

Satellite-Inferred Morning-to-Evening Cloudiness Changes¹

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(Manuscript received 25 June 1979, in final form 9 April 1980)

ABSTRACT

Outgoing infrared radiation (IR) values inferred from radiance measurements in the water vapor window (10.5–12.5 μm) taken at approximately 0900 and 2100 LT by scanning radiometers aboard the polar orbiting NOAA satellites are compared in order to determine whether a significant diurnal variation exists. Data with a resolution of 2.5° in latitude and longitude are mapped for latitudes between 50°N and 50°S for two seasons, June–August 1975 and December 1975–February 1976. On the basis of these maps it is possible to identify broad categories of geographical regions which display similar patterns of 12 h differences in outgoing IR. For several of these categories composite histograms are constructed in order to investigate the morning to evening difference in outgoing IR for ranges of values corresponding to high clouds, middle clouds and low clouds.

Over land regions and coastal waters it is found that the 12 h differences are dominated by middle and high clouds, likely of convective origin. The difference patterns are consistent with widely held views concerning the modulation of convection by diurnally oscillating, thermally driven boundary-layer circulations.

Over the tropical oceans the pattern of morning to evening differences in outgoing IR shows remarkable geographical consistency. There is evidence of a morning bias in high cloudiness (possibly of convective origin) and low cloudiness (stratus, stratocumulus and trade wind cumulus), and an evening bias in middle cloudiness. Because of the compensation between these three cloud regimes the net morning to evening differences in outgoing IR are rather small except over the eastern oceans where the low cloud regime predominates and tends to produce a weak but statistically significant evening maximum.

1. Introduction

Satellite observations of outgoing infrared radiation (IR) inferred from radiance measurements in the water vapor window (10.5–12.5 μm) provide a data base for investigating diurnal variations in cloudiness on a global basis.³ However, the interpretation of such observations is rather complicated because changes in ground temperature and changes in fractional cloud coverage in various height ranges both make substantial contributions to diurnal differences in outgoing IR. In addition, the 10.5–12.5 μm spectral interval is not a clear window within which we can ignore the infrared emission by high concentrations of water vapor in the lower troposphere.

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³ A discussion of the regression approach used to derive the total IR flux from the measurements in the water vapor window, together with a more detailed description of the data set used in this study can be found in Gruber and Winston (1978). In the determination of the regression relations the data of Roberts *et al.* (1976, *Appl. Opt.*, 15, 2085–2090) have been used to take into account the continuum absorption by water vapor in the 8–12 μm band.

Over bare terrain the ground temperature can vary as much as 15 K between 0900 and 2100 LT, because of the low heat capacity and the low thermal conductivity of soil and rock. When the water vapor content of the atmospheric column is low the transmissivity of the atmospheric window is close to unity. Under these conditions a 1 K change in ground temperature will result in approximately a 2 W m^{-2} change in outgoing IR.

We can obtain a rough estimate of the effect of changes in cloudiness on outgoing IR by assuming an atmospheric temperature lapse rate of 6.5 K km^{-1} , and clouds with unit emissivity and perfect transmissivity of the water vapor window. Under these conditions we have calculated the difference in outgoing IR due to fractional changes in cloud cover for cloud layers at various levels. The results are shown in Table 1. These values represent an upper limit to the effect of cloudiness changes on outgoing IR.

Winston *et al.* (1972) and Raschke and Bandeen (1970) have presented global maps of day (1200 LT) minus night (0000 LT) outgoing IR. The daytime outgoing IR was found to be larger than nighttime IR over virtually all of the land masses. It is clear that diurnal changes in ground temperature must have made a major contribution to these differences.

Over the oceans their analysis of 12 h differences shows apparently random patterns of negative and positive values.

Riehl and Miller (1978), using measurements with a spatial resolution of ~ 100 km from the NOAA satellite system, documented the morning to evening difference in cloud top temperatures over selected regions of the tropical continents and oceans. They eliminated the influence of diurnal variations in ground temperatures on their results by considering only the range of outgoing IR which corresponds to high cloud tops such as might be associated with convective precipitation. They found that over Venezuela and West Africa the frequency of these very low values in outgoing IR was greater during the evening than during the morning, while over the Arabian Sea and the GATE area the reverse was true. They also reported that the absolute frequency of the very cold clouds was less over sea than over land.

In the following sections we will undertake a global survey of morning to evening (0900–2100 LT) differences in outgoing IR. On the basis of this survey we will identify and define the geographical extent of a number of regimes in which the characteristics of the underlying terrain and the morning minus evening differences in outgoing IR appear to be relatively uniform. For some of these regimes we will analyze the frequency distribution of outgoing IR in order to determine the contributions of high, middle and low clouds to the observed morning to evening differences.

2. Results

The data used in this study are the National Environmental Satellite Service (NESS) 2.5° gridded total outgoing infrared radiation values derived from the National Oceanic and Atmospheric Administration (NOAA) satellite system. The polar orbiting NOAA satellite system is described by Schwalb (1972) and the data set is described by Gruber (1977) and Gruber and Winston (1978). Three-month averages of the 0900 LT minus the 2100 LT outgoing IR were computed at each grid point. Interpolated values, which comprise less than five percent of the data, were excluded. Numerous histograms of the morning minus evening outgoing IR were examined in order to determine the character of the frequency distributions. Fig. 1 shows sample histograms for (a) an oceanic monsoon region, (b) an island monsoon region, (c) an oceanic stratus region and (d) a subtropical oceanic region. All appear to be reasonably close to normal distributions.

The geographical pattern of the 12 h difference in outgoing IR shows a considerable amount of small-scale variability, some of which is un-

TABLE 1. Change in outgoing IR per tenth increase in fractional cloud cover.

Cloud-top height (km)	Change in outgoing IR (W m^{-2})
17 (tropical tropopause)	-23
10	-14
5	-7
1	-1.4

doubtedly a reflection of sampling fluctuations related to our rather short (3-month) averaging period. In order to reduce the influence of these sampling fluctuations on the appearance of the 12 h difference maps to be presented in this paper, we modified the difference fields by setting equal to zero 1) all difference values at grid points which were not judged to be statistically significant at the 95% level (as determined from a two-tailed test based on the Student's t distribution, assuming that each day's data were independent); and 2) difference values at grid points which tested out as statistically significant at the 95% level but were surrounded by points whose values were not judged to be statistically significant.

The resulting morning minus evening IR differences are mapped in Fig. 2. An uneven contour interval has been used in order to resolve the small but statistically significant negative differences over the oceans. Note that there is no zero contour.

We will now summarize and attempt to interpret some of the major features in Fig. 2 on the basis of the frequency distribution of outgoing IR. For each of a selected number of geographical regions, we show in Fig. 3 composite histograms of morning and evening IR. Only paired 0900 and 2100 LT measurements for the same day and grid point are included in these distributions. In these histograms, the horizontal scale is labeled in terms of equivalent blackbody temperature at the bottom and in terms of outgoing IR at the top. If the outgoing IR is fairly uniform over a given $2.5^\circ \times 2.5^\circ$ grid square at a particular observation time, the equivalent blackbody temperature can be identified with a range of cloud-top heights. As a convenience for interpreting the satellite measured parameters over the tropics a summary of the tropical standard atmosphere is given in Table 2. Note that the areas under each pair of morning and evening histograms in Fig. 3 must be equal, apart from small differences associated with missing observations.

Hence if there is an excess of occurrences of low outgoing IR (high, cold cloud tops) at 0900 LT, there must be an excess of occurrences of high outgoing IR (lower, warmer cloud tops and/or clear sky) at 2100 LT and vice versa. The horizontal displace-

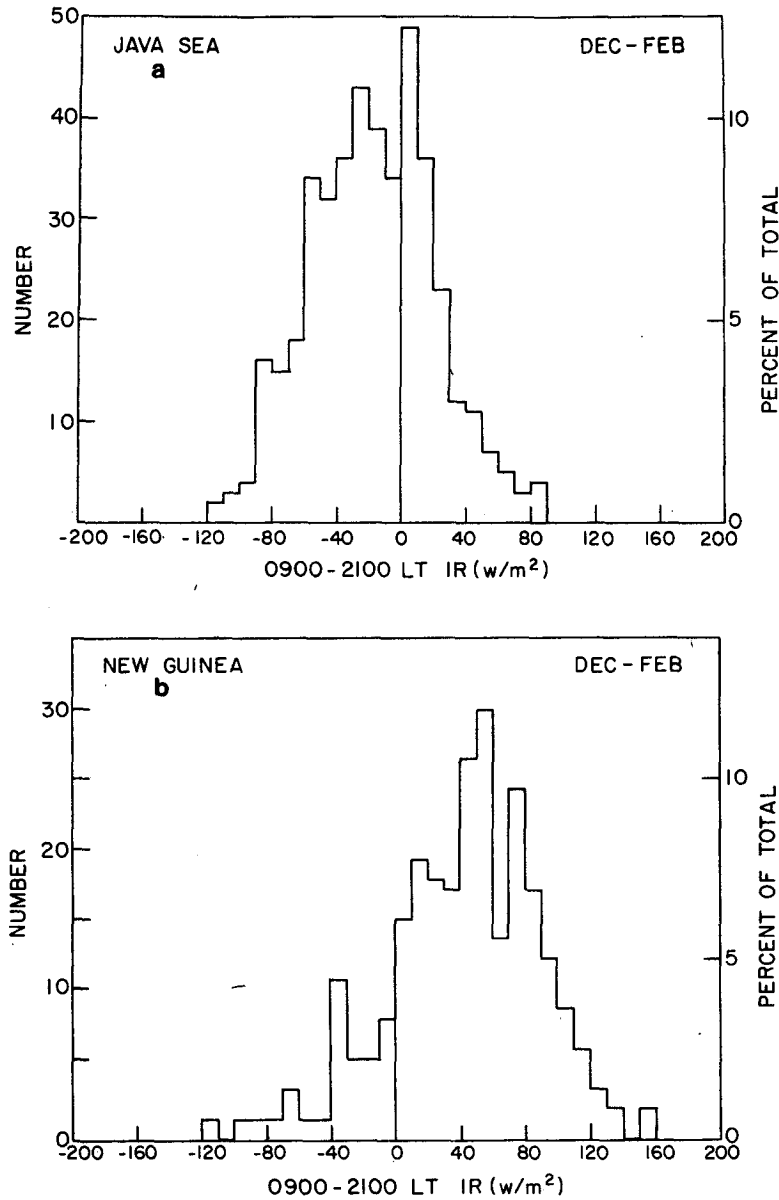


FIG. 1. Frequency distribution of daily 0900 LT minus 2100 LT outgoing IR from December 1975 through February 1976 (a) for the Java Sea, (b) for the island of New Guinea, (c) for the strip extending along 5°S latitude, from 115 to 105°W longitude (Pacific Ocean), and (d) for the strip extending along 25°N latitude, from 147.5 to 157.5°E longitude (Pacific Ocean).

ment (on the scale of outgoing IR) between the centroids of the areas under the 0900 and 2100 LT histograms in Fig. 3 gives the net 12 h difference in outgoing IR in Fig. 2.

a. Tropical islands

Large islands in the tropics and subtropics of the summer hemisphere generally show a large (25–50 W m⁻²) excess of morning outgoing IR over evening outgoing IR. Fig. 3a is a composite histo-

gram of morning and evening IR for 30 grid points located on the islands of Java, Sumatra, Borneo and New Guinea.

The lowest values of outgoing IR, which correspond to the coldest cloud tops, are seen to occur more frequently at 2100 LT than at 0900 LT over the islands. We expect to see such a bias over these regions where convective cloudiness forced by surface heating gradients reaches its maximum in the late afternoon and early evening. The larger values of outgoing IR (>210 W m⁻²) are more frequently

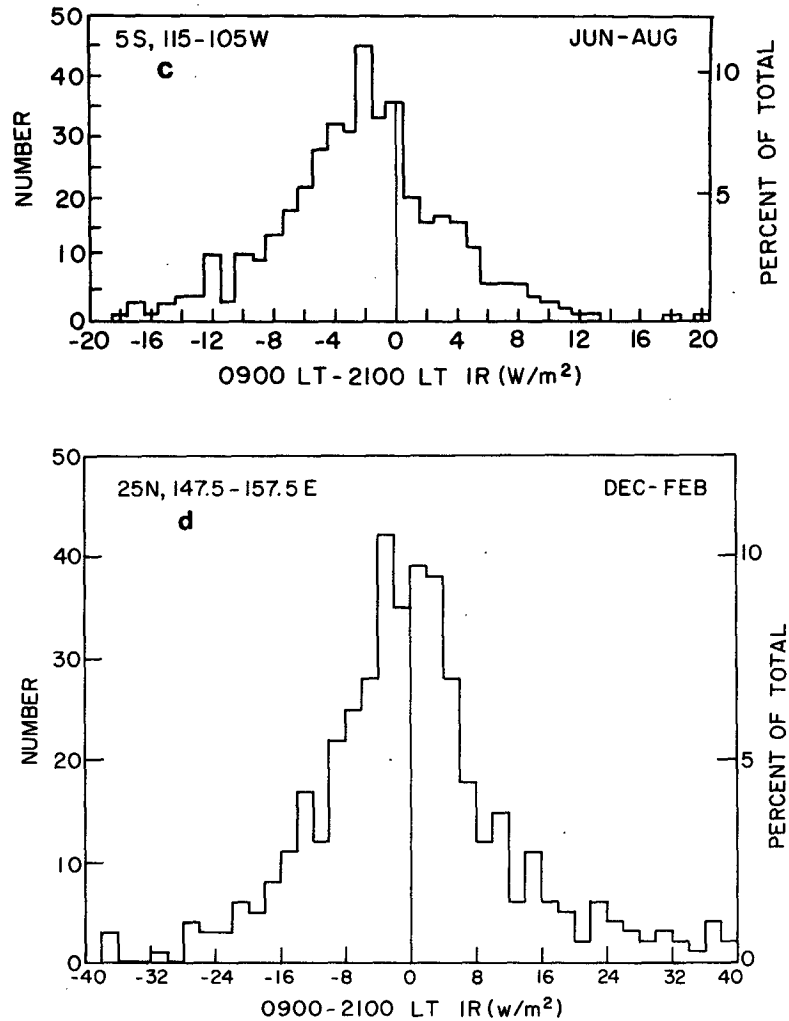


FIG. 1. (Continued)

observed at 0900 LT when the surface and lower (warmer) clouds are more frequently visible to the satellite-borne sensors because of the relative absence of higher clouds. It is not obvious from this particular distribution whether there is any significant diurnal variation in the amount of low cloudiness.

b. Coastal waters

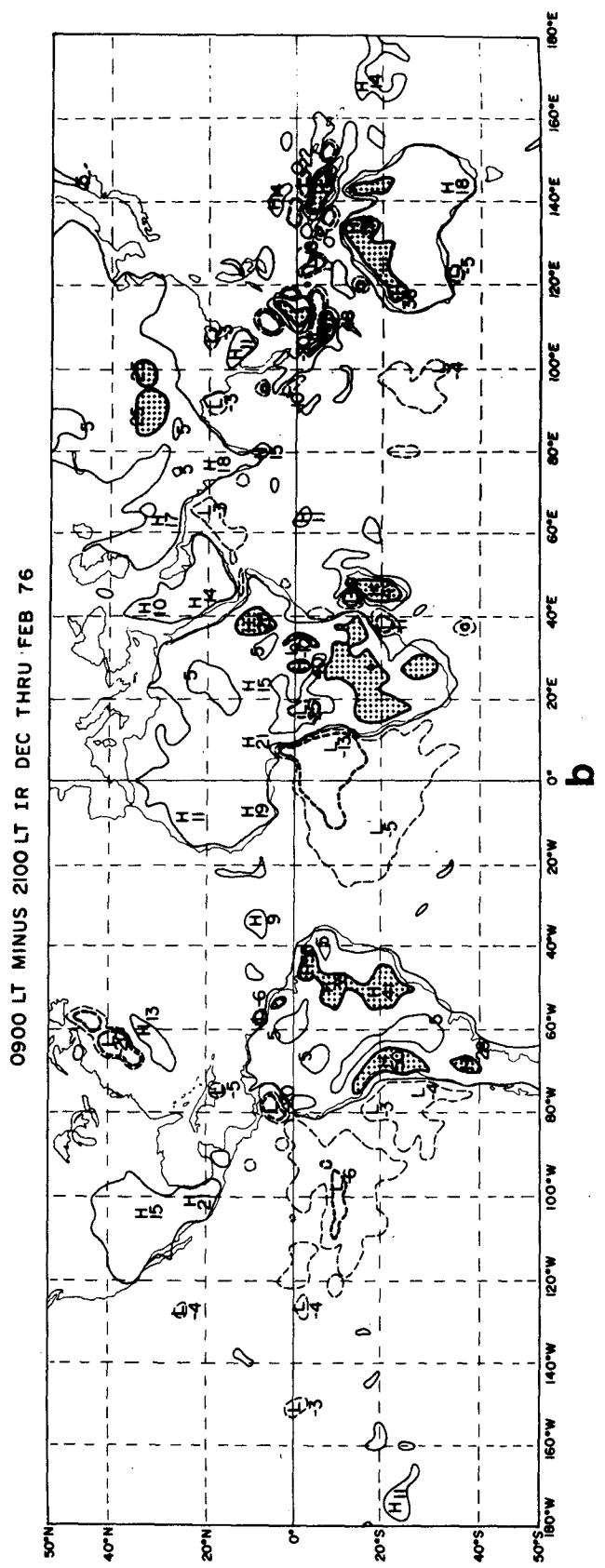
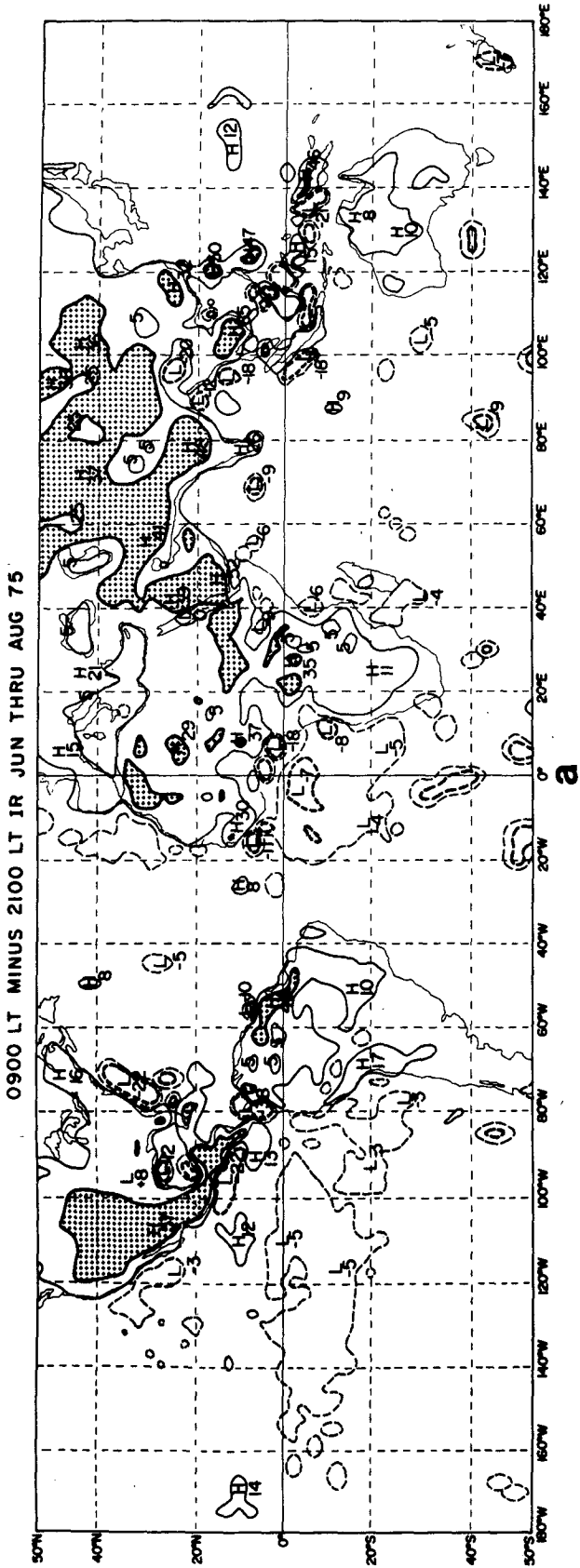
Over some coastal waters partially surrounded by land, outgoing IR is higher in the evening than in the morning (negative differences in Fig. 2). This tendency is quite pronounced over parts of the Arabian Sea, the Bay of Bengal, and the straits that separate Madagascar from continental Africa, particularly during their respective summer seasons. Fig. 3b is a composite histogram for 30 grid points over the waters surrounding the islands mentioned in Section 2a. It can be seen that the

higher outgoing IR at 2100 LT is mainly a reflection of the relatively greater frequency of high cloudiness at 0900 LT. This feature is suggestive of an early morning enhancement of convective activity over coastal waters in association with land-sea breeze circulation systems.

c. Mountains and plateaus

Regions of mountains and high plateaus exhibit a large morning bias in outgoing IR. It is of interest to determine whether this is a reflection of large diurnal variations in cloudiness or large variations in ground temperatures. A composite histogram for 18 grid points over the western United States is shown in Fig. 3c. As in Fig. 3a the frequency of low values of outgoing IR ($\leq 210 \text{ W m}^{-2}$), indicative of high, cold cloud tops is much larger at 2100 LT.

Outgoing IR in the range from 210 to 250 W m^{-2} , which may be associated with middle clouds or



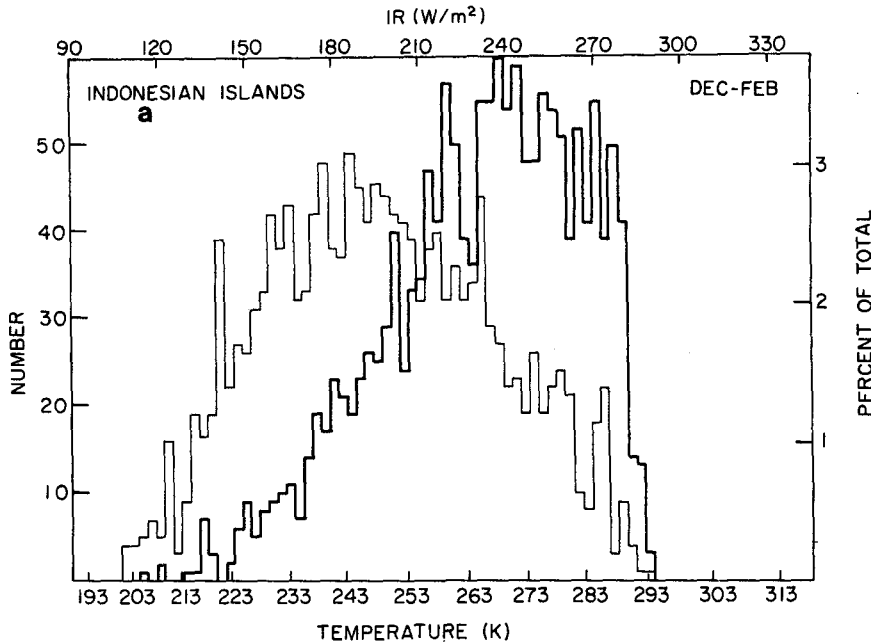


FIG. 3a. Frequency distributions of 0900 LT outgoing IR (dark) and 2100 LT outgoing IR (light). The bottom horizontal scale is labeled in terms of equivalent blackbody temperature as computed from measured window radiance via the Planck function. For 30 grid points located on the islands of Borneo, Java, Sumatra and New Guinea, December 1975–February 1976.

patchy high clouds, also shows a bias toward 2100 LT. It is interesting to note that outgoing IR with values in excess of $\sim 300 \text{ W m}^{-2}$ (black-body temperatures $\geq 300 \text{ K}$) are observed only at 0900 LT. Hence the diurnal cycle in ground temperature accounts for part of the bias of outgoing IR toward the morning hours in these regions.

d. Lowlands and basins

In contrast to the mountain ranges and elevated plateaus, many low-lying continental regions are characterized by small differences between morning and evening outgoing IR and even, on occasion, by higher evening outgoing IR. This behavior is indicative of roughly comparable amounts of morning and evening cloudiness over these regions. Inspection of composite histograms for several of these regions revealed no single, dominant pattern of morning and evening differences.

e. Low-latitude oceans

In Fig. 2 large regions of the tropical eastern oceans are covered by small but statistically signif-

icant biases in outgoing IR toward the evening hours. With the exception of these regions the differences in outgoing IR between morning and evening over the low-latitude oceans tend to be not significantly different than zero. There is some tendency for small patches of weak positive values 0900 LT > 2100 LT to be aligned along the position of the inter-tropical convergence zone (ITCZ) and the cloud band which runs southeastward from New Guinea.

We have examined composite histograms for regions of the eastern oceans, the western oceans, the ITCZ and the trade wind belts and have found them to be remarkably similar in terms of their overall appearance. Figs. 3d and 3e are composite histograms for the tropical North and South Pacific, during their respective summers.

The frequency of outgoing IR with values less than 150 W m^{-2} is about twice as high in morning as in evening, in agreement with results of Riehl and Miller (1978) for more limited geographical regions. This result is indicative of a widespread morning bias in the frequency of dense cirroform clouds, possibly of convective origin.

The mid-range of outgoing IR (values between 180 and 250 W m^{-2}) shows a higher frequency of oc-

FIG. 2a. Seasonal mean 0900 LT minus 2100 LT outgoing IR, modified as described in Section 2 for (a) June–August 1975 and (b) December 1975–February 1975. Contour intervals are -5 W m^{-2} (dark dashed), -1 W m^{-2} (light dashed), $+5 \text{ W m}^{-2}$ (light solid) and $+25 \text{ W m}^{-2}$ (dark solid). Values greater than $+25 \text{ W m}^{-2}$ are stippled.

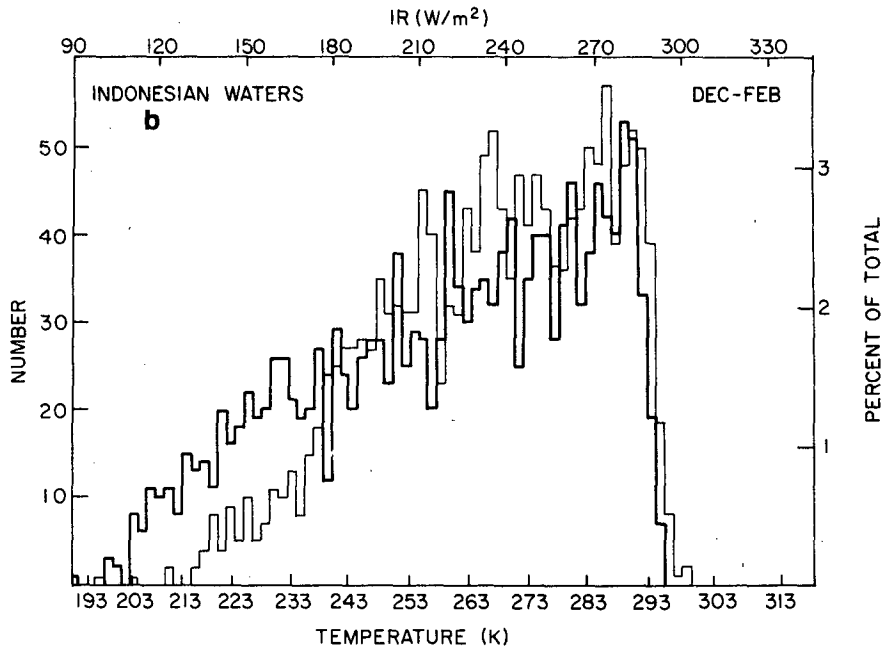


FIG. 3b. As in Fig. 3a except for 30 grid points over the coastal waters of the islands of Borneo, Java, Sumatra and New Guinea, December 1975–February 1976.

currence during the evening hours, which we interpret as a reflection of an evening bias in the frequency of middle cloud decks, with tops between 5 and 10 km. (Broken cirroform clouds may also be characterized by IR emission which falls within this

mid-range, but it seems unlikely that high clouds which fill, or nearly fill, the 2.5° × 2.5° grid squares would exhibit a morning bias, as reflected in the frequency of very low values of outgoing IR, while high clouds that only partially fill the grid

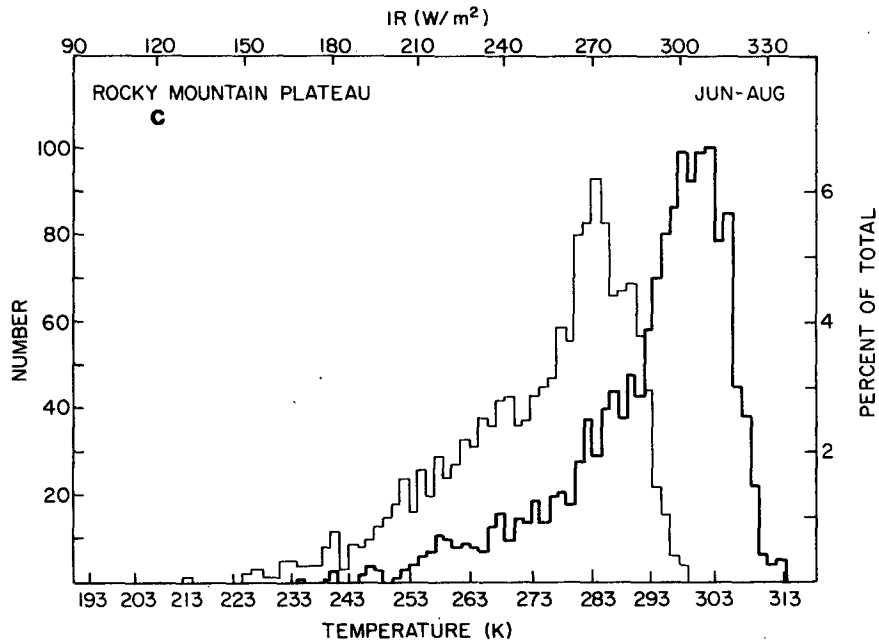


FIG. 3c. As in Fig. 3a except for 18 grid points over that portion of the western United States bounded by 37.5 and 42.5°N latitude and 115 and 102.5°W longitude, June–August 1975.

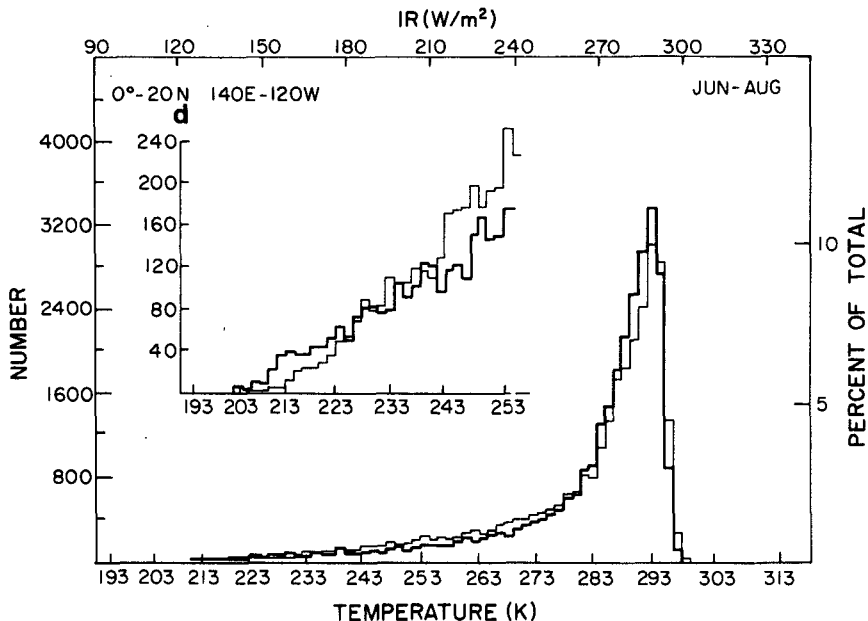


FIG. 3d. As in Fig. 3a, but for 369 grid points from 0 to 20°N latitude, 140°E to 120°W longitude (Pacific Ocean), June–August 1975. The insert shows the left-hand side of the frequency distribution with an expanded scale.

squares would exhibit an evening bias; it seems more likely that these two ranges of outgoing IR are dominated by clouds in different height ranges.)

Values of outgoing IR between 255 and 285 $W m^{-2}$ have a higher frequency of occurrence at 0900 LT while those greater than 290 $W m^{-2}$ occur preferentially at 2100 LT. We interpret these biases as

evidence of a morning bias in the extent of low cloudiness at 2100 LT. The interpretation of this result is subject to some degree of ambiguity because of the substantial emission from atmospheric water vapor in the planetary boundary layer at tropical latitudes as noted by Cox and Griffith (1979). Barring large, systematic diurnal variations

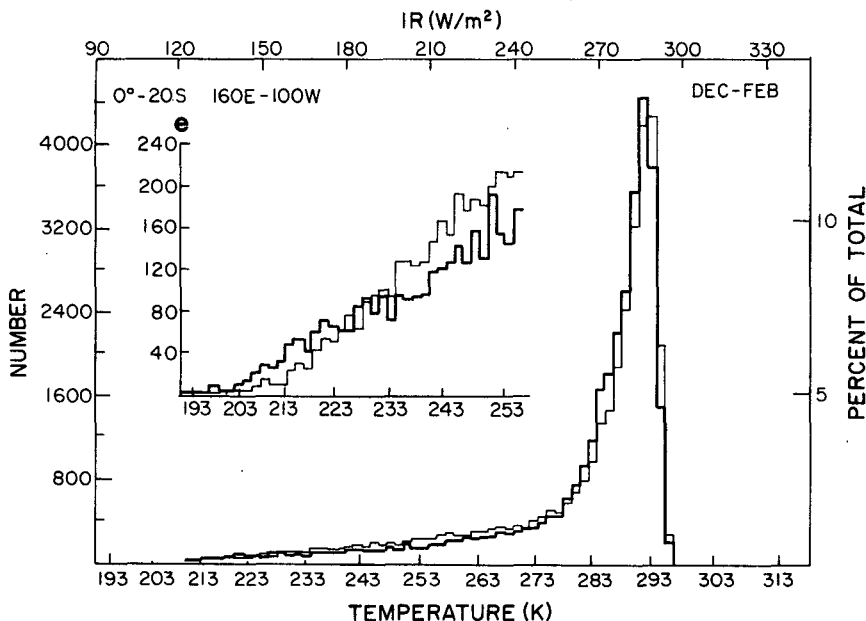


FIG. 3e. As in Fig. 3d except for 369 grid points from 0°N to 20°S latitude, 160°E to 100°W longitude (Pacific Ocean), December 1975–February 1976.

TABLE 2. Tropical atmospheric sounding.

Pressure (mb)	Temperature (K)	Height (km)
850	293	1.5
700	284	3.0
500	268	5.8
300	242	10.0
200	219	12.2
100	197	16.5

in the low-level temperature profiles, these biases in outgoing IR indicate that either low cloudiness or the thickness of the planetary boundary layer (or both) are greater at 0900 LT than at 2100 LT. We believe that much of the observed bias is due to diurnal variability in low cloudiness for two reasons: 1) such diurnal variability is evident in SMS visible imagery during daylight hours (see, e.g., Simon, 1977) and 2) day-to-day variability in outgoing IR shows a negative correlation with albedo changes in the low cloud regions of the eastern oceans (Hartmann and Short, 1980).

A diurnal modulation in the 255–285 $W m^{-2}$ range of outgoing IR was observed not only in the stratus regimes of the eastern subtropical oceans, where middle and high clouds tend to be absent, but over most of the tropical and subtropical oceans with the exception of the major cloud bands where the frequency of middle and high clouds is high enough to obscure observations of the lower clouds. Hence, a morning bias in low clouds seems to be a widespread phenomenon over the low-latitude oceans; it is not confined to the regions of negative values in Fig. 2.

3. Conclusions

The results shown in the previous section are indicative of well-defined and consistent patterns of diurnal variability of cloudiness over large regions of the globe.

Over land regions and coastal waters, the diurnal variation in outgoing IR is consistent with the widely held view that cloudiness associated with convective activity is strongly modulated by boundary-layer circulations which favor enhanced afternoon and evening cloudiness over islands and regions of elevated terrain and enhanced late-night and morning cloudiness over coastal waters; particularly over straits and gulfs and other configurations which are partially landlocked or have concave coastlines. The extent of these topographically related features into the open oceans appears to be limited to a few hundred kilometers.

Over the tropical oceans the observed diurnal variation in outgoing IR exhibits a three-tiered structure with a pronounced morning bias in the

frequency of high clouds and low clouds and a weak but statistically significant evening bias in middle clouds.

If we can assume that outgoing IR with values less than 150 $W m^{-2}$ can be identified with cloudiness which is primarily of convective origin which was generated within a few hours prior to 0900 LT, then the morning bias in high clouds is consistent with the existence of a widespread morning maximum in convective rainfall over the tropical oceans, as recently proposed by Gray and Jacobson (1977) on the basis of analysis of rainfall data from a large number of stations on small, isolated tropical islands. This bias toward the morning hours appears to be quite substantial, particularly for the coldest, highest cloud tops, as seen in Table 3. If it is indeed a reflection of a morning maximum in convective activity, it seems reasonable to expect to find an even stronger bias in the frequency of very low values of outgoing IR in data sets with horizontal resolution high enough to more effectively resolve individual convective cloud systems.

Another distinctive characteristic of the morning to evening differences in outgoing IR over the tropical oceans is the evidence of a morning bias in low cloudiness, not only in the regions of persistent summertime stratus over the subtropical eastern oceans where one has previously been believed to exist (see, e.g., Simon, 1977), but also over the central and western tropical oceans. In view of the widespread occurrence of the morning bias in low clouds, it seems likely that it involves not only stratus decks, but also trade wind cumulus. These results also support the plausibility of a widespread diurnal cycle in the height of the trade-wind inversion as suggested by Kraus (1963). The morning to evening differences in low clouds, averaged over the tropical Pacific during summer, as deduced from Figs. 3d and 3e, is on the order of 13% (38 067 occurrences of outgoing IR between 255 and 285 $W m^{-2}$ at 0900 LT vs 33758 at 2100 LT). The true percentage difference in low cloud coverage is probably somewhat larger than the above estimates, since some of the occurrences of outgoing IR in this "low cloud range" are associated with partial coverage of the $2.5^\circ \times 2.5^\circ$ grid

TABLE 3. Total number of observations with equivalent blackbody temperature less than the specified values, from the frequency distributions in Figs. 3d and 3e. Corresponding percentages are in parentheses.

Temperature	0900 LT	2100 LT
<208 K (–65°C)	147 (70)	63 (30)
<213 K (–60°C)	270 (72)	103 (28)
<218 K (–55°C)	532 (68)	254 (32)
<223 K (–50°C)	754 (65)	408 (35)

squares by middle cloud decks, which do not show a morning bias.

Perhaps the most unexpected result of this study is the identification of a widespread evening bias in the frequency of occurrence of outgoing IR with a broad range of values which we have associated with middle clouds ($180\text{--}250\text{ W m}^{-2}$; $243\text{--}273\text{ K}$ cloud top temperatures, averaged over a $2.5^\circ \times 2.5^\circ$ grid square). The apparent diurnal modulation of the middle clouds, as deduced from Figs. 3d and 3e, is on the order of 10–20% (12 866 occurrences of outgoing IR in this range of values at 2100 LT versus 11496 at 0900 LT). The percentage difference might be somewhat larger if middle cloud decks could be distinguished from broken high clouds in the outgoing IR data. In any case, the evening bias in the frequency of outgoing IR in this mid-range of values is large enough to cancel the contributions of the morning bias in high and low clouds to the IR radiation budget so that the outgoing IR over the tropical oceans is nearly the same at 0900 and 2100 LT. It is only over the subtropical eastern oceans, where the frequency of middle clouds is very low, that Fig. 3 shows a significant bias in outgoing IR toward the evening hours.

In retrospect, it can be seen that the small values of 0900–2100 LT differences in outgoing IR over the tropical oceans are somewhat misleading. The atmosphere exhibits a strong, but rather complicated response to the diurnal cycle in the sun's heating. It so happens that the resulting net change in outgoing IR between these two particular hours of the day is rather small, but there is no guarantee that the difference would be small for other 12 h differences or for other parameters in the radiation budget.

The remarkable geographical uniformity of the morning to evening differences in cloudiness over the tropical oceans suggests that the processes responsible for them may be fundamentally different from the more regional boundary-layer forcing which prevails over land and coastal waters. Gray and Jacobson (1977) have proposed one possible mechanism which involves the response of deep cumulus convection to diurnal variations in the shortwave radiation balance in disturbed regions of the tropics. A comprehensive discussion of physical mechanisms is beyond the scope of this paper.

The results of this study demonstrate the need for adequate resolution of the diurnal cycle in observing systems designed to monitor the earth's radiation budget. Furthermore, a definitive identification of the contributions of high, medium and low clouds to the radiation budget will require data with much higher horizontal resolution than that used in this study. For example, if we had had available for

each $2.5^\circ \times 2.5^\circ$ grid square, not only the instantaneous observations of spatially averaged outgoing IR, but also instantaneous counts of the number of individual image elements within that square whose outgoing IR was in the high, middle and low cloud ranges (say, <150 , $180\text{--}250$, $255\text{--}285\text{ W m}^{-2}$, respectively), it would have been possible to resolve with much greater accuracy, detail and statistical significance, the diurnal cycle in the coverage of these three basic cloud types. This information is (or was) available in the full resolution NOAA satellite observations, and it could be (or could have been) recovered, archived and processed at a modest cost.

Acknowledgments. The authors would like to thank Harold J. Edmon and David S. Gutzler for their assistance with computer graphics and translations.

This work was supported by the Climate Dynamics Program, Climate Dynamics Research Section, Atmospheric Sciences Division, National Science Foundation under Grant 78-07369.

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