# Observations of Cloud Infrared Effective Emissivity

Stephen K. Cox

*Department of Atmospheric Science, Colorado State University, Fort Collins 80523*

(Manuscript received 24 June 1975, in revised form 27 October 1975)

ABSTRACT

This paper presents mean greybody infrared effective emissivity values of clouds deduced from 300 International Quiet Sun Year (IQSY) radiometersonde ascents. The cloud effective emissivity data are presented for two latitude regions: midlatitude and tropical. Mean cloud effective emissivity values for the surface to 300 mb layer ranged from 0.41 to 0.64 for the midlatitude data and from 0.54 to 0.84 for the tropical data. Clouds in the pressure interval from 400 to 600 mb exhibited the largest mean emissivity values. These data should be very useful for incorporation of realistic cloud radiative properties into modeling of atmospheric dynamics and climate.

## 1. Introduction

As numerical prediction and general circulation models become more sophisticated in dealing with the dynamics of the atmosphere, it becomes desireable to depict more realistically the radiative effects of clouds. The models described by Manabe (1969), Oliger *et al.* (1970), Sasamori (1968) and Arakawa *et al.* (1974) have chosen somewhat arbitrary greybody infrared emissivity values for clouds. The necessity for a somewhat arbitrary selection of grey emissivity values is understandable since the models do not include the cloud microphysical properties essential to a rigorous calculation of the emissivity.

Only a few individual case study reports of measured infrared cloud emissivities have appeared in the published literature, notably those of Kuhn (1963), Kuhn and Weickman (1969), Allen (1971), Paltridge (1971, 1974) and Platt (1973, 1975). Yamamoto *et al.* (1966) and Hunt (1973) have given summaries of spectral infrared window emissivity characteristics of clouds based upon calculations and Zdunkowski and Crandall (1971) reported calculations of cloud emissivity in several spectral bands. Plass and Kattawar (1971) reported on the transfer of infrared radiation by water and ice clouds.

The effective emissivity used in this paper is a very useful tool; it enables one to deduce from broadband infrared observations a characteristic emissivity value of a cloud layer. This emissivity may then be used to reproduce the observed irradiance profile in a pseudo conventional broadband transfer computation. One may then infer the infrared heating rate directly from the calculated irradiance profiles without ever explicitly separating the absorptive and scattering components of the effective emissivity. Thus, this parameter represents a very convenient and simple way of incorporating observations of infrared broadband cloud characteristics into dynamic models requiring specification of radiation as a forcing function.

It is the purpose of this paper to present cloud layer broadband infrared effective emissivity values calculated from a data set consisting of approximately 300 Suomi-Kuhn balloon-borne radiometersonde ascents.

## 2. Radiometersonde data set

One of the few large data sets of broadband infrared divergence as a function of height were collected under the auspices of NOAA's Atmospheric Physics and Chemistry Laboratory during the International Quiet Sun Year (IQSY). Three hundred Suomi-Kuhn radiometersonde soundings from the IQSY radiation project representing two different latitude zones were analyzed for cloud emissivity values. The midlatitudes were primarily represented by soundings at Green Bay, Wisc., and Sterling, Va., with about 20% of the midlatitude ascents being made from other midwestern U. S. upper air stations. Guam (13°N, 145°E) and Palmyra Island (5°N, 162°E) ascents accounted for the second group of soundings representing a moist tropical Pacific regime. With the exception of Palmyra Island, all data groups contained soundings for all four seasons.

## 3. Analysis technique

The balloon-borne radiometersonde measures air temperature, relative humidity, pressure and radiometer temperatures, from which one may determine the upward and downward irradiances. From the above data, one must then deduce cloud top and cloud base, discard broken cloud cases, and calculate the effective infrared emissivity of the cloud deck.

Kuhn (1963) has shown that the changes of slopes of the upward and downward irradiances as a function of height may be used to detect clouds. The radiometersonde data were used to detect clouds in the following way. A numerical radiative transfer calculation (Cox, 1973) was performed using as input data the measured profiles of temperature and relative humidity. The computation was repeated $N$ times for an ascent with $N$ data levels, each assuming that a different layer of the atmosphere was saturated with water vapor. Such a series of computations was made for both the upward and downward irradiances. The calculated changes with respect to height of the upward and downward irradiance values were then compared with the measured radiometersonde data. If the observed change in irradiance through a layer exceeded by an amount $\alpha$ the change calculated when that layer was assumed saturated, the layer was defined as containing a cloud. A value 1.4 times the estimated error of the radiometersonde (Kuhn and Johnson, 1966), 9.8 W m$^{-2}$, was assigned to $\alpha$. The technique described above worked successfully when applied to data reported by Kuhn and Suomi (1965) for which independent aircraft observations of cloud top and base were available.

The problem of broken or horizontal inhomogeneous clouds is a nemesis to calculations of cloud emissivity. In order to overcome this problem, the upward and downward irradiances were examined independently. Only when the observed changes in both the upward and downward irradiances exceeded that computed for the saturated water vapor condition in that layer, was a case selected for inclusion as a cloud sample. In this way, the contamination of the cloud sample by broken cloud conditions was minimized. This technique was discussed in more detail by Cox (1971).

For each layer in which a cloud was detected by the above technique, two emissivity variables for the layer were calculated.

Following Kuhn (1963), the effective emissivity may be defined as

$$\epsilon(\uparrow)=\frac{H_B(\uparrow)-H_T(\uparrow)}{H_B(\uparrow)-\sigma T_T^4}\quad\text{for the upward irradiance,}\qquad(1)$$

$$\epsilon(\downarrow)=\frac{H_B(\downarrow)-H_T(\downarrow)}{\sigma T_B^4-H_T(\downarrow)}\quad\text{for the downward irradiance.}\qquad(2)$$

In Eqs. (1) and (2), $H(\uparrow)$ and $H(\downarrow)$ refer to the upward and downward measured infrared irradiances, respectively. The subscripts $T$ and $B$ refer to the top and bottom of the cloud layer, respectively, and $\sigma$ is the Stefan-Boltzman constant. It is necessary to define a separate effective emissivity for the upward and downward irradiances because the spectral distribution of energy for the two irradiance streams are quite different. This also explains why, in general, $\epsilon(\downarrow)>\epsilon(\uparrow)$ in the following tables. A more complete discussion of this effect is given by Cox (1971). One readily sees that $\epsilon(\uparrow)$ and $\epsilon(\downarrow)$ are the ratios of the divergence of observed irradiances to the irradiances expected if the cloud were a blackbody.

TABLE 1. Midlatitude cloud infrared effective emissivity.

| Pressure (mb) | $\epsilon(\downarrow)$ [Eq. (2)] Mean | Standard deviation | $\epsilon(\uparrow)$ [Eq. (1)] Mean | Standard deviation | Number of cases |
|---|---|---|---|---|---|
| 950 | 0.48 | 0.30 | 0.56 | 0.34 | 134 |
| 850 | 0.54 | 0.35 | 0.54 | 0.32 | 92 |
| 750 | 0.48 | 0.35 | 0.43 | 0.31 | 80 |
| 650 | 0.57 | 0.36 | 0.50 | 0.27 | 46 |
| 550 | 0.64 | 0.34 | 0.53 | 0.29 | 31 |
| 450 | 0.64 | 0.34 | 0.55 | 0.27 | 30 |
| 350 | 0.45 | 0.40 | 0.41 | 0.35 | 30 |

## 4. Results

Tables 1 and 2 summarize the results of applying Eqs. (1) and (2) to the IQSY radiometersonde data set. The cloud emissivities were assigned to the 100 mb layer in which they were detected; if the cloud were thicker than 100 mb, its emissivity was entered in two or more layers. In Tables 1 and 2 the mean values of the effective emissivity of the upward and downward irradiances for all clouds in that layer and the rms deviations from the means are given.

The data presented in Tables 1 and 2 have several characteristics which deserve mention. When the temperature lapse rate approaches zero, the cloud detection scheme outlined above becomes insensitive. Any layer where the absolute value of the temperature lapse rate was less than 2°C km$^{-1}$ was not included in the cloud sample since the expected change in the irradiance stream becomes comparable to the error of the radiometersonde itself. In the midlatitudes, the tropopause and near-isothermal lower stratosphere are often found in the 300 to 100 mb layer; therefore, no emissivity values are given for pressures less than 300 mb.

Neither of the two latitude samples of effective emissivity show a strong tendency with height between the surface and 300 mb. For the midlatitude case, cloud emissivities range from 0.41 to 0.64 for this

TABLE 2. Tropical cloud infrared effective emissivity.

| Pressure (mb) | $\epsilon(\downarrow)$ [Eq. (2)] Mean | Standard deviation | $\epsilon(\uparrow)$ [Eq. (1)] Mean | Standard deviation | Number of cases |
|---|---|---|---|---|---|
| 950 | 0.62 | 0.24 | 0.67 | 0.32 | 101 |
| 850 | 0.69 | 0.30 | 0.69 | 0.27 | 38 |
| 750 | 0.63 | 0.34 | 0.60 | 0.28 | 25 |
| 650 | 0.69 | 0.38 | 0.61 | 0.31 | 11 |
| 550 | 0.81 | 0.32 | 0.59 | 0.26 | 8 |
| 450 | 0.68 | 0.37 | 0.54 | 0.26 | 10 |
| 350 | 0.84 | 0.18 | 0.61 | 0.18 | 6 |
| 250 | 0.47 | 0.38 | 0.35 | 0.25 | 10 |
| 150 | 0.27 | 0.23 | 0.17 | 0.14 | 47 |

700 mb thick layer. For the tropical case, the mean emissivity values for this same layer range from 0.54 to 0.84. Tropical clouds generally have higher emissivity values than their midlatitude counterparts.

It is interesting to note that the highest mean emissivity values were found between 400 and 600 mb for the midlatitude data and between 300 and 600 mb for the tropical data. Neither the reasons for the higher emissivity middle tropospheric clouds nor the ramifications of this observation are particularly obvious. The higher values of cloud effective emissivity in these layers may partially be explained by the mean water vapor distribution with height. As a cloud top nears the top of the bulk of the water vapor mass in the atmosphere, the divergence of the downward irradiance from the top to the bottom of the cloud will be greater; hence, the numerator of (2) will be greater. At the same time, the distribution of $H(\uparrow)$ through the cloud is relatively unaffected.

The effective emissivities $\epsilon(\uparrow)$ and $\epsilon(\downarrow)$ are more similar in the lower layers where the $H(\downarrow)_T$ at the cloud top is relatively large; the main contribution to $H(\downarrow)_T$ is from the water vapor above, however, since for pressures less than 800 mb, $\epsilon(\downarrow)$ and $\epsilon(\uparrow)$ begin to diverge, as is most apparent in Table 2. The argument appears to hold for the data in Table 1 as well, although the 300 to 400 mb layer data suggest that there may be other factors to consider.

The potential ramifications of the higher mean effective cloud emissivities in the middle troposphere depend upon the perspective of the individual making such an assessment. The noted configuration represents near-optimum conditions for radiative cloud destabilization with maximum cooling from the top of the cloud. The large values of mean cloud emissivity for high clouds also point out their potential importance to dynamic modeling (Albrecht and Cox, 1975). While there are undoubtedly many other possible ramifications that the data presented in Tables 1 and 2 may have, these are too diverse to attempt even a partial list. Hopefully the incorporation of these data by other investigators in their own applications of dynamic and climate modeling will help reveal the importance, or lack of importance, of including realistic radiative characteristics of clouds in numerical models.

## 5. Conclusions

The infrared effective emissivity values for clouds presented in this paper represent the largest climatological sample of such properties yet available. Mean cloud emissivity values for the surface to 300 mb layer ranged from 0.41 to 0.64 for midlatitude data and from 0.54 to 0.84 for tropical data. Clouds in the pressure interval from 400 to 600 mb exhibited the largest mean emissivity values. These data should be extremely useful to numerical modelers desiring to include realistic radiative effects of clouds in their models.

*Acknowledgments.* I wish to express my sincere appreciation to Dr. P. M. Kuhn and Ms. Lois Stearns, of NOAA's Atmospheric Physics and Chemistry Laboratory, who were instrumental in the acquisition and reduction of the IQSY data set used in this study.

This research was supported by NOAA Grant E 22-113-68(G) and by the Global Atmospheric Research Program, NSF and the GATE Project Office, and the National Oceanic and Atmospheric Administration under Grants OCD 72-01681 A03 and OCD 74-21678.

## REFERENCES

Albrecht, B., and S. K. Cox, 1975: The large-scale response of the tropical atmosphere to cloud-modulated infrared heating. *J. Atmos. Sci.*, **32**, 16–24.

Allen, J. R., 1971: Measurements of cloud emissivity in the 8–13 $\mu$ waveband. *J. Appl. Meteor.*, **10**, 260–265.

Arakawa, A., A. Mintz and collaborators, 1974: The UCLA Atmospheric General Circulation Model. Dept. of Meteorology, UCLA, Los Angeles [Available from the author at the Dept. of Meteorology, University of California, 405 Hilgaard Avenue, Los Angeles.]

Cox, S. K., 1971: Cirrus clouds and the climate. *J. Atmos. Sci.*, **28**, 1513–1515.

——, 1973: Infrared heating calculations with a water vapor pressure broadened continuum. *Quart. J. Roy. Meteor. Soc.*, **99**, 669–679.

Hunt, G. E., 1973: Radiative properties of terrestrial clouds as visible and infrared thermal window wavelengths. *Quart. J. Roy. Meteor. Soc.*, **99**, 346–369.

Kuhn, P. M., 1963: Measured effective long-wave emissivity of clouds. *Mon. Wea. Rev.*, **91**, 635–640.

——, and V. Suomi, 1965: Airborne radiometer measurements of effects of particulates on terrestrial flux. *J. Appl. Meteor.*, **4**, pp. 246–252.

——, and D. R. Johnson, 1966: Improved radiometersonde observations of atmospheric infrared irradiance. *J. Geophys. Res.*, **71**, 367–373.

——, and H. K. Weickman, 1969: High altitude radiometric measurements of cirrus. *J. Appl. Meteor.*, **8**, 147–154.

Manabe, S., 1969: Climate and ocean circulation. Part I: The atmospheric circulation and the hydrology of the earth's surface. *Mon. Wea. Rev.*, **97**, 739–774.

Oliger, J., R. Wellck, A. Kasahara and W. Washington, 1970: Description of NCAR Global Circulation Model. National Center for Atmospheric Research, Boulder Colo. [Available from Publications Dept., NCAR.]

Paltridge, G. W., 1971: Solar and thermal radiation flux measurements over the east coast of Australia. *J. Geophys. Res.*, **96**, 2857–2864.

——, 1974: Infrared emissivity, shortwave albedo and the microphysics of stratiform water clouds. *J. Geophys. Res.*, **79**, 4053–4058.

Plass, G. N., and G. W. Kattawar, 1971: Radiative transfer in water and ice clouds in the visible and infrared regions. *Appl. Opt.*, **10**, 738–748.

Platt, C. M. R., 1973: Lidar and radiometric observations of cirrus clouds. *J. Atmos. Sci.*, **30**, 1191–1204.

——, 1975: Infrared emissivity of cirrus—Simultaneous satellite lidar and radiometric observations. *Quart. J. Roy. Meteor. Soc.*, **101**, 119–126.

Sasamori, T., 1968: The radiative cooling calculation for application to general circulation experiments. *J. Appl. Meteor.*, **7**, 721–729.

Yamamoto, G., M. Tanaka and K. Kamitani, 1966: Radiative transfer in water clouds in the ten micron region. *J. Atmos. Sci.*, **23**, 305–315.

Zdunkowski, W. G., and W. K. Crandall, 1971: Radiative transfer of infrared radiation in model clouds. *Tellus*, **23**, 517–527.