Study on Cloud–Radiation Effect on Climate in Eastern Asia①

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Received October 21, 1991; revised January 13, 1992

ABSTRACT

In this paper, the decade data of meteorological satellite and surface meteorological observation of China have been analysed. The relationship between cloud and radiation has been studied. A set of empirical formulae of the ralationships between the albedo and cloud amount, the outgoing longwave radiation and cloud amount in Chinese different districts and different seasons has been deduced. They express simply the response of both planet reflectivity and earth–atmosphere outgoing longwave radiation to the change of cloud amount. So that the sensitivity of net radiation of the earth–atmosphere system to the change of cloud amount and the ratio of cloud reflective effect to greenhouse effect can be estimated. In this paper, the radiative process of the earth–atmosphere system, cloud and radiative balance and its effect on climate have been synthetically studied.

I. INTRODUCTION

Cloud and radiation play the important roles in climate formation. Cloud cover influences the exchange of energy and water cycles. The cloud covers nearly 50% of the global sky. The clouds that affect the average earth's reflectivity account for 2 / 3 of the total cloud amount. The cloud reflectivity of solar radiation is different, e. g., Ci is 36%, Sc is 60–80%. The cloud absorptivity of solar radiation is smaller than 10%, but clouds can absorb almost the total amount of earth infrared radiation, thus making greenhouse effect. Middle–low clouds are mainly of reflectivity. In general, on the globe, cloud cooling effect is larger than the cloud anathermal effect. Cloud effect may play an important role in the local climate. If the liquid water content of a cloud is direct proportional to absolute temperature, the cloud would play a stabilizing role, i.e., the increase of earth temperature will be in company with the increase of cloud amount, then causing the increase of global reflectivity and decrease of earth temperature. Therefore, clouds make a negative feedback cycle. In comprehensive survey, the effect of clouds on climate is controlled by two opposite factors. One is reflective effect: clouds increase the global reflectivity of solar radiation; the other is greenhouse effect, clouds prevent the earth outgoing longwave radiation from escaping to space. On the globe, the change of cloud amount causes the refectivity effect and greenhouse effect, but the first effect is twice as large as the second. Especially for low cloud, the reflectivity effect is several times larger than the greenhouse effect. On tropic oceans, the effect is obvious. The reflectivity of ocean surface is low (10%), there exists big reflectivity difference between clear and cloudy days. If on the globe, the cloud amount is increased by 4%, the decreasing temperature effect will be equal to or larger than the double CO_2 increasing temperature effect. Cloud effect is an important composition of earth climate. The cloud effect on climate not only depends on

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①The project is supported by National Natural Sciences Fundation of China (NNSFC).

cloud amount, but also on cloud height, cloud type and cloud geographical distribution.

In this paper, by combining meteorological satellite observation data with surface meteorological observation data, the cloud–radiation effect in the Eastern Asia will be further studied.

In this paper, the 1974–1984 NOAA satellite data and meteorological data of the same period were used to analyse the relationship between cloud and radiation. In different districts of China and in different seasons, the dependences of planet reflectivity, earth–atmosphere outgoing long–wave radiation on cloud amount have been discussed. The radiation process of earth–atmosphere system, cloud–radiative balance and its effect on climate will be discussed synthetically.

II. RADIATIVE BALANCE OF EARTH–ATMOSPHERE SYSTEM

The radiative budget of the earth–atmosphere system can be written as

$$R = W(1 - a_s) - E \ , \tag{1}$$

where W is solar radiation, a_s planet reflectivity, and E outgoing long–wave radiation of the earth–atmosphere system.

Suppose the relationship of planet reflectivity a_s, outgoing long–wave radiation of the earth–atmosphere system E and total cloud amount N, low cloud amount n, can be expressed as

$$a_s = a_0 + a_1 N + a_2 n \ , \tag{2}$$

$$E = b_0 + b_1 N + b_2 n \ , \tag{3}$$

where a_0, a_1, a_2, b_0, b_1 and b_2 are parameters, N is total covering fraction (%), and n low cloud covering fraction (%).

The monthly average values of 1974–1984 for these factors have been used. a_s and E were gotten from satellite observations. N and n were obtained from surface meteorological observations. The regression analysis shows that the correlation coefficients (r) of functions (2) and (3) are 0.96 and 0.78 respectively. Parameters a_0, a_1, a_2, b_0, b_1 and b_2 changes with district and season.

In this paper, the satellite data include outgoing longwave radiation, planet reflectivity and solar radiation absorption by the earth–atmosphere system. The observation time and observation instrument of outgoing longwave radiation as well as the time of satellite passing through equator are shown in Table 1.

Table 1. Data of Outgoing Longwave Radiation of NOAA Satellite Observation

satellite	time passing over equator	period	instrument	channel
NOAA 2,3,4,5.	9:00, 21:00	74,6–78,6	SR	10.5–12.5μm
TIROS–N	9:00, 15:00	79,1–80,1	AVHRR	10.5–11.5μm
NOAA 6	7:30, 19:30	80,2–81,7	AVHRR	11.5–12.5μm
NOAA 7,8	2:30, 14:30	81,8–84,11	AVHRR	11.5–12.5μm
NOAA 9	2:30, 14:30	84,12–85,12	AVHRR	11.5–12.5μm

The data have been dealt with as follows:

(1) The earth outgoing longwave radiation has diurnal variation. So that the average value of day and night observation data was taken as a day average, in order to eliminate the influence of the diurnal variation.

(2) The infrared radiation observation of NOAA satellite was carried on in a narrow

window band. So that it was necessary to transform the narrow band infrared data into total longwave radiation. According to Nimbus–7 satellite data, there exists the regression relationship between data of ERB total longwave radiation and 10–12μm infrared window radiation. By means of the relation, we transformed different band infrared radiation into total longwave radiation. All data values were put on the $2.5^\circ \times 2.5^\circ$ grid of global distribution.

(3) Cloud amount data were obtained from surface meteorological observation in 1974–1984. There were 59 representative observatories chosen for studying cloud–radiation effect.

III. RESULTS AND ANALYSIS

1. *Earth's Planet Reflectivity Formula*

The earth's planet reflectivity a_s may be expressed with a function of total cloud amount N and low cloud amount n, i.e.,

$$a_s = a_0 + a_1 N + a_2 n \ . \tag{2}$$

By the decade (1974–1984) data of satellite and surface meteorological observations, the regression formulae have been carried out. In the whole China, the correlation coefficient for regression formula (2) was 0.96. The regression formulae of 10 representative observatories are shown in Table 2.

Parameters a_0, a_1 and a_2 change with districts and seasons. $a_1 = \partial a_s / \partial N$, a_2 is an adjustment factor.

2. *Check on the Quality of Earth Planet Reflectivity Formula* (2)

The earth's planet reflectivity formula (2) was derived from regression of the 1974–1984 decade data. In order to check the quality of formula (2), the 1985 observation data were used. The expectant values, calculated form formula (2), in comparison with those of observation data, are shown in Appendix I.

Table 2. Planet Reflectivity Formulae in China

station	earth planet reflectivity a_s			
	spring	summer	autumn	winter
Beijing 39.56N, 116.17E	0.14+0.31N+0.07n	0.10+0.31N+0.03n	0.15+0.51n–0.75N	0.19+0.24N+0.54n
Erenhot 43.39N, 111.56E	0.11+0.50N–0.44n	0.13+0.36N–0.12n	0.10+0.47N–0.07n	0.13+0.73N+0.65n
Changchun 43.54N, 125.13E	0.16+0.24N+0.03n	0.11+0.46N–0.19n	0.09+0.54N–0.20n	0.02+0.84N+0.76n
Shanghai 31.10N, 121.26E	0.04+0.43N+0.01n	0.07+0.41N–0.02n	0.08+0.56N–0.30n	0.09+0.36N+0.01n
Guangzhou 23.08N, 113.19E	–0.41+1.18N–0.1n	–0.37+0.45N+0.58n	0.18+0.33N+0.02n	0.07+0.95N–0.40n
Chengdu 30.40N, 104.01E	0.02+0.41N+0.08n	0.16+0.43N–0.03n	–0.24+0.64N+0.02n	–0.27+0.63N+0.05n
Kunming 25.01N, 102.41E	0.18+0.24N+0.13n	0.24+0.78N–0.59n	0.11+0.54N–0.27n	0.04+0.65N–0.04n
Lhasa 29.40N, 91.08E	0.15+0.68N–0.37n	0.16+0.74N–0.81n	0.15+0.58N–0.39n	0.16+0.44N+0.01n
Dunhuang 40.09N, 94.41E	0.03+0.43N+0.65n	–0.05+0.67N–0.78n	0.11+0.60N–1.36n	0.01+0.96N+1.2n
Urumqi 43.47N, 87.37E	–0.38+1.89N–2.97n	–0.06+0.69N–0.1n	–0.05+0.94N–0.45n	0.24+0.51N+0.05n

In different districts of China, the differences between expectant value and observation value were small. The RMS deviation of whole year average was 2%, and the RMS deviation of monthly mean was 7%. So that the formulae, presented in Table 2 are suitable for application.

3. *Planet Reflectivity Distribution*

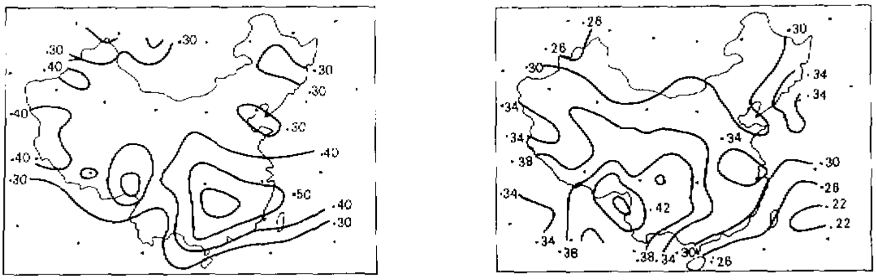
The planet reflectivity distribution is shown in Fig.1. In China, the average planet reflectivity is a little larger than that of the global average. In Fig.1, the maximum values appear in South China and Northwest China in winter. These phenomena are caused by a lot of clouds in South China and snow covers in Northwest China in winter.

4. *Outgoing Longwave Radiation of Earth–Atmosphere System*

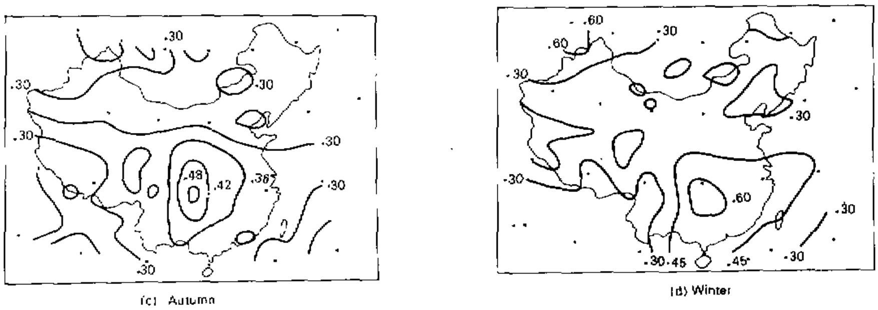
The relationship between total cloud amount N, low cloud amount n and outgoing longwave radiation E is

$$E = b_0 + b_1 N + b_2 n \ , \tag{3}$$

where b_0, b_1 and b_2 are parameters, related to the district and season. By combining the decade (1974–1984) data of satellite and surface meteorological observations, a set of regression formulae of China has been carried out. In the whole China the correlation coefficient γ for regression formula (3) was 0.78. The regression formulae of 10 representative observations are shown in Table 3. The distribution of outgoing longwave radiation is shown in Fig.2.

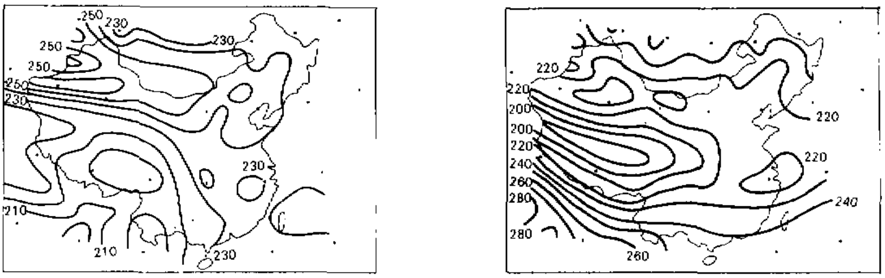


(a) Spring (b) Summer



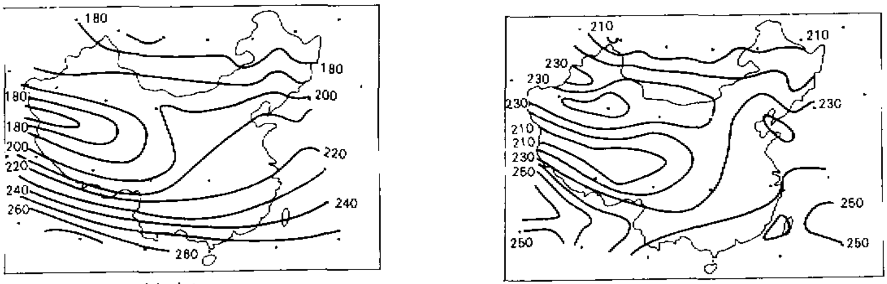
(c) Autumn (d) Winter

Fig.1. Distribution of planet reflectivity a_s.



(a) Spring

(b) Summer



(c) Autumn

(d) Winter

Fig.2. Distribution of outgoing longwave radiation E.

5. *Check on the Quality of Outgoing Longwave Radiation Formula* (3)

The outgoing longwave radiation formula (3) was derived from the regression of the 1974–1984 decade data. In order to check the quality of formula (3), the 1985 observation data were used. The expectant values, calculated from formula (3), in comparison with those of observation data, are shown in Appendix II.

In different districts of China, the differences between expectant value and observation value were small. The RMS deviation of whole year average was 1%, and the RMS deviation of monthly mean was 4%. So that the formulae, presented in Table 3 are suitable for application.

6. *Outgoing Longwave Radiation Distribution*

The outgoing longwave radiation distribution of China is shown in Fig.2, where the high value appears in Xinjiang and low value in the Qinghai–Xizang Plateau.

7. *Distribution of Solar Radiation Absorption*

The solar radiation absorption of the earth–atmosphere system Q has the form

$$Q = Q_0(1 - a_s) , \tag{4}$$

where Q_0 is astronomical radiation, and a_s is planet reflectivity. Its distribution in China is shown in Fig.3. The low value region of solar radiation absorption corresponds to the high value region of planet reflectivity. Owing to the change of astronomical radiation with latitude, in the distribution of solar radiation absorption of China also appears latitude effect. The effect of outgoing longwave radiation opposite to reflectivity appears obviously in the low latitude region. The phenomenon is caused by cloud layer.

Table 3. Outgoing Longwave Radiation Formulae in China

station	outgoing longwave radiation (OLR) E (W/m^2)			
	spring	summer	autumn	winter
Beijing 39.56N, 116.17E	206.8−41.0N+196.3n	272.8−124.4N+140.9n	202.0−26.9N+3.3n	208.7−84.5N+101.2n
Erenhot 43.39N, 111.58E	243.6−160.9N+580.2n	248.0−125.3N+367.2n	255.6−169.0N+347.1n	199.5−44.9N−142.7n
Changchun 43.54N, 125.13E	223.7−37.6N+47.5n	235.9−98.0N+103.2n	244.9−46.6N+45.7n	208.2−93.9N+66.4n
Shanghai 31.10N, 121.26E	260.7−31.4N−30.4n	253.5−182.1N+31.7n	268.7−68.8N+24.6n	250.0−107.7N+89.6n
Guangzhou 23.08N, 113.19E	286.3−245.0N+189.9n	257.9−174.5N+150.6n	256.7−71.0N+13.0n	251.1−91.0N+60.1n
Chengdu 30.40N, 104.01E	283.7−98.5N−26.3n	314.5−140.2N+7.6n	163.9−62.5N+208.4n	245.3−83.5N+30.5n
Kunming 25.01N, 102.41E	223.4+0.1N−58.7n	212.5−123.7N+123.9n	222.1−143.5N+141.3n	222.5−30.8N−30.5n
Lhasa 29.40N, 91.08E	150.2−47.5N+162.1n	290.7−120.9N+388.7n	205.9−114.8N+142.1n	205.8−42.6N−14.9n
Dunhuang 40.09N, 94.41E	365.5−244.0N+118.1n	259.7−96.1N+965.0n	302.6−298.6N+822.4n	227.7−98.1N+26.2n
Urumqi 43.47N, 87.37E	418.6−555.2N+944.4n	320.8−189.0N+71.1n	326.0−280.4N+170.8n	200.4−30.9N+2.1n

Table 4. Astronomical Radiation Q_0 (W/m^2) in China

station	astronomical radiation Q_0			
	spring	summer	autumn	winter
Guangzhou 23.08N, 113.19E	431	454	355	289
Shanghai 31.10N, 121.26E	418	465	312	228
Dunhuang 40.09N, 94.41E	398	467	268	172
Urumqi 43.47N, 87.37E	385	466	243	144

8. *Cloud–Climate Effect*

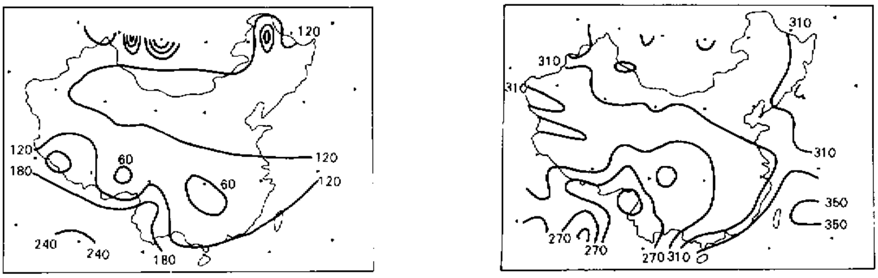
The net radiation sensitivity, caused by cloud amount change is composed of reflectivity effect and greenhouse effect,

$$\delta = \frac{\partial Q}{\partial A} - \frac{\partial E}{\partial A} , \tag{5}$$

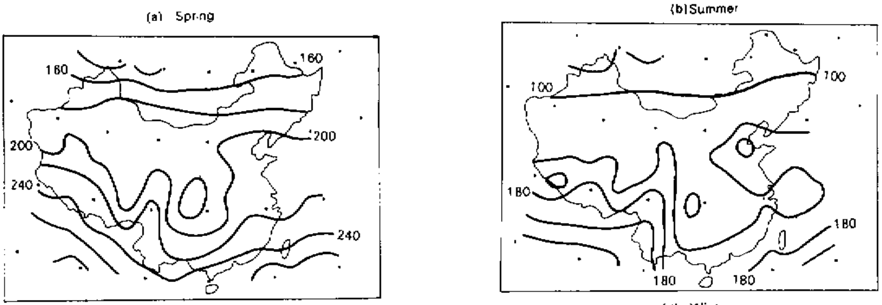
where Q is solar radiation absorption of the earth–atmosphere system, A is cloud cover fraction, and E is the outgoing longwave radiation.

Thus from formulae (3) and (4), we have

$$\delta = -Q_0 a_1 - b_1 \tag{6}$$



(a) Spring (b) Summer



(c) Autumn (d) Winter

Fig.3. Distribution of solar radiation absorption.

and

$$\frac{\partial Q}{\partial E} = -Q_0\frac{a_1}{b_1} \ . \tag{7}$$

The values of several representative observatories are shown in Table 5. For the Southeast coastal region (Guangzhou and Shanghai),

$$\delta = -95$$

and for the Northwest region (Dunhuang and Urumqi),

$$\delta = -52$$

and

$$\frac{\partial Q}{\partial E} = -2 \ .$$

The above conclusion coincides with the result of Ohring et al. (1981).

Owing to neglecting the effect of $\partial n / \partial N$ in Eq.(6), the error of δ may be caused. It $\partial n / \partial N \sim 1/3$, $\Delta\delta / \delta$ may be 28%.

VI. DISCUSSION

(1) Cloud amount data by surface meteorological observation Nvs cloud cover fraction data by satellite observation N^* .

Table 5. Sensitivity of Net Radiation in China

station	Guangzhou	Shanghai	Dunhuang	Urumqi
δ	−130	−61	−31	−74
$\partial Q / \partial E$	−1.98	−2.54	−1.08	−1.53

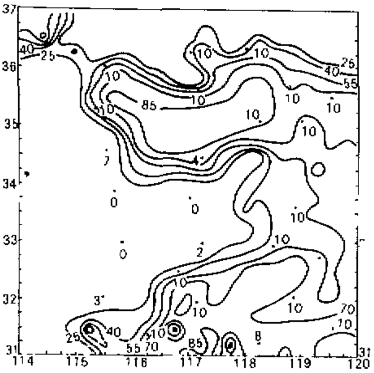


Fig.4. Distribution of cloud amount N and cloud cover fraction N^* 0626 12 July, 1986. —(%)— TOVS cloud cover fraction N^* • classified cloud amount of surface observation N.

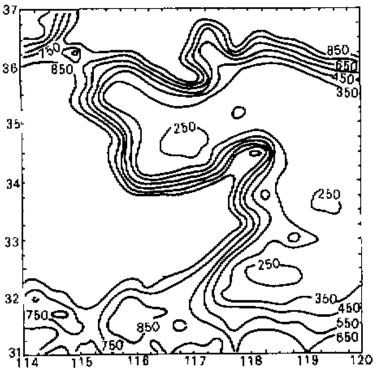


Fig.5. Distribution of cloud height (hPa) 0626 12 July, 1986.

The cloud cover fraction by satellite observation is similar to cloud amount by surface meteorological observation, but the satellite value N^* is smaller than that of surface meteorological value N.

Cloud cover fraction by satellite TIROS–N TOVS observation is as follows:

The i–channel radiance of cloudy sky I_i can be expressed as

$$I_i=(1-N^*)B_{\mathrm{iclear}}+N^*B_{\mathrm{icloud}}(T_c)\ , \tag{8}$$

where B_{iclear} is radiance of clear sky, B_{icloud} is radiance of cloud, and T_c the cloud top temperature.

According to simulation result of channels HIRS–4, HIRS–5, HIRS–6 and HIRS–7, we have

$$A_4B_{\mathrm{4cloud}}(T_c)+A_5B_{\mathrm{5cloud}}(T_c)+A_6B_{\mathrm{6cloud}}(T_c)+A_7B_{\mathrm{7cloud}}(T_c)=A_0\ , \tag{9}$$

where $A_0=0.8563$, $A_4=-0.2213$, $A_5=0.9189$, $A_6=1$ and $A_7=0.3083$. Correlation coefficient $\gamma=0.999996$, and variance $s=0.06$.

From a set of Eqs.(8) and (9), we have

$$N^*=\frac{\sum_{i=4}^{7}A_iB_{\mathrm{iclear}}-\sum_{i=4}^{7}A_iI_i}{\sum_{i=4}^{7}A_iB_{\mathrm{iclear}}-A_0}\ . \tag{10}$$

The distributions of cloud cover fraction N^* and cloud amount N are shown in Fig.4. The cloud height distribution is shown in Fig.5.

The relationship between satellite cloud cover fraction N^* and cloud amount of surface meteorological observation N is

$$N^*=6.6+7.0N \qquad \gamma=0.72\ , \quad s=20\ . \tag{11}$$

2. *Radiative Balance on the Atmospheric Top and on the Earth Surface*

Owing to more and more satellite data, people try to find the method to transform satellite data into the radiative balance of the earth's surface.

According to results of Pinker et al. (1984), the radiative balance of atmospheric top is similar to that of the earth's surface. The correlation coefficient between them is 0.76. By data of 21 American observatories, the regression formulae have been deduced as

$$R_s = 101.814 + 1.195R \ , \tag{12}$$

$$R_s = 0.484 + 0.374R + 0.601 \times 10^{-4} R^2 \ , \tag{13}$$

$$R_s = 0.467 \times 10^2 + 0.285R + 0.862(LWD) \ , \tag{14}$$

where R is radiative balance of the atmospheric top (W / m^2), R_s is radiative balance of the earth's surface (W / m^2), and LWD is daytime longwave radiation.

V. CONCLUSION

(1) By combining the NOAA satellite data of radiative balance of the earth–atmosphere and the surface meteorological data of cloud amount, the planet reflectivity and the outgoing longwave radiation may be expressed by the total cloud amount and the low cloud amount. The empirical formulae can be deduced by statistical regression, i.e.,

$$a_s = a_0 + a_1 N + a_2 n \ ,$$

$$E = b_0 + b_1 N + b_2 n \ ,$$

where a_0, a_1, a_2, b_0, b_1 and b_2 are parameters, depending on district and season. Their correlation coefficients are 0.96 and 0.78 respectively.

The statistical regression was carried out by the 1974–1984 decade historical data. In order to check the quality of the regression formulae (2) and (3), the 1985 observation data were used. The difference between the expectant value, calculated by regression formula, and observation value are as follows: for annual mean, planet reflectivity $<5\%$, outgoing longwave radiance $<3\%$; for monthly mean, 9 / 10 of planet reflectivity $<1\%$, and 9 / 10 of outgoing longwave radiation $<5\%$.

Formulae (2) and (3) to express the planet reflectivity and outgoing longwave radiation of the earth–atmosphere system are suitable for application. They are in good response to total cloud amount change.

(2) According to the above calculation, the ratio of reflectivity effect to greenhouse effect, on the average in China, is $\partial Q / \partial E = -2$. It coincides with the result of climate numerical simulation.

(3) According to the above calculation, the net radiation sensitivity can be derived. For the different areas of China, we have

Southeast coast of China	$\delta = -95$.
Northwest part of China	$\delta = -52$.

These results coincide with those of climate simulation of Ohring (1981).

(4) Study on radiative process with satellite data has good prospects. Therefore, many subjects should be paid more attention in further researeh, e. g., how to link surface radiative balance with the earth–atmospheric radiation process of satellite observation, which can be supplied for lack of surface observation, what is the detailed effect of atmospheric factors in radiative balance.

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Appendix I. Planet Reflectivity, and Comparison of Expectant Value, Calculated from Formula (2) with Observation Value *1. observation, 2. calculation, 3. difference, 4. relative deviation (%)*

month		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	annual average
Beijing 59.56N, 116.17E	1	0.281	0.300	0.311	0.238	0.258	0.286	0.287	0.255	0.197	0.254	0.429	0.304	
	2	0.290	0.296	0.307	0.236	0.261	0.286	0.289	0.240	0.204	0.221	0.420	0.308	
	3	0.009	−0.004	−0.004	0.002	0.003	0.001	0.002	−0.015	0.007	−0.033	−0.009	0.004	
	4	3	1	−1	−1	1	0	1	−6	3	−13	−2	1	−1
Erenhot 43.39N, 111.56E	1	0.252	0.363	0.278	0.252	0.245	0.278	0.276	0.255	0.237	0.309	0.222	0.420	
	2	0.257	0.321	0.277	0.245	0.257	0.275	0.286	0.249	0.233	0.307	0.235	0.422	
	3	0.005	−0.042	0.001	−0.007	0.012	0.003	0.010	−0.006	−0.004	0.002	0.013	0.002	
	4	2	12	0	−3	5	−1	4	−2	−2	−1	6	0	0
Changchun 43.54N, 125.13E	1	0.263	0.360	0.299	0.271	0.360	0.299	0.350	0.250	0.369	0.412	0.248	0.283	
	2	0.241	0.254	0.318	0.273	0.332	0.328	0.336	0.236	0.292	0.405	0.250	0.283	
	3	−0.022	0.106	0.019	0.002	−0.028	0.029	−0.014	0.014	−0.104	−0.007	0.002	0.000	
	4	−8	29	6	1	8	10	4	−6	26	−2	1	0	−5
Shanghai 31.10N, 121.26E	1	0.363	0.384	0.319	0.327	0.371	0.413	0.405	0.364	0.354	0.333	0.390	0.209	
	2	0.359	0.364	0.319	0.327	0.372	0.416	0.401	0.357	0.378	0.311	0.393	0.209	
	3	−0.004	−0.020	0.000	0.000	0.001	0.003	−0.004	0.007	0.024	0.022	0.003	0.000	
	4	1	−5	0	0	0	1	−1	−2	7	−7	1	0	−1
Guangzhou 23.08N, 113.19E	1	0.606	0.534	0.383	0.606	0.620	0.391	0.354	0.221	0.291	0.544	0.594	0.340	
	2	0.595	0.557	0.386	0.582	0.551	0.428	0.382	0.237	0.278	0.536	0.593	0.378	
	3	−0.011	0.023	0.003	−0.024	−0.069	0.037	0.028	0.016	−0.013	−0.000	−0.001	0.038	
	4	2	4	1	−4	−11	9	8	7	−4	−1	0	11	1
Chengdu 30.40N, 104.01E	1	0.446	0.413	0.375	0.390	0.428	0.372	0.341	0.414	0.328	0.212	0.378	0.324	
	2	0.439	0.420	0.366	0.391	0.420	0.386	0.303	0.382	0.325	0.182	0.359	0.304	
	3	−0.007	0.007	0.009	0.001	0.008	0.014	0.038	−0.032	−0.003	0.030	−0.019	0.020	
	4	2	2	2	0	−2	4	−11	−8	−1	−14	−5	−6	3
Kunming 25.01N, 102.41E	1	0.266	0.365	0.329	0.266	0.348	0.416	0.381	0.322	0.248	0.208	0.329	0.323	
	2	0.250	0.359	0.335	0.304	0.380	0.411	0.374	0.326	0.285	0.235	0.322	0.305	
	3	−0.016	−0.006	0.006	0.038	0.032	−0.005	−0.007	0.004	0.037	0.027	−0.007	0.018	
	4	6	−2	2	14	9	−1	−2	1	15	13	−2	−5	3
Lhasa 29.40N, 91.08E	1	0.409	0.409	0.405	0.357	0.427	0.303	0.350	0.204	0.206	0.310	0.399	0.269	
	2	0.354	0.394	0.421	0.355	0.436	0.309	0.346	0.224	0.196	0.311	0.411	0.284	
	3	−0.055	−0.015	0.016	−0.002	0.009	0.006	−0.004	0.020	0.010	−0.007	0.012	0.015	
	4	−13	−4	4	−1	2	2	−1	10	−5	2	3	5	0
Dunhuang 40.09N, 94.41E	1	0.300	0.249	0.276	0.325	0.265	0.249	0.237	0.216	0.287	0.439	0.347	0.301	
	2	0.289	0.248	0.261	0.327	0.263	0.245	0.237	0.212	0.296	0.550	0.350	0.308	
	3	−0.011	−0.001	−0.015	0.002	−0.002	−0.004	0.000	−0.004	0.009	0.111	0.003	0.007	
	4	−4	0	5	1	−1	−1	0	−2	3	25	1	2	2
Urumqi 43.47N, 87.37E	1	0.394	0.371	0.278	0.394	0.248	0.278	0.221	0.237	0.285	0.505	0.597	0.389	
	2	0.372	0.345	0.280	0.372	0.222	0.318	0.207	0.259	0.286	0.506	0.551	0.370	
	3	−0.022	−0.026	0.002	−0.022	−0.026	0.040	−0.014	0.022	0.001	0.001	−0.046	−0.019	
	4	−6	−7	1	−6	−11	11	7	9	0	0	−8	−5	−2

Appendix II. Outgoing Longwave Radiation, and Comparison of the Expectant Value from Formula (3) with Observation Value 1. observation, 2. calculation, 3. difference, 4. relative deviation (%)

month		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	annual average
Beijing	1	209.7	223.6	236.2	219.6	227.0	235.4	238.9	224.6	220.6	195.5	196.8	204.0	
59.56N, 116.17E	2	221.2	221.8	222.3	230.6	223.4	230.2	238.4	229.5	218.4	199.5	198.5	108.9	
	3	11.5	1.8	13.9	11.0	-3.6	-5.2	-0.5	1.9	-2.2	4.0	1.7	-15.1	
	4	5	1	-6	5	-2	-2	0	2	1	2	1	7	0
Erenhot	1	221.2	208.9	236.1	211.2	229.5	236.1	239.4	220.8	205.7	199.1	187.2	175.3	
43.39N, 111.56E	2	209.5	219.6	238.2	218.9	221.2	234.5	236.7	220.7	213.6	187.8	193.2	175.6	
	3	-1.7	10.7	2.1	7.7	-8.3	-1.6	-2.7	-0.1	7.9	-11.3	6.0	2.3	
	4	-1	5	1	4	-4	-1	-1	0	4	-6	3	1	1
Changchun	1	208.6	202.2	224.1	210.0	202.2	224.1	231.8	232.2	192.7	176.6	189.6	186.0	
43.54N, 125.13E	2	217.0	217.5	217.0	210.3	210.3	211.3	234.3	237.3	234.4	180.1	188.3	186.2	
	3	8.4	15.3	-7.1	0.3	8.1	12.8	2.5	5.1	41.7	3.5	-1.3	0.2	
	4	4	0	-3	0	4	-6	1	2	22	2	-1	0	3
Shanghai	1	211.9	215.0	233.8	223.9	217.0	221.8	227.8	230.5	221.2	216.0	207.1	221.4	
31.10N, 121.26E	2	225.0	224.3	231.4	221.8	216.6	217.6	226.1	230.0	228.7	216.9	205.7	223.6	
	3	13.1	9.3	-2.4	2.1	0.4	4.2	1.7	-0.5	7.5	0.9	-1.4	2.2	
	4	6	1	-1	-1	0	-2	-1	0	3	0	-1	1	1
Guangzhou	1	235.5	218.2	226.0	235.5	220.4	229.0	243.3	259.3	248.9	222.2	221.6	232.2	
23.08N, 113.19E	2	238.1	225.8	230.9	234.2	223.4	226.3	231.4	255.9	235.2	222.5	221.2	231.8	
	3	-2.4	7.6	4.9	-1.3	3.0	-2.7	11.9	3.4	4.3	0.3	0.4	-0.4	
	4	1	4	2	-1	1	-1	-5	-1	2	0	0	0	0
Chengdu	1	177.2	193.5	206.2	189.9	182.5	194.5	219.2	216.5	201.8	196.3	181.2	191.1	
30.40N, 104.01E	2	179.3	184.6	198.8	191.0	183.2	194.2	201.3	207.0	199.6	198.1	184.9	188.6	
	3	2.1	-8.9	-7.4	1.1	0.7	-0.3	-17.9	-9.5	-2.3	1.0	3.7	2.5	
	4	1	-5	4	1	0	0	-8	-4	-1	1	2	-1	-2
Kunming	1	212.3	194.3	217.7	212.3	205.8	194.8	209.2	211.0	221.8	207.0	193.8	199.7	
25.01N, 102.41E	2	214.6	202.3	206.4	207.6	199.0	195.3	208.9	213.4	216.5	205.0	196.4	199.8	
	3	2.3	8.0	-11.3	-4.7	-6.0	0.5	-0.3	2.4	-5.3	-2.0	2.6	0.1	
	4	1	4	-5	2	3	0	0	1	-2	1	1	0	-1
Lhasa	1	181.4	191.5	200.1	185.3	177.6	227.0	213.6	236.9	203.8	186.4	178.6	196.1	
29.40N, 81.08E	2	205.3	193.0	193.9	197.1	177.1	217.4	216.1	213.3	213.0	186.8	177.0	191.6	
	3	23.9	1.5	-6.1	11.8	-0.5	-9.6	2.5	-23.6	9.2	0.4	-1.6	-4.5	
	4	13	1	-3	6	0	4	1	-10	4	0	1	-2	0
Dunhuang	1	222.9	258.2	239.7	213.9	242.8	243.7	240.7	245.1	211.5	176.4	195.6	202.4	
40.09N, 84.41E	2	220.2	248.3	240.9	214.6	249.3	234.6	240.7	248.9	207.1	174.0	194.6	197.2	
	3	-2.7	-9.9	1.2	0.7	6.5	-8.9	0.0	3.8	-4.4	-2.4	-1.0	-5.2	
	4	-1	-4	1	0	3	-4	0	2	2	-1	-1	3	-1
Urumqi	1	202.7	210.0	235.1	202.7	238.7	235.1	250.0	249.6	222.5	179.0	181.8	194.6	
43.47N, 87.37E	2	208.8	216.0	234.3	209.4	245.7	223.1	252.8	238.3	229.2	184.1	181.5	192.3	
	3	6.1	6.0	-0.8	6.7	7.0	-12.0	2.8	-11.3	6.7	5.1	-0.3	-2.3	
	4	3	3	0	3	3	-5	1	5	3	3	0	1	1