) at specified height

Run	Date	Time	Height (m)						
			2	50	100	150	200	250	300
(1a)	Nov. 4 '66	1608—1650	15.5	15.1	14.7	14.4	14.2	14.0	14.1
(1b)	Nov. 4	1901—2000	11.1	13.3	13.6	13.5	13.3	13.0	12.8
(2)	Nov. 4	2206—2257	9.9	12.4	12.9	13.0	13.3	13.0	12.8
(3)	Nov. 5	0104—0155	8.8	10.3	10.9	11.7	12.2	12.8	13.1
(4)	Nov. 5	0417—0515	6.9	9.6	9.6	10.8	12.2	12.2	12.1
(5)	Nov. 5	1545—1610	18.2	17.8	17.3	16.9			
(6)	Aug. 16 '67	2038—2112	28.6	29.7	29.8	29.9	29.9		
(7a)	Aug. 16	2310—2332	28.1	29.0	29.1	28.8	28.7		
(7b)	Aug. 17	0017—0043	27.6	28.4	28.2	28.0	27.9		
(8a)	Aug. 17	0128—0200	26.5	27.8	27.6	27.2	27.1	26.9	
(8b)	Aug. 17	0232—0244	25.8	27.5	27.4	27.1	26.7		
(9a)	Aug. 17	2030—2100	28.6	28.2	27.9	27.2	27.1		
(9b)	Aug. 17	2105—2127	28.4	28.2	28.0	28.0	28.1		
(9c)	Aug. 17	2133—2204	28.1	27.9	27.6	27.5	27.5	27.5	
(10a)	Aug. 18	0310—0338	25.8	25.9	26.0	26.1	26.3		
(10b)	Aug. 18	0355—0425	25.3	25.4	25.8	25.8	25.7	25.6	
(10c)	Aug. 18	0425—0454	25.2	25.3	25.7	25.7	25.6	25.5	
(11)	Oct. 14 '67	2020—2100	16.8	19.3	18.9	18.6	18.1	17.9	
(12)	Oct. 14	2214—2242	17.3	17.8	17.6	17.3	16.8		
(13a)	Oct. 15	0224—0251	13.6	15.9	15.9	15.7	15.6	15.4	
(13b)	Oct. 15	0330—0356	13.2	15.2	15.5	15.3	15.2	15.1	
(14a)	Oct. 15	0439—0517	12.3	13.8	13.8	14.2	14.5	14.9	
(14b)	Oct. 15	0548—0611	11.7	13.2	14.0	14.6	15.0	15.0	
(15a)	Oct. 15	2118—2144	14.8	15.7	15.4	15.1	14.9	14.6	
(15b)	Oct. 15	2226—2248	14.2	15.0	14.8	14.4	14.2	14.1	
(16a)	Oct. 16	0034—0100	12.9	14.2	13.9	13.6	13.4	13.3	
(16b)	Oct. 16	0134—0155	12.4	13.9	13.6	13.3	13.1	12.8	
(17a)	Oct. 16	0410—0441	10.9	12.8	13.3	13.1	13.0	12.8	
(17b)	Oct. 16	0510—0542	10.3	12.9	13.1	12.8	12.8	12.9	

APPENDIX D

Specific humidity (g/kg) at specified height and "surface" temperature T_0 ($^{\circ}\text{C}$)
measured by thermocouple

Run	Date	Time	Height (m):							T_0
			0*	2	50	100	150	200	250	
(12)	Oct. 14 '67	2214—2242	9.2	7.5	7.1	6.9	6.9	6.8		15.6
(13a)	Oct. 15	0224—0251	8.1	7.4	6.2	6.1	6.0	5.9	5.9	12.8
(13b)	Oct. 15	0330—0356	7.7	7.3	6.5	6.3	6.6	6.6	6.5	12.2
(14a)	Oct. 15	0439—0517	7.4	7.3	7.0	7.0	6.9	6.6		11.7
(14b)	Oct. 15	0548—0611	7.0	7.2	7.2	6.9	6.8	6.5	6.2	10.9
(15a)	Oct. 15	2118—2144	8.2	7.3	6.9	6.8	6.9	6.8	6.8	13.5
(15b)	Oct. 15	2226—2248	7.8	7.1	6.8	6.7	6.8	6.5	6.3	12.9
(16a)	Oct. 16	0034—0100	7.1	6.7	6.5	6.5	6.4	6.3	6.4	11.5
(16b)	Oct. 16	0134—0155	6.9	6.8	6.5	6.4	6.3	6.3	6.4	11.0
(17a)	Oct. 16	0410—0441	6.5	7.1	6.4	5.7	5.6	5.5	5.7	10.2
(17b)	Oct. 16	0510—0542	6.3	7.1	5.8	5.8	5.8	5.6	5.4	9.8

* Specific humidity at surface is assumed as saturation value for T_0