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34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - I

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"Cloud Effect on Climate"

Franz H. BERGER
Institut für Meteorologie, FU Berlin
Berlin
Federal Republic of Germany

Abstract

Clouds play an important role in long term climate change. Their impact on the climate system can be examined by their influence on the radiation budget of the atmosphere and by their interactions with other variables of the climate system (cloud feedback).

To compare the influence of clouds in the climate change two parameters are used: the *cloud effect* and the related parameter *cloud sensitivity*. The total cloud effect (shortwave and longwave) has been derived from narrow-band radiance measurements (NOAA AVHRR) and from broad-band ERB (earth radiation budget) measurements (NIMBUS 7 and ERBE) by different methods. All these results show that clouds cool the climate system in a range from 17 to 35 WM^{-2}. In comparison to this a doubling of CO_2 concentrations leads to an heating effect in the atmosphere of 4 Wm^{-2} or to a global warming of 3.5 to 5 K.

The cloud sensitivity, which represents the differential response to changes in cloud cover, determines the cloud feedback effect in climate model simulations. These results can be compared with the cloud effect by a linear relation between the mean flux at the top of the atmosphere and the mean averaged cloud amount. These (annual, global mean) results are in the same order of magnitude as the results obtained from the global mean cloud effect. But regions with small cloud effect - due to low cloud amount - can still be highly sensitive to changes in cloud amount. So there can be a strong cloud feedback effect in regions where the cloud effect is small.

If one compare all these different results, it can be concluded that clouds may have a very strong influence on the climate system and on climate change, and that we are far from knowing the exact magnitude of this influence.

1 Introduction

Clouds are an important factor in regulating the radiative energy balance of the global climate system. Their impact on the incoming and outgoing radiation at the top of the atmosphere, and their interactions with other variables of the climate system (cloud feedback) are not well understood and remain the major source of uncertainty in climate prediction.

In the presence of clouds, a large part of incoming radiation will be reflected. The clouds also absorb the longwave radiation emitted by the warmer earth. They emit energy into space at the colder temperatures of the cloud tops. The reduction in the outgoing, emitted radiation is the greenhouse effect (that is the combined absorption and emission in the thermal region). This effect is similiar to the effects of atmospheric gases.

To study such an influence, a number of researchers have examined the climatic effects of increasing atmospheric CO_2 concentrations. All these model studies show the increased CO_2 would produce an increase in surface and tropospheric temperatures. If the CO_2 concentration is doubled, the radiative heating of the surface-troposphere system (given by the negative of the change in the net radiative flux at the top of the troposphere) decreases from 4.6 Wm^{-2} at the equator to 2.2 Wm^{-2} at 80° N. As a result, the change in Northern Hemisphere mean surface temperature is 2.93 K ([22]). The results of two general circulation models (GCM's) ([10],[24]), which include the cloud feedback in response to the doubling of atmospheric CO_2, show a 4 K change in mean global surface temperature.

Radiative-convective equilibrium models (RCM), which have been extensively applied to the CO_2 climate problem, have been applied to study cloud optical thickness feedbacks ([23]). Clouds other than thin cirrus lead to a stronger increase of albedo than to an increase of greenhouse effect. This negative sign of the feedback shows that clouds act as a thermostat and reduce the surface temperature and tropospheric warming caused by the doubling of CO_2. Such a negative feedback can be substantial, because the surface temperature increase is reduced by about one half.

Recent research includes optical thin cirrus clouds: the amount in Somerville's RCM is 28%. Temperature changes caused by a doubling of CO_2 (equivalent to an increase of the solar constant by 2%) is compared with temperature changes due to cloud optical thickness feedback. In the second study the optical properties have been allowed to vary, so that the optical cloud feedback mechanism could operate. As optical thickness increases, cloud albedo increases as does cirrus cloud infrared opacity [29]. Comparing these two comparing studies (Tab. 1) shows the typical effect of an increased radiative energy input: the surface temperature increases and the magnitude of the increases is greater in the upper troposphere. In the stratosphere, where radiative equilibrium prevails, the increase is smaller.

This calculation, including the cloud optical thickness feedback, shows that the positive greenhouse effect - caused by the thin cirrus - overwhelmed the negative feedback due to the increase in negative feedback of low-level clouds. This result suggests that the sign, as well as the magnitude, of the influence of clouds on climate may depend on the global cloud amount, especially for different cloud types, and on the parameterization in climate models.

As one can see from these reflections on cloud feedback to climate, the earth's climate system is vastly complex and it is important to consider each problem separately, which might lead to clarification of our knowledge of this complex problem. The International Satellite Cloud Climatology Project (ISCCP) gives a first answer to the problem of determining the distribution of clouds over the globe [15].

Tab.1.: Results from an atmospheric radiative-convective model coupled to an ocean mixed layer model. The left-hand column shows the nominal pressure at the 15 model layers. The next column shows temperature in the control run. The third and fourth columns show the increases in temperature caused by increasing the solar constant by 2%, both without and with the feedback effects of cloud optical thickness changing with temperature (from [29]).

Pressure (hPa)	Control temperature (K)	Temperature change without cloud optical thickness feedback (K)	Temperature change with cloud optical thickness feedback (K)
4.7	235.79	0.63	0.49
19.5	209.50	0.73	0.58
45.0	206.11	0.72	0.62
80.0	203.35	0.97	0.85
125.0	203.02	1.10	1.05
187.5	202.47	0.95	0.62
262.5	208.33	3.13	5.10
350.0	225.78	3.29	5.32
450.0	242.00	3.39	5.43
550.0	255.40	3.28	5.26
650.0	265.34	3.03	4.81
775.0	275.29	2.68	4.23
900.0	282.91	2.42	3.80
960.3	286.58	2.31	3.61
989.2	287.90	2.29	3.57

2 Cloud sensitivity

A relation between the radiation balance of the earth's atmosphere system and variations in the amount of cloud cover, the effect on the surface temperature of variations in cloudiness and the dynamic feedback mechanism relating changes in surface temperature to the formation of clouds gives the effect of variation in cloudiness on the climate system.

Early studies in the 70's with simple models and empirical data have shown the important feedback role clouds play in climate. Budyko (1969, [5]) shows the dependence of outgoing infrared flux F on surface temperature T_S and cloud cover fraction A_C:

$$F = 223 + 2.2T_S - (48 + 1.6T_S)A_C \quad (1)$$

where F is in Wm^{-2} and T_S in °C. The coefficients were derived by regression of F, calculated from observed atmospheric parameters, against global observations of T_S and A_C. Cess (1976, [6]) found that in both hemispheres the dependence could be expressed to good approximation as

$$F = 257 + 1.6T_S - 91A_C \quad (2)$$

There are two important differences between the two formulas: Cess used observed values of the outgoing infrared fluxes, based upon analysis of satellite measurements, and his regression was performed with zonal, mean January-July averaged data. He considered only latitude variations, in contrast to Budyko, who considered geographic and seasonal variations to determine the regression coefficients.

For sensitivity studies it is usually assumed that the radiation budget components can be expressed in terms of a very small number of variables (eq. 1, 2). The dependence on each variable can then be expressed very compactly in terms of derivatives.

In equilibrium the globally and annually averaged net radiation balance must be zero, so it follows that:

$$F = S = S_0(1 - \alpha_T) \quad (3)$$

where F is the outgoing longwave emission from the earth-atmosphere, S is the absorbed solar radiation, S_0 is the incident solar flux at the top of the atmosphere, and α_T is the planetary albedo. Here F and α_T are assumed to depend only on the surface temperature T_S. Schneider and Mass ([26]) suggested the sensitivity parameter

$$\beta = S_0 \frac{dT_S}{dS_0} \quad (4)$$

which is a measure of the sensitivity of the global mean surface temperature to variations in the global mean solar flux density S_0. The derivative is assumed to be evaluated for the equilibrium climate. By differentiating and rearranging, β can be expressed as

$$\beta = \frac{S}{-\frac{dR}{dT_S}} = \frac{F}{-\frac{dR}{dT_S}} \quad (5)$$

where R is the net radiation budget at the top of the atmosphere. So the sensitivity parameter β is just equal to the magnitude of the absorbed solar or emitted terrestrial radiation, which must be equal each other in the equilibrium. The complexity in solving this equation can easily be imagined by noting that in general

$$\frac{dR}{dT_S} = \frac{\partial R}{\partial T_S} + \sum_{i=1}^{N} \frac{\partial R}{\partial x_i}\frac{dx_i}{dT_S} \quad (6)$$

where x_i is the list of variables that can influence the net radiation. N is not a small number of different characteristics. In order to study the role of cloudiness the only characteristic used should be the fractional area coverage of cloudiness A_C. In this case,(6) becomes

$$\frac{dR}{dT_S} = \frac{\partial R}{\partial T_S} + \frac{\partial R}{\partial A_C}\frac{dA_C}{dT_S} \quad (7)$$

where it has been assumed that the climate, including the cloudiness, is uniquely related to the global mean surface temperature. This mathematical expression consists of the result of the temperature change and of the result of the cloudiness changes associated with the temperature change. The first term of the latter can be written as

$$\delta = \frac{\partial R}{\partial A_C} = -S_0 \frac{\partial \alpha_p}{\partial A_C} - \frac{\partial F}{\partial A_C} \qquad (8)$$

where δ is the cloud-climate sensitivity parameter, defined by Schneider (1972, [25]). This parameter is a product of two terms, the solar δ_{SW} and the infrared δ_{IR} climate-sensitivity parameter. For the infrared parameter, Schneider (1972) derives a value of -75 Wm^{-2}, assuming a tropospheric lapse rate of -6.5 K/km and a cloud height of 5.5 km.

Using Budyko's relation of 1969, the sensitivity of the infrared flux to cloud amount gives

$$\delta_{IR} = \frac{\partial F}{\partial A_C} = -72 \mathrm{Wm}^{-2}, \qquad (9)$$

when the mean global surface temperature is 288 K. Cess' result has shown a higher sensitivity of the infrared flux: -91 Wm^{-2} for the Northern hemisphere. So there is a good agreement between the first two results despite some differences in the assumptions. In Schneider's simple theoretical model, everything is held fixed except cloud amount, while Budyko includes the effects of the seasonal and geographic changes in atmospheric parameters. Also the surface temperature is held constant.

For the solar radiation the cloud-climate sensitivity δ_{SW} can be written

$$\delta_{SW} = -S_0 \frac{\partial \alpha_p}{\partial A_C} \qquad (10)$$

where $\alpha_p = \alpha_C A_C + \alpha_S(1 - A_C)$. α_C is the albedo of the cloudy fraction of the earth, and α_S is the albedo of the cloudless fraction of the globe. Schneider (1972) assumed that α_C =0.5 and α_S=0.12 for the global average case. Using the mean annual, global incident solar flux (342 Wm^{-2}) the solar radiation sensitivity coefficient is -130 Wm^{-2}. So the net sensitivity of clouds is the difference between the solar and infrared sensitivity parameters, and it is for Schneider's model, -55 Wm^2. Cess obtained for the solar radiation -89Wm^{-2} (α_C=0.44) and for the net coefficient + Wm^{-2} for the Northern Hemisphere. Such a small effect suggests that clouds have a small effect on the net radiation energy balance of the climate system. The main difference between Schneider-Budyko and Cess' approach is that the regression against zonal means, where infrared fluxes are responding more to other factors than to cloud amount, masks the true sensitivity coefficient.

Another step in cloud-climate research is the observational studies of the earth radiation budget (ERB). These studies use and used narrow- and broad-band satellite observations. Ohring and Clapp (1980, [18]) have used the Advanced Very High Resolution Radiometer (AVHRR) visible and infrared measurements from the NOAA polar orbiting meteorological satellites and monthly averaged (45 months) values for a 10° longitude by 10° latitude grid. They calculated the cloud-climate sensitivity after Schneider (1972, [25]). For the infrared region a new regression equation has been obtained

$$F = 240 + 1.8T_S - 60A_C \qquad (11)$$

The multiple correlation coefficient for this equation is 0.95. According to this equation, the global infrared cloud sensitivity is -60 Wm^{-2}. This result is greater than the value of Budyko from simulations of monthly mean outgoing longwave radiation at 260 points, uniformly distributed around the world. In their study they have used two data sets - the first is based on the cloud albedo of Cess (1969) and the second on the values of Ohring and Adler (1978, [16]) - and estimated for the total cloud-climate sensitivity -57 Wm^{-2} / -67 Wm^{-2} and for the infrared cloud sensitivity -36 Wm^{-2} / -43 Wm^{-2} (based mostly on Northern Hemisphere data).

Other investigations calculate the change in longwave, shortwave and the net flux as a function of latitude for cirrus clouds and for all other clouds combined (Fig.1, [2]). These results indicate that, annually averaged, cirrus clouds have a warming effect on the cli-

Tab.2: Cloud/climate sensitivities derived from the radiative transfer model and cloud parameterization of Peng et al. (1982) and based upon cloud cover data compiled by London (1957). From [2].

10% increase in amount	ΔN (Wm^{-2})
All clouds	-1.1
All clouds, day only	-2.7
All clouds, night only	+3.2
Low clouds	-1.7
Low + Mid clouds	-2.8
Cirrus	+1.7
Change in Cirrus Parameters	
10% Increase in amount	+1.7
Lower height 33 hPa	-1.7
Reduce emissivity 0.8 to 0.65	-3.7
Day/Night distribution	
+10 % day, -10% night	-4.3

mate system at all latitudes. The same approach has been used to determine the global average cloud sensitivity of the net flux at the top of the atmosphere. Table 3 shows that all combined clouds have a cooling effect, and cirrus clouds have a cooling effect which, however, could be offset by a 33 hPa reduction in height or by reducing their emissivity. Another very interesting fact is that a 10 % shifting of nighttime clouds to daytime will cancel the CO_2 doubling effects.

Hartmann and Short (1980) and Cess (1982) have introduced similiar *cloud factors*, by rearranding equation (8), to obtain:

$$Cloud\ factor = \left[S_0 \frac{\partial \alpha_p}{\partial F} + 1\right] \qquad (12)$$

or:

$$\epsilon = -\left[\frac{S_0}{4}\frac{\partial \alpha_p}{\partial F}\right]^{-1} \qquad (13)$$

Hartmann and Short conclude from their *cloud factor*:

- If it is 0, the infrared and solar effects cancel exactly
- If it is 1, there is only a IR effect and
- if it is -N, the albedo effect is N+1 times as large as the IR effect.

On the other side, the statements are similiar:

- ϵ=1, both effects cancel,
- ϵ >1, the IR effects dominate and
- $\epsilon < 1$, the albedo effect dominates.

Using the work of Ohring and Clapp [18], Cess estimated for the global earth that $\epsilon \approx 0.4$. While from the work of Hartmann and Short [13], an $\epsilon < 0.5$ can be inferred. Cess [7] has also compared NOAA (narrow-band) and ERBE (broad-band) measurements and found that the measurements made by narrow-band instruments are two times smaller than the derivations from broad-band measurements. Results of other studies are shown in table 3. ERBE narrow-band estimates (from Smith and vonder Haar [28]) are in a good agreement with the NOAA (narrow-band) estimates form Hartmann and Short.

3 Total cloud effect

A convenient diagnostic earth radiation budget parameter was introduced by Ramanathan (1985, [19], [9], [20]). It was first called *Cloud Forcing*, and then renamed *Cloud Effect*. This parameter is defined as the difference between the radiative flux (at the top of the atmosphere), which occurs in the presence of clouds, and which would occur if clouds were removed but the atmospheric state otherwise unchanged. The term Cloud forcing can also be used to denote warming or cooling tendencies due to cloud-radiation interaction.

At the top of the atmosphere, the net radiation budget can be expressed as

$$R = S_0(1-\alpha_p) - F. \qquad (14)$$

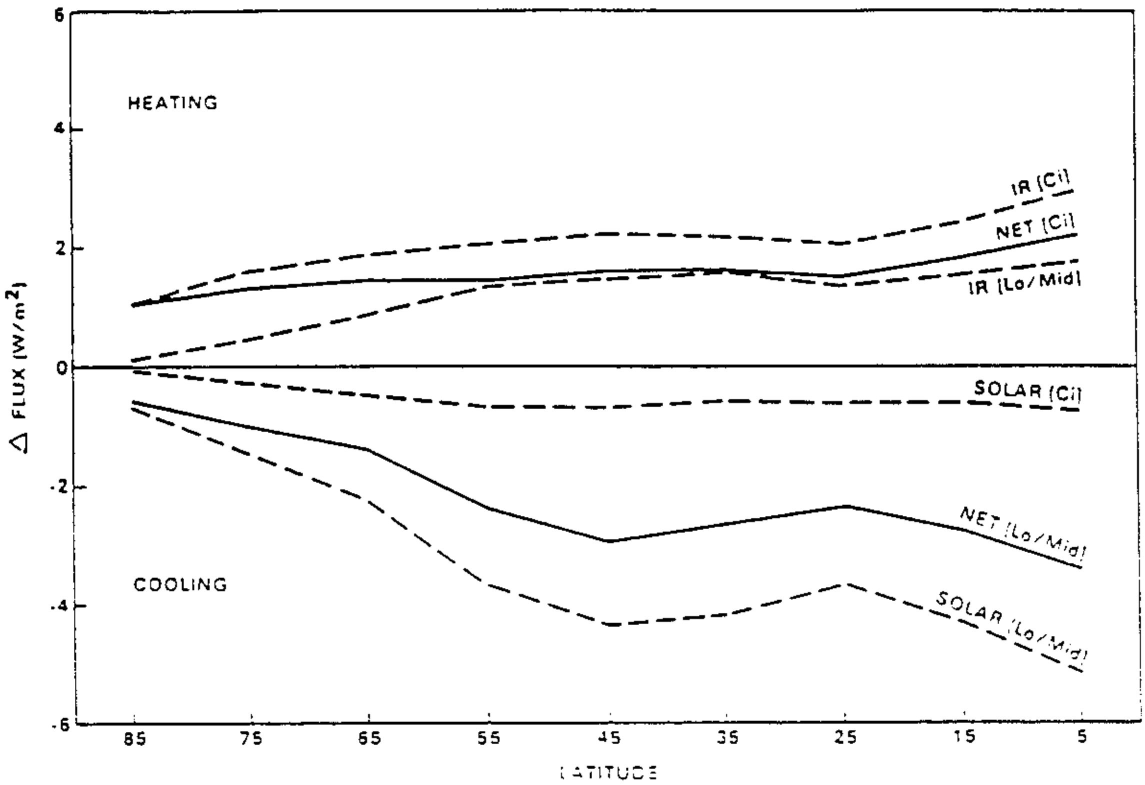


Fig.1.: Change of flux into the earth-atmosphere system resulting from a 10% (relative) increase in cloud amount for cirrus clouds (ci) and for all other clouds (lo/mid), shown for shortwave (solar), longwave (lw) and net radiation components. (From [2]).

Tab.3.: Estimates of ϵ for individual latitude zones. The values of Smith and Vonder Haar [28] are for JJA and DJF (in parenthesis). From [30]

Latitude	Ellis and Vonder Haar	Campbell and Vonder Haar	NOAA - NESS	Smith and Vonder Haar (ERBE NFOV)
20-10°N	1.2	1.4	0.7	0.43(0.51)
10- 0°N	0.9	1.6	0.5	0.38(0.40)
0-10°S	1.6	1.5	0.6	0.30(0.30)
10-20°S	1.5	1.1	0.5	0.28(0.31)
20°N-20°S	1.3	1.3	0.6	

For an atmospheric column consisting of fractional cloud cover A_C and a clear sky fraction $(1 - A_C)$, we can write

$$R = (1 - A_C)R_C + A_C R_O \tag{15}$$

where the subscripts C and O refer to the value of the net radiation budget for clear skies and for overcast skies. With the definition above, Ramanathan defined for the terrestrial infrared radiative effect

$$F = F_C(1 - A_C) + F_O A_C \tag{16}$$

$$F = F_C - CFIR \tag{17}$$

where

$$CFIR = A_C(F_C - F_O) \tag{18}$$

or

$$CFIR = F_C - F. \tag{19}$$

For the solar cloud radiative effect, he obtained the following equation

$$CFSW = \frac{S_0}{4}(\alpha_C - \alpha) \tag{20}$$

where α is the albedo for cloudy (clear plus overcast) sky, α_C is the clear sky albedo. Therefore the cloud radiative effect $CFNET$ [12] becomes

$$CFNET = (F_C - F) + \frac{S_0}{4}(\alpha_c - \alpha) \tag{21}$$

Considering the two forcing terms, $CFIR$ is generally positive and $CFSW$ is generally negative.

The are significant differences between the cloud-radiative effect and the cloud-sensitivity: the cloud effect denotes the radiative heating of the planet due to clouds. The cloud-sensitivity indicates the rate of change of the cloud forcing with cloud cover. Another difference is that the cloud-sensitivity involves estimation of either a derivative with respect to A_C or the overcast parameters. Estimations of these terms from observed data are fraught with numerous difficulties. In contrast, estimation of cloud effect is relatively more straightforward, since it does not

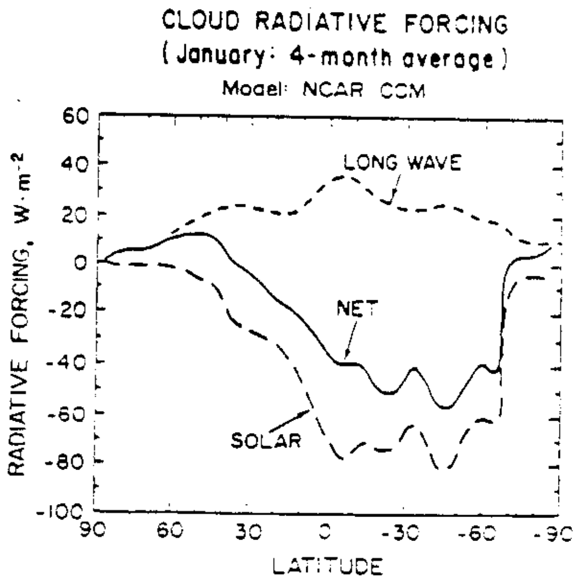


Fig.2.: Cloud radiative forcing as derived from a general circulation model simulation (from Charlock and Ramanathan [9])

involve cloud cover or the parameters for overcast skies [20].

To convert the results obtained from cloud-sensitivity studies to cloud effect, the net *forcing* effect is

$$CFNET = CFIR + CFSW = \overline{A_C}\delta \tag{22}$$

where $\overline{A_C}$ represents the ensemble average cloud amount within the temporal and spatial domain of the measurements. (So only a variation of the ensemble average is allowed to vary.) Usually, A_C is assumed to be 0.5. But one must be careful to distinguish between the total cloud effect and the cloud sensitivity. Because regions with small cloud effect - due to low cloud amount - can still be highly sensitive to changes in cloud amount. So, there can be a strong cloud feedback effect in regions where the cloud effect is small.

Model calculations has been used to examine the nature of cloud effect. So Charlock and Ramanathan [9] calculate the zonal averages as simulated by a general circulation model (Fig.2.).

Fig.1 indicates that the net cloud effect is negative over the whole planet, and a negative value means a reduction in the net radiative ener y absorbed by the earth-atmosphere system. The longwave cloud effect is highly positive and shows a peak near the equator, because of the frequency of high clouds. In the polar regions the longwave effect is a minimum, because the temperature difference between the surface and the cloud top temperature is small. The secondary minima in the subtropics are caused by a minimum frequency of high clouds near the descending branches of the Hadley cell in both hemispheres.

Another step in cloud-climate studies is the estimation of global-mean radiative effect, together with its infrared and solar components. Table 4 summarizes results, predicted by seven different GCM's. The results given in table 4 refer to specified simulations for a specified month (January or July), employing prescribed sea surface temperatures for that month. All these different GCM's predict a negative total cloud-radiative effect, so that clouds have a large long-wave heating effect but a significantly larger solar cooling effect.

Arking [2] used to compare these results with the cloud-climate sensitivity A_C=0.5. So a relation exists between the simple model-based results (from Schneider [25], the high sensitivity results from Ohring et al (1981, [17]) and the cloud radiative results from different satellite data sets (Tab.5., [21], [1]).

From the ERB Experiment lauched in 1984, quantitative estimates of the global distributions of cloud-radiative effect have been obtained. This experiment includes three satellites in different orbits. For the estimation of cloud effect, the scanner measurements of NOAA-9 and ERBS were have been used. The nadir footprint was 35 km. With these data sets, diurnal average fluxes based on a daily basis have been calculated, then averaged over the days in the month. Gruber and Stowe (1989) [11] have analyzed several different selection time scales. The first results produced from ERBE are regional cloud-radiative effect maps based on the April 1985 data ([21], [11]). The completed analysis for April 1985 will discussed below.

Ramanathan (1989) has found that the longwave cloud forcing reaches peak values over the tropical regions and decreases towards the poles. In general, clouds reduce the longwave emission to space. This reduction of the longwave emission is a result of the longwave emission from cold, high optically thick clouds. These clouds reduce the emission more than low clouds because of the higher temperature difference between cloud and surface. In regions where cirrus clouds dominate the cloud-radiative effect is a maximum (50-100 Wm^{-2}). Maxima can be found in three regions:

- the tropical Pacific and Indian oceans surrounding Indonesia and the Pacific intertropical convergence zone north of the equator,
- the monsoon region in Central Africa and the deep convective regions of the northern third of South Africa and
- the mid-latitude storm tracks in the Pacific and Atlantic oceans.

These results are similiar to those of Gruber and Stowe (1989), they have also compared the results caused by ERBE and by AVHRR data and found out that ERBE estimates are generally greater than those from AVHRR over the tropical and subtropical deserts of both hemispheres. The largest differences tend to occur over the cloudy tropics, resulting in steeper gradients in the ERBE cloud-effect field. Over the Artic regions, AVHRR is greater than ERBE.

For the shortwave cloud forcing, there is a peak in the mid-latitudes, unlike the longwave effect [21]. In the tropical monsoon and deep convection regions, large negative values have been observed. In these regions, the reduction of absorbed solar radiation as a result of clouds exceeds 100 Wm^{-2}. So the net effect is nearly cancelled by the longwave and

Tab.4.: Intercomparison of cloud-radiative effect as predicted by several general circulation models; the seasonal solar forcing has been corrected to the mean sun-earth distance.

References	Cloud radiative effect Wm^{-2} infrared	solar	total
Herman et al. (1980)			
GLAS GCM Jan.	40	-54	-14
Charlock & Ramanathan (1985) [9]			
mod. NCAR CCM Jan.	23	-45	-22
Ramanathan (1987) [20]			
NCAR CCM Jan.	35	-57	-22
Randall & Harhvardan (1986)			
UCLA/Goddard GCM Jan.	55	-57	-2
UCLA/Goddard GCM July	53	-52	+1
Mitchell (1986)			
UKMO GCM Jan.	40	-74	-34
UKMO GCM July	42	-69	-27
Cess & Potter (1987) [8]			
OSU/LLNL GCM Jan.	42	-62	-20
OSU/LLNL GCM July	39	-52	-13
Slingo & Slingo (1988) [27]			
NCAR CCM1	30	-51	-21

Tab.5.: Estimates of the annual, global mean effect of clouds on the net downward flux of radiation energy at the top of the atmosphere (C) and the longwave (C_{SW}) and shortwave (C_{SW}) components. From [2].

Investigation	Basis	C_{LW}	C_{SW}	C_{SW}/C_{LW}	C
Schneider * (1972)	Simple Model	37.5	-65	1.7	-27.5
Cess * (1976)	Empirical	45.5	-44.5	1.0	+1.0
Ohring et al. *[a] (1981)	NOAA AVHRR	17.5	-53	3.0	-35.5
Ramanathan et al. (1989)	ERBE	31	-48	1.5	-17
Ardanuy et al. (1989)	Nimbus 7	24	-51	2.1	-27
Cess and Potter *[b] (1987)	GCM Models	23 to 55	-45 to -74	1 to 2	+1 to -34

* To convert the published cloud sensitivity coefficients to cloud effect of clouds we used A_C=0.5.

[a] Mean for 0° to 60° N latitude, based on narrow-band measurements.

[b] Based on analysis of six GCM models (Tab.4.), averaging January and July conditions.

shortwave term. Near cancellation does imply a negligible role of clouds in the regional climate, because modeling results [20] suggest that the negative shortwave cloud effect is due to the divergence of shortwave fluxes (cooling) at the earth's surface. In contrast, the positive longwave cloud effect is caused by the convergence of longwave fluxes (heating) in the troposphere. Such a cloud system may lead to a significant pertubation of the vertical gradients of radiative heating or cooling patterns.

A negative cloud effect occurs over the mid- to high-latitude oceans: this effect is particularly large and is about 50 - 100 Wm^{-2}. In the Western Sahara Desert and the Sahel regions of Africa, the positive cloud effects arise from the longwave cloud effect accompanied by negligible shortwave effect. The cloud effect is also positive over snow-covered regions of Canada and the Arctic, where both terms are positive.

Table 6 shows a comparison of global cloud effect estimates in Wm^{-2}, and it shows that the cloud effect reduces the absorbed solar radiation by 44.5 to 51.9 Wm^{-2} and the longwave emission to space by 30 to 32 Wm^{-2}, when averaged over the globe. The differences in the monthly values are a result of both seasonal and interannual variations in the parameters that govern cloud effect. Considering the net total cloud effect shows that clouds reduce the radiative heating of the planet, which means clouds have a net cooling effect on the global climate. This effect is larger in January (maximum cooling effect) than in April, where it is the minimum cooling effect. In comparison to GCM results, there is a qualitative agreement, but there are quantitiative differences between various models (Tab.4).

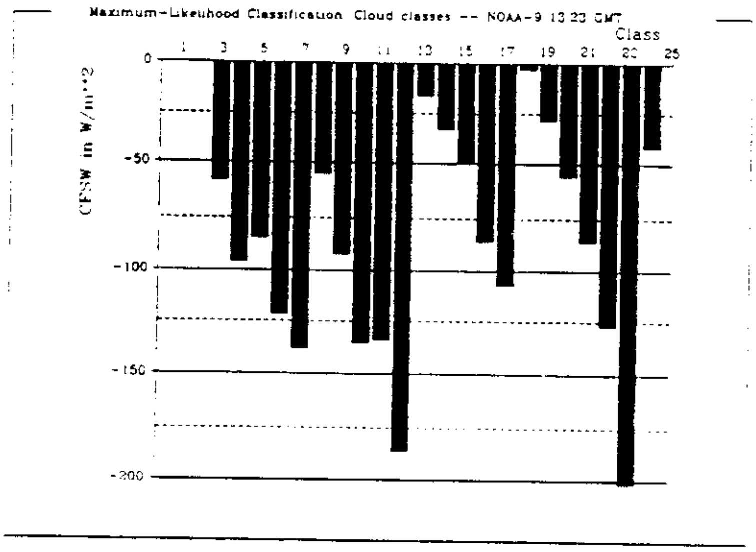
Another step in cloud effect studies is the estimation of cloud effect for different cloud types with a higher spatial and temporal resolution. After a maximum-likelihood classification for different cloud types, especially cirrus clouds with varying optical thickness, their optical properties have been determined [4]. Using NOAA-9 AVHRR data from the first ICE Experiment (Oct. 1987, the shortwave flux has been calculated witn ch.nnel 1 and 2, the longwave flux with channel 4 and 5. Figures 3 to 5 show the estimation of the different cloud effect components, leading to a large longwave heating and a large solar cooling effect. The result for the net radiative cloud effect for each cloud class shows that cloud effect

- for low clouds (classes 3,4),
- for multilayered clouds with a low cloud base (classes 5-7),
- for middle-level clouds (classes 8,9) and
- for multilayered cloud with smaller emission (classes 10-12)

gives a cooling effect. In contrast, cloud effect of cirrus clouds (classes 13-17 mean cirrus above land, class 18-22 mean cirrus above sea) shows that these clouds have a heating effect. Class 24 (high, dense, cold cloud), has a similiar emission as class 23 (thick cirrus). So the longwave cloud effect is of the same order of magnitude. But for the shortwave, we have determined that the albedo of high, dense clouds is influenced by the albedo of the middle-level clouds. From this we conclude that the cloud effect of high, cold cloud (Cb) is similiar to that of middle-level clouds.

4 Conclusion

It has been recognized that clouds, which constantly cover ~50% (cirrus clouds ~20%) of the global sky, are the most important regulators of the radiation balance of the earth-atmosphere system. Generally, in respect to cloud effect on climate, the diagnostic parameter $C_{LW} > 0$, $C_{SW} < 0$ and the net effect $C < 0$. Especially for high, semi-transparent cirrus clouds, the longwave emission is more important than the shortwave absorption, and so an increase of cirrus clouds could lead to an increase in the temperature of the earth-atmosphere system. It will thus be important



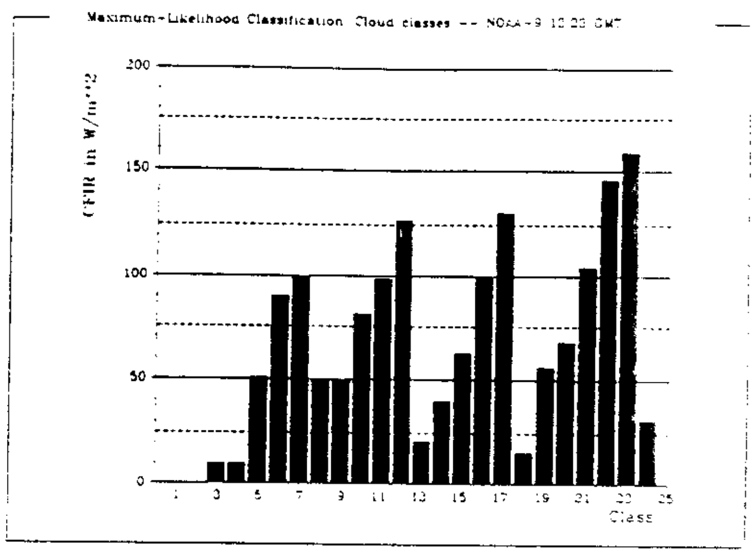


Fig.3 and 4: Shortwave (left) and longwave cloud effect for 21 cloud classes (class 1 and 2 are land and sea surface); class 24 represents the mean effect over the whole image (1024 x 1024 pixels; the test area is the German Bight during the International Cirrus Experiment 1987; the data set is a NOAA-9 overflight on October 24, 1987, 13:23 UT). Class 24 represents the mean effect over the whole image. From [3]

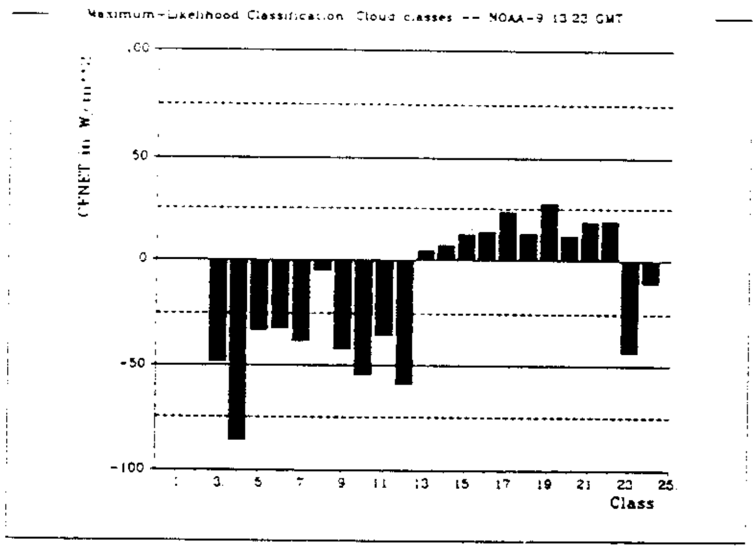


Fig. 5: The net radiative effect for the same classes as in figure 7 and 8.

Tab. 6.: Comparison of global cloud effect (forcing) estimates in Wm^{-2}; from [21]

ERBE data Wm^{-2}

	April 1985	July* 1985	October* 1985	January* 1985	GCM's+
C_{LW}	31.3	30	32	30.6	23 to 55
C_{SW}	-44.5	-46.3	-49.4	-51.9	-45 to -74
C	-13.2	-16.4	-17.4	-21.3	+1 to -34

* Analysis not completed for these months.
\+ On the basis of the summary in table 4

in the future to study in more detail the global cirrus cloud climatology, including cloud cover, height and thickness, the dynamics of clouds, the cloud-radiation field and the fundamental physical parameterization of cirrus clouds. All these efforts should improve our knowledge about cirrus and other clouds [14].

It will also be very useful to monitor cloud-climate parameters over a long-time period, and there will be a possibility to compare the regional and seasonal variations in the cloud effect fields with model simulations. These observations of long-term changes in cloud effect can be used to provide confirmation of untestable ideas [23] and climate model results regarding climate change. Some GCM studies, which suggest that a radiative heating of about 4 Wm^{-2} resulting from doubling CO_2 concentrations, would lead to a global warming of 3.5 to 5 K. But the size of the observed cloud effect is about four times as large as that for the doubling. Thus, small changes in cloud-radiative effect fields can play an important role as a climate feedback-mechanism. Also of interest is to examine how a change of climate can perturb the cloud effect, which in turn can feed back into long-term climate change. In summary, the cloud effect concept contributes to our understanding of climate, of the strong influence on climate change, and of the magnitude of this influence.

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