On the Infrared Transmission Through Cirrus Clouds and the Estimation of Relative Humidity from Satellites

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ABSTRACT

On the basis of satellite and other types of information, it is shown, both on observational and theoretical grounds, that cirrus clouds have a higher transmission for radiation at 10 μ than for radiation at 6 μ. Thus, in the case studied, at 10 μ the cirrus clouds had a fractional transmission of about 50%, while at 6 μ the clouds were essentially opaque. This fact has an important bearing on attempts to use a "humidity diagram" to estimate relative humidity above clouds. The satellite data show that measurements at 6 or 10 μ can be used to locate regions of substantial cloudiness, which are therefore regions of high relative humidity in the troposphere. To use these satellite measurements to estimate the relative humidity above clouds would be misleading. However, the use of radiation measurements in both channels can perhaps be helpful for specifying the transmissivity of cirrus clouds, and in the absence of clouds, for locating regions of low relative humidity.

1. Introduction

The distribution of water vapor in the earth's atmosphere has long been a subject of interest to atmospheric scientists. In the past most of the available information has been obtained from radiosonde observations. However, in recent years several studies have involved the use of radiation data from satellites to infer the mean relative humidities in the middle and upper troposphere (Möller and Raschke, 1963, 1964; Raschke and Tannhäuser 1965; Allison and Warnecke, 1965; Raschke, 1966; Raschke and Bandeen, 1967). These studies used satellite intensity measurements from the 6.3-μ water vapor channel and 8–12 μ atmospheric window channel; and based on certain assumptions and model atmospheres, the mean relative humidities were estimated.

The band width of the water vapor channel and of the window channel were somewhat different in the TIROS and Nimbus satellites. For Nimbus II (Aracon Geophysics Company, 1966), which we shall discuss in this paper, the spectral intervals were as follows:

Water vapor channel	6.4—6.9 μ
Window channel	10—11 μ

The 6-μ spectral interval is located in the center of a strong absorption band of water vapor. Therefore, the energy received at the satellite is mainly due to the radiation emitted by the water vapor in the atmosphere; and under cloudless conditions and normal water vapor distribution most of the energy is emitted from the layers above 600 mb, with a maximum contribution from the levels near 400 mb. The actual contribution to the intensity measured by the satellite depends on the temperature and moisture distribution in the middle and upper troposphere, and lower stratosphere (Raschke and Bandeen, 1967).

Except for the 9.6-μ ozone absorption band and some weak absorption due to water vapor and carbon dioxide, the window channel region is relatively transparent. Therefore, a measurement at 10 μ gives a first approximation to the effective temperature of the emitting cloud, ground or water surface under the satellite. By correcting for the absorptions due to intervening gases, more accurate temperatures of the emitting surfaces can be obtained from intensity measurements in the 10-μ channel (Wark *et al.*, 1962).

Thus, the intensities measured from a satellite in the 6-μ channel should be sensitive to the water vapor and temperature distribution in the atmosphere above an opaque surface; and the intensity measurements at 10 μ should be mainly influenced by the temperature of the emitting surface under the satellite. From these considerations Möller and Raschke (1963, 1964) developed a diagram from which the relative humidity in the atmosphere, *above* the emitting cloud or surface, could in principle be determined. This diagram was developed further and employed to "measure" the relative humidity over large sections of the world (Raschke and Tannhäuser, 1965; Raschke and Bandeen, 1967). We shall refer to this diagram as the "humidity diagram."

In the application of the humidity diagram serious discrepancies occur, especially in areas of high, cold cloud layers. During an investigation to explain the discrepancies, we found, as others have found (McClain, private communication; Raschke and Bandeen, 1967) that the intensities in the 10-μ window channel alone

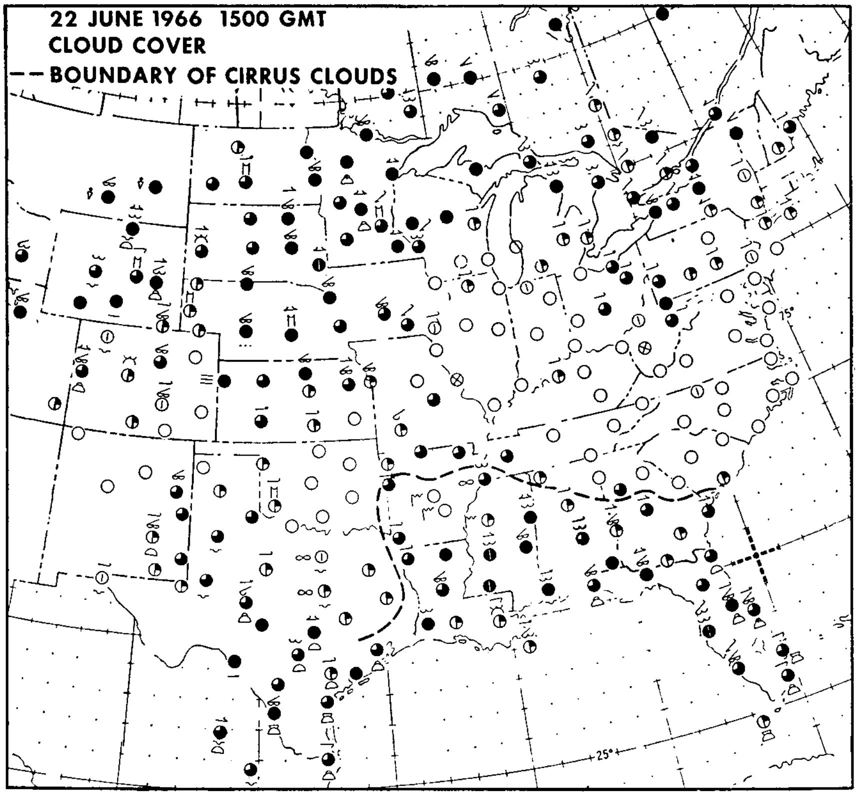

Fig. 1. Cloud cover chart from surface observations for 1500 GMT 22 June 1966. The broken line shows the boundary of cirrus clouds reported by the surface observers.

are negatively correlated with the relative humidity averaged over deep layer of the troposphere; that is, cloudy areas with low values of intensity at 10 μ are areas of high relative humidity in the mid-troposphere, while areas with high values of intensity at 10 μ are regions with low relative humidity. A similar relationship holds also when the 6-μ intensities are used. This implies merely that *inside* (not above) deep clouds, the relative humidity is large; and in areas with low clouds, or few clouds, or very thin clouds, the relative humidity, averaged over deep layers of middle troposphere, tends to be significantly smaller.

Unfortunately, however, when the 6-μ observations are used together with the 10-μ channel observations in the "humidity diagram" for cloudy areas, the results are misleading. The "humidity diagram" requires the underlying surface to be equally "black" for both spectral regions; but cirrus clouds are often more transparent for 10-μ radiation than they are for 6-μ radiation. This fact leads to high calculated values of relative humidity above clouds, even when the relative humidity there is very low.

In cloudless areas, however, the combined use of both channels may contribute to the recognition of regions of low relative humidity. It may, in fact, turn out that the combined use of both channels is more useful in locating the presence of cirrus clouds and in discussing the cirrus cloud properties, than in estimating relative humidity above clouds. The purpose of this paper is to discuss the observations and calculations leading to these conclusions.

2. The basic data

The data selected for study were the Nimbus II data for 22 June 1966 during the satellite pass over the eastern half of the United States. The time of satellite pass was about 1630 GMT.

Clouds. Fig. 1 shows the cloud cover and cloud type obtained from surface reports at 1500 GMT. Near the Gulf Coast cloudy conditions prevailed with low, middle and high clouds reported generally. Almost clear conditions prevailed over the Carolinas, Virginia and parts of Illinois, Indiana, Kentucky and Tennessee, where strong anticyclonic conditions existed. The broken line in Fig. 1 shows the boundary of cirrus as reported by the surface observers. An Eastern Airlines flight from Tampa, Fla., to Atlanta, Ga. (Kadlac, private communication), reported cirrus cloud tops up to about 12 km over Tampa becoming thinner as they moved north and completely clearing 50 mi south of Atlanta. There were some thunderstorms in the vicinity of Tampa but the aircraft did not encounter any turbulence. This aircraft report was very useful for further

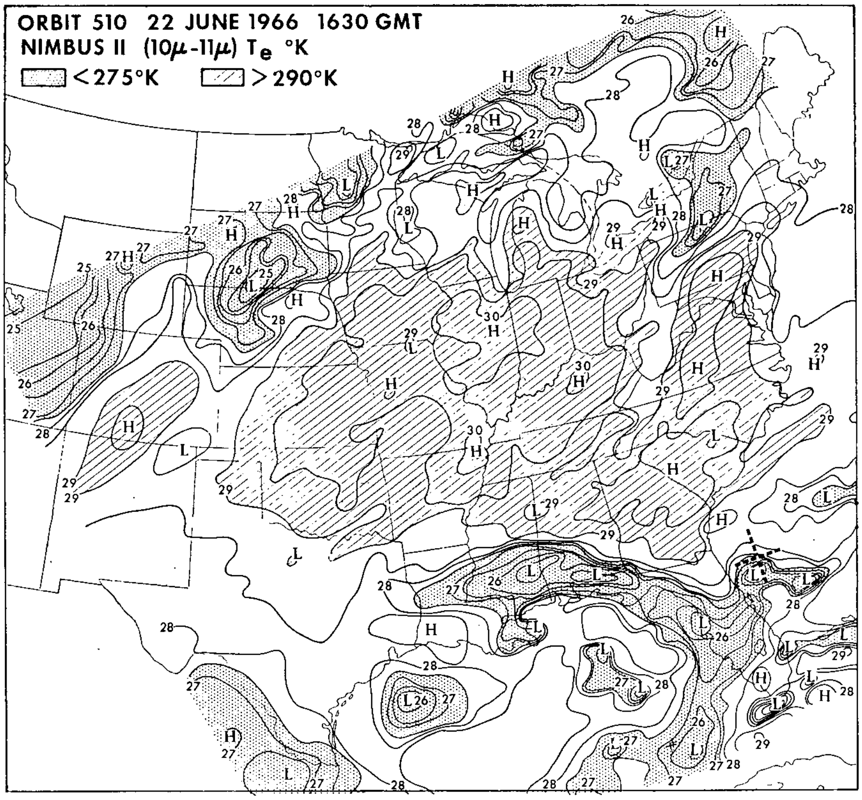

FIG. 2. Equivalent black-body temperature T_e (°K) measured by the 10-μ channel on Nimbus II, orbit 510, 22 June 1966. The isotherms are drawn at 5K intervals (e.g., 28 represents 280K). H and L represent regions of high and low temperatures.

calculations of the cloud radiative transmission discussed later in this paper.

Radiation chart (*10* μ). Fig. 2 shows the analysis of the 10-μ channel measurements received from Nimbus II. The data are intensities displayed as isotherms of equivalent black-body temperatures T_e drawn at 10K intervals. Along the Gulf Coast a region of low temperatures existed with the coldest temperatures less than 250K. A very sharp gradient of T_e is located over northern Florida, southern Georgia, Alabama and central Mississippi. Over the midwestern and eastern United States, T_e>290K, and in some areas, >300K. These high temperatures indicate relatively clear conditions. A comparison between Figs. 1 and 2 shows very good agreement. Whenever there are high thick clouds, temperatures are low, and over clear areas, the temperatures are high. The sharp gradient in T_e occurs close to the region where the cloud cover changes from nearly overcast to either scattered or clear conditions. The sudden change in temperature over northern Florida and southern Georgia indicates decreasing cloudiness which agrees with the Eastern Airlines aircraft report mentioned above.

Humidity chart. Mean relative humidities for the layer 400-275 mb were obtained for stations over the eastern half of the United States, from the 1200 GMT radiosondes on 22 June 1966; usually, this is the layer from which most of the energy arrives at the satellite in the 6-μ band for cloudless conditions. Fig. 3 shows the analysis of the relative humidity for the layer. Again a prominent feature is the strong gradient over the southern states. In the cloudy region, where the 10-μ channel showed very cold temperatures, the relative humidities are high. Low humidities occurred in the cloudless regions where high temperatures were found in the 10-μ channel. This relationship is shown also in Fig. 4, where relative humidity at the radiosonde stations has been plotted against T_e as observed by Nimbus II. In this small sample, for the cloudless cases which all had T_e at 10 μ greater than 294K, the mean relative humidity of the 400-275 mb layer was less than 50%; for the cloudy cases, T_e was colder and the average relative humidity was larger. McClain (private communication) correlated the 10-μ data with the relative humidity between 1000–500 mb and found the correlation to be −0.57. Raschke and Bandeen (1967) give a correlation coefficient of −0.54 for a similar relationship for the mid-troposphere.

Radiation chart (*6* μ). The distribution of equivalent black-body temperatures obtained from the 6-μ channel is shown in Fig. 5. As in Fig. 2, the lower temperatures occur over cloudy regions and relatively high tempera-

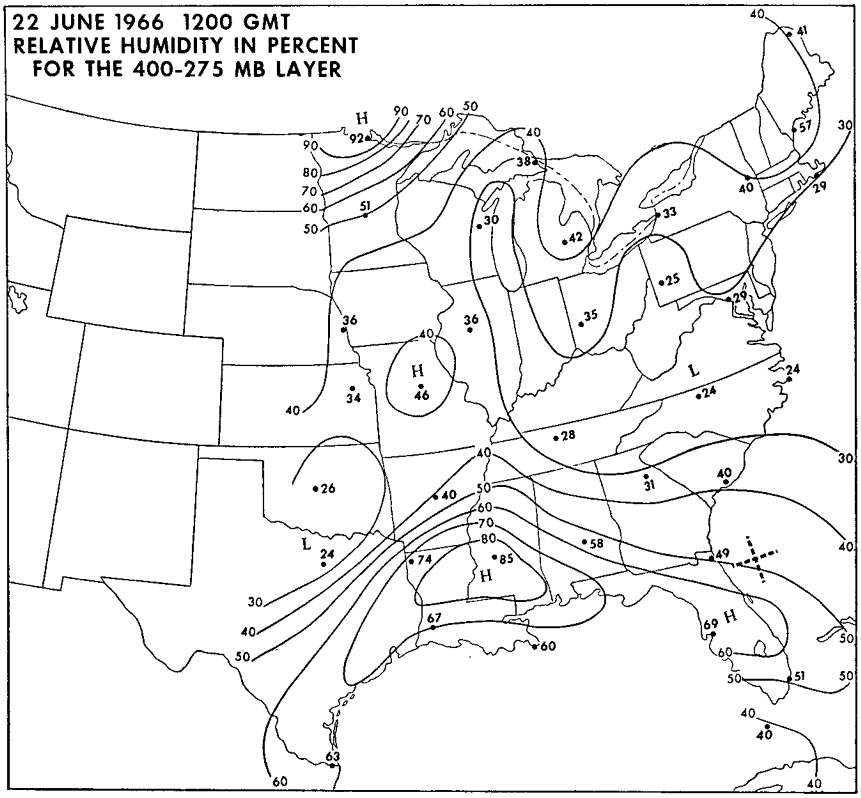

FIG. 3. Mean relative humidity (in per cent) from radiosonde observations, for the layer 400–275 mb at 1200 GMT 22 June 1966. H and L represent regions of high and low relative humidities. The analyzed isolines were drawn independently of the satellite data. The satellite data might suggest some modifications in the analysis.

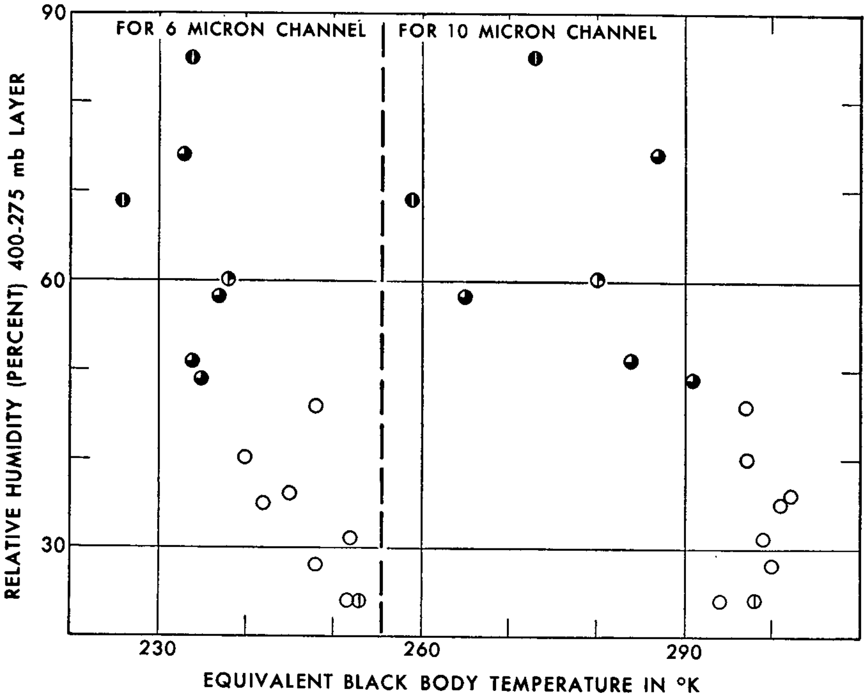

FIG. 4. Mean relative humidity observed from radiosondes for the layer 400–275 mb as a function of the equivalent black-body temperatures in the 10- and 6-μ channels. Only stations where relative humidity values are available are included.

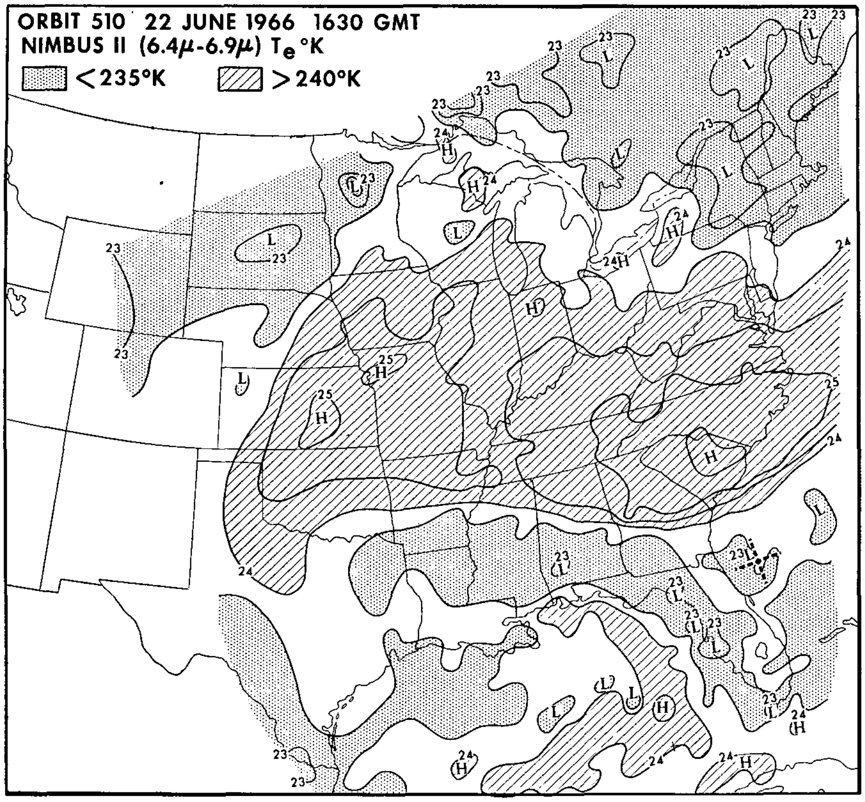

FIG. 5. Equivalent black-body temperature T_e (°K) measured by the 6-μ channel on Nimbus II, orbit 510, 22 June 1966. The isotherms are drawn at 5K intervals (e.g., 24 represents 240K). H and L represent regions of high and low temperatures.

tures occur over clear areas. There is considerable similarity between the patterns of the radiation data. Again the relative humidity is correlated with T_e for 6 μ as shown in Fig. 4.

Relative humidity in cloudy conditions. As mentioned earlier, if clouds were equally opaque for 10-μ and 6-μ radiation, it would be possible (Möller, 1962; Möller and Raschke, 1963, 1964; Raschke and Bandeen, 1967) to estimate the relative humidity above the clouds. Air temperature generally decreases with height and cold water vapor above the cloud would tend to decrease radiation received by the satellite in the 6-μ water vapor band with its strong emissivity; above very cold clouds, however, the water vapor may have little effect. By contrast, the radiation received by the satellite in the transparent 10-μ water vapor window would more nearly correspond to the cloud temperature. In other words, the greater the difference between T_e for 6 μ and T_e for 10 μ, the greater would be the amount of water vapor above the cloud, *if the cloud were opaque* for both wavelength regions.

However, since the temperature usually increases with depth below the cloud top, if the cloud is more transparent for 10-μ radiation than for 6-μ radiation, a large difference would be observed between the two values of T_e even if no water vapor existed above the cloud. This large difference in T_e would be erroneously interpreted as a high relative humidity above the cloud, if the clouds had been assumed to be opaque.

It now remains to show that the cirrus cloud layer, in the case under discussion, was more transparent for 10-μ radiation than for 6-μ radiation.

3. Transmissivity of cirrus clouds

The previously mentioned Eastern Airlines flight reported a middle cloud deck over Tampa with top at 5 km and above it a cirrus deck with a base at 7 km and top estimated at 12 km. The aircraft was flying at 10.5 km. To assign temperatures to these cloud heights, the 1200 GMT radiosonde was used; the data are listed in Table 1. Over the same region the Nimbus II satellite measured about 260K in the 10-μ channel and about 226K in the 6-μ channel.

Both the 6 and 10-μ Nimbus II radiometers had onboard calibration. For the 10-μ channel the calibration seemed to be satisfactory. For the 6-μ channel the calibration method was much more complicated and the absolute values are in some doubt.

If we accept the 10-μ radiation value, we note that $T_e = 260\text{K}$ is warmer than any temperature that appeared in the cirrus cloud. The most logical explana-

Table 1. Cloud height and temperature distribution over Tampa, Fla., at the time of the Eastern Airlines flight.

Type	Cloud height (km)	Temperature (°K)
Cirrus top	12	215
(Airplane altitude)	10.5	—
Cirrus base	7	255
Middle cloud top	5	273
		Satellite observation
		$T_e(10\,\mu)=260$K
		$T_e(6\mu)=226$K

tion of that fact is that the cirrus clouds were partially transparent and that some energy arrived at the satellite from the region below the cirrus cloud.

To investigate the cirrus cloud properties further, a simplified radiation model, based on the methods of Twomey *et al.* (1966, 1967), was used to calculate the differences in the radiative properties of the cloud layers in the two spectral intervals. In this model two layers of clouds were assumed. The lower layer with a temperature T_B of 273K was assumed completely opaque for both channels. A second layer, approximately 5 km thick, to simulate the cirrus cloud, was located above the lower layer. The theoretical model (Twomey *et al.*, 1966, 1967) provides for only one temperature in the upper cloud layer. Thus, in the calculations the following temperatures T_c were considered for the upper (cirrus) layer: $T_c=210$, 220, 235 and 250K. Also the computations were made separately for the following effective drop-size radii in the cirrus cloud: 4, 10, 30 and 100 μ. The wavelengths considered were 10 and 6 μ.

In the first calculation the top of the lower cloud deck was assumed to have a temperature, $T_B=273$K; another cloud deck was assumed above it with a thickness of 5 km and $T_c=210$K. The calculations were performed for the 10-μ wavelength radiation using each of the four drop sizes mentioned above. From this calculation, the optical thickness of the upper cloud was determined which would yield the satellite-observed temperature in the 10-μ channel, namely 260K. From the optical thickness and the drop size one can obtain the amount of liquid water content in the top layer. This type of calculation was repeated for the three other upper cloud temperatures, 220, 235 and 255K. Table 2 shows the liquid water content computed for different cloud temperatures and drop-size distributions. After the amount of liquid water content was calculated, it was kept constant and was used to calculate the transmission through the cloud for the 6-μ water vapor channel, again for the different cloud temperatures and drop size distributions. The clouds were assumed saturated with water vapor and absorption by the water vapor was taken into account. The results are shown in Fig. 6.

Table 2. Amount of liquid water (gm m^{-3}) required for agreement with satellite observation.

Cloud temperature (°K)	Drop radius (μ)			
	100	30	10	4
210	8×10^{-3}	2×10^{-3}	1.2×10^{-3}	0.8×10^{-3}
220	9×10^{-3}	2.6×10^{-3}	1.4×10^{-3}	0.9×10^{-3}
235	12×10^{-3}	3.4×10^{-3}	1.8×10^{-3}	1.2×10^{-3}
255	30×10^{-3}	8×10^{-3}	3.9×10^{-3}	2.9×10^{-3}

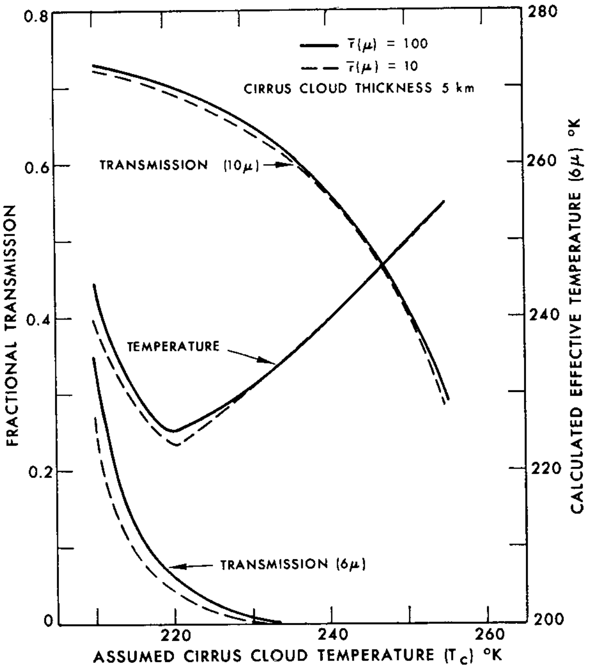

Fig. 6. Computed fractional transmission of cirrus cloud for the 10- and 6-μ channels, and the calculated effective temperature at 6 μ as a function of assumed cloud temperatures.

Fig. 6 shows that the fractional transmission through the upper (cirrus) cloud is much larger for 10-μ radiation than the transmission for 6-μ radiation. For example, when the upper cloud temperature was taken as 235K, about 60% of the upwelling energy was transmitted through the upper cloud for 10-μ radiation. But for 6-μ radiation under those conditions, the upper cloud did not transmit any energy; the cloud was opaque. Even at the coldest temperature considered, $T_c=210$K, a significant difference exists for the cloud at the two wavelengths. The transmission through the upper cloud at 6 μ increases to about 30% for $T_c=210$K, because the amount of water vapor in the cloud is small; but the water vapor amount is still large enough to absorb at 6 μ so that the energy transmitted is significantly smaller than the 70% transmitted at 10 μ. These results agree with the conclusions reached by Brewer and Houghton (1956). They have shown from aircraft measurements that the emissivity of cirrus clouds

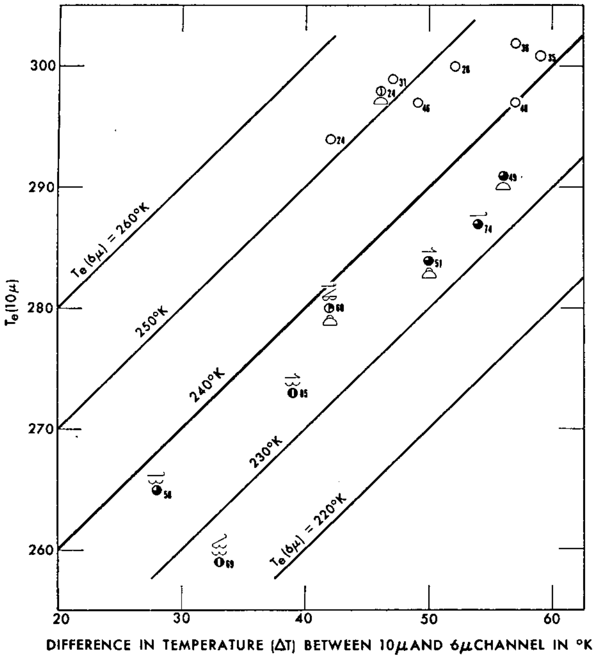

FIG. 7. The difference in temperature ΔT between the 10- and 6-μ channels as a function of the temperature in the 10-μ channel. The sloping lines are lines of constant 6-μ temperature. The amount and type of clouds at each station are shown. The numbers near the cloud symbols indicate the relative humidity of the 400–275 mb layer.

varied between 5 and 90%. For thin cirrus clouds approximately 9000 ft thick, the emissivity was only 5–10%. In addition, Fig. 6 shows that there is only a small difference in the transmission for the various drop sizes.

Fig. 6 also shows the calculated temperatures which would be observed in the 6-μ channel by a satellite above these clouds. For $T_c \geqslant 230$K, the equivalent temperature which would be observed at the satellite is very close to the cloud temperature. This occurs because the absorption and emission by water vapor is strong enough to make the cloud opaque. (It should be noted, by contrast, that at 10 μ the satellite would observe a temperature of 260K for all assumed cloud temperatures T_c.) However for $T_c < 230$, the cloud also begins to be somewhat transparent at 6 μ and allows energy from the underlying cloud, whose temperature is 273K, to reach the satellite. For example, for $T_c = 210$K, the satellite would observe a temperature of about 240K. Calculations (not shown) indicate that even a cloud whose thickness is 1 km would be opaque for $T_c = 235$K. Such a temperature occurred in the real cloud about 2 km below the cloud top. Therefore, the equivalent temperature as observed by the satellite would be lower than 235K. Further calculation suggests that T_e should be about 225K, after consideration of the cold cloud above the 235K level. The observed T_e from Nimbus II was about 225±5K (depending on the calibration coefficient used).

4. Relative humidity vs. T_e (10 μ) and T_e (6 μ)

In clear areas, if the atmosphere is dry, the absorption in the 10- and 6-μ channels should be small and the difference between the two channels should also be small. If there is considerable amount of water vapor in the atmosphere, the absorption is large for the 6-μ compared to the 10-μ channel, and the difference between the channels should be larger. Therefore, in Fig. 7 the difference between the two channels was plotted against the 10-μ channel. The figure applies for both clear and cloudy conditions. The mean relative humidities for the layer 400-275 mb and the cloud types were also plotted near the cloud symbols.

Fig. 7 shows that for the case studied here, when the 10-μ radiation was relatively low (260-285K), clouds existed and the relative humidity in the upper troposphere was relatively high. For these cloudy cases the 6-μ T_e was also rather low, and except for one case was close to 235K. Thus, even though cirrus clouds were reported in most of the cloud cases, the 10-μ T_e varied from 259 to 287K, while the T_e for 6 μ was confined to temperatures below 239K. The colder 6-μ temperature may be a better indication of the cirrus cloud height than the 10-μ T_e.

Fig. 7 also suggests that the presence of cirrus clouds may be detected from the combination of the 10 and the 6-μ channel data, and that the transparency at 10 μ and/or the amount of the cirrus clouds is indicated by the difference ΔT between the two channels; the greater the difference, the more transparent the cirrus clouds.

When the 10-μ radiation was high (290-300K) the atmosphere was cloudless. For the cloudless case, the 6-μ radiation also tends to be relatively high. There is also a slight tendency for ΔT to be related to the relative humidity. For $\Delta T \approx 60$K, the relative humidity tended to be near 40%; for $\Delta T \approx 45$K, the relative humidity tended to lie near 30%, although one exception occurred at Columbia, Mo., where relative humidity was 46%. However, these data are too few for this relationship to be considered established.

5. Relative humidity estimates in cloudless areas

Because of the transparency of the cirrus clouds for 10-μ radiation, the humidity diagram cannot be expected to give reliable estimates of relative humidity over areas with high clouds. However, in cloudless areas the relative humidity estimates may be more reliable. To test this the mean relative humidities for the layer 400-275 mb obtained from soundings were compared with the relative humidities obtained from the "humidity diagram," using the information from the 10- and 6-μ channels. The results are shown in Fig. 8. The humidities obtained from the "humidity diagram" are considerably lower than the observed values. The differences have two possible causes. First, the radiation measurements on Nimbus II may be in error. The 10-μ radiation seems to have been adequately calibrated on board the satellite, but the on-board calibration method was more complicated and uncertain for the 6-μ channel. If T_e in the 6-μ channel as reported from Nimbus II were about 5K too high, the relative humidities computed from the humidity diagram would come into closer agreement with the radiosonde data as shown in Fig. 8.

If the Nimbus II values were correct, then the assumptions made in the humidity diagram would need to be reexamined. For the cloudless case these would involve the influence of a constant temperature lapse rate, the assumption of constant relative humidity with height, and the acceptance of certain absorption coefficients for water vapor averaged over the 6-μ water vapor band and weighted for the instrument characteristics. Comparison between actual and assumed temperature distribution for middle latitudes over clear areas showed that the assumed values were higher by about 8K in the upper troposphere and lower stratosphere. This difference alone will not account for the observed differences in the relative humidities. Also, a cursory examination of the assumptions suggests the discrepancy in Fig. 8 cannot be explained by deficiencies in the assumptions, if the absorption coefficients derived from Howard *et al.* (1956), which were used, are correct. Therefore, tentatively, the more likely reason for the discrepancy is that the Nimbus 6-μ data are in error.

6. Conclusions and critique

Radiation measurement in the window channel (10–11 μ) on the Nimbus II satellite can locate the major regions of cloudiness, and therefore, the regions of high relative humidity in the middle and upper troposphere. Data from the water vapor channel (6.4–6.9 μ) do not seem to aid in the relative humidity determination in cloudy situations. Raschke and Bandeen (1967) use both the 10-μ and the 6-μ channels to determine water vapor distribution in clear *and cloudy* areas. They point out that the method requires clouds to be opaque for *both* spectral regions, and that the method would in principle yield *only* the relative humidity *above* clouds.

Then, after they have presented the computed relative humidity all over the world, they concede that the method may yield erroneous values in regions of major cloudiness.

The results presented above in Figs. 4, 6 and 7 show that the results of Raschke and Bandeen are doubtless in error in principle for the areas of major cloudiness; the high values of relative humidity which they obtain are not relative humidities *above* clouds, but relative humidities *in* clouds. And this result can be obtained with the aid of the 10-μ channel alone. However, the water vapor channel may aid in obtaining the cloud top heights more precisely than the window channel for cirrus clouds. This is so because cirrus clouds are more opaque for the water vapor channel than for the window channel.

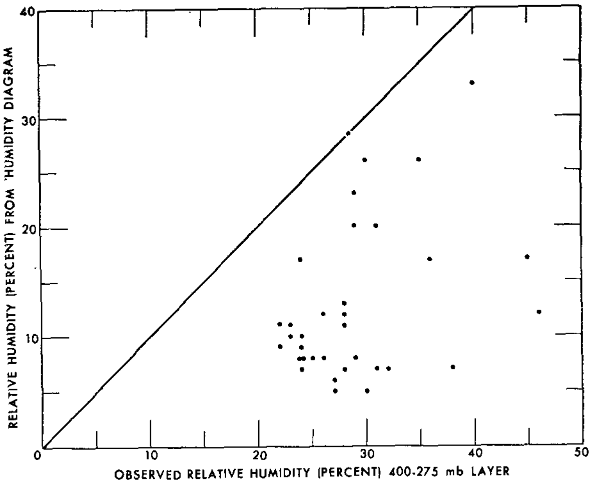

Fig. 8. Comparison of relative humidities during cloudless conditions from the "humidity diagram" and the observed mean relative humidities for the layer 400–275 mb.

In cloudless areas, the relative humidity in the upper troposphere was low in this study; nevertheless, for midtropospheric regions a combination of the measurements in the two radiation channels may aid in separating the somewhat moister regions from the drier ones.

However, the calibration of the radiometers is of crucial importance, since rather small errors in the 6-μ channel calibration can lead to large errors in relative humidity, as shown in Fig. 8. Hence, again the results of Raschke and Bandeen are questionable. Their results were obtained with TIROS radiometers. No on-board calibration was available to them. The TIROS radiometers were notorious for their degradation, and several attempts have been made to correct for the degradation. But Raschke and Bandeen found it even necessary to correct the corrections. Thus, their true values of the 6-μ intensities must be doubtful at least. And in view of the sensitivity of the computed relative humidity to the 6-μ intensities in cloudless areas, comparison of their results with radiosondes measurements in cloudless areas would have been useful.

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