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INTRODUCTION

The Intertropical Convergence Zone (ITC) over the tropical oceans is characterized by a cloud belt with a varied structure of single to double lines or clusters along latitudes 0-10N depending on the season. The infrared radiometers in the Nimbus satellites provide excellent data for interpreting relative cloud heights and fields of vertical motions in the ITC. It is the purpose of this paper to analyze some cross-sections through the ITC obtained from infrared measurements made by Nimbus 3. Supplementary aircraft measurements with infrared and microwave radiometers during the Nimbus 3 overpass are also analyzed.

NIMBUS 3 RADIOMETERS

Nimbus 3 satellite, launched in April 1969, contained a Medium Resolution Infrared Radiometer (MRIR) with 5 channels, with a spatial resolution of about 50 km. The channel sensitive to radiation at 10.5 - 11.5 μm, in an atmospheric window, measures the surface or cloud top temperature with a correction from 0 to about 7°K for atmospheric water vapor. The channel at 6.3 - 7.1 μm, in a water vapor absorption region, is sensitive to a layer between about 250 and 450 mb. The 20 - 23 μm channel, in the rotational water vapor absorption region, is sensitive to an atmosphere layer between about 400 and 600 mb. The 0.2 - 4.0 μm channel allows the determination of the albedo, or more precisely the bidirectional reflectivity. A channel at 15 μm, in a CO_2 absorption band, measures the temperature of a layer extending from the upper troposphere to the lower stratosphere and is not discussed in this paper. The two water vapor channels are useful for determining moist and dry regions in the middle to upper troposphere and therefore for inferring fields of vertical motions. For deep high clouds with temperatures at cloud top less than about 225K both water vapor channels and the 11 μm channel should measure radiation with approximately the same equivalent blackbody temperature (T_{BB}). On Nimbus 3 the 20 μm channel generally gave lower equivalent temperatures than that of 11 μm or 6.7 μm. The reason for this is not entirely clear. It may be that the emissivity of the cloud is greater at 20 μm than at 11 or 6.7 μm so that radiation in the latter spectral regions originate from deeper within the cloud where temperatures are higher. However, unpublished calculations by Curran indicate that, although the emissivity of some water clouds behave in this manner, the same is not true for ice clouds which should characterize clouds with top at 225K or less. It is possible that calibration errors at low temperatures may be the reason for low readings by the 20 μm radiometer.

The Nimbus 3 satellite also contained an Infrared Interferometer Spectrometer (IRIS) which provides radiances from about 5 to 20 μm with a spectral resolution of 0.1 μm and a spatial resolution of

150 km. For clear sky conditions it is possible to invert the radiances and to determine by successive approximations the vertical temperature and humidity distribution of the atmosphere (Conrath et al. 1970). Some humidity profiles with IRIS measurements were obtained in connection with the ITC cross sections.

Some flights of a NASA CV990 aircraft were made in connection with the Bomex experiment over the tropical Atlantic during the summer of 1969. One flight was made across the ITC on 11 July 1969 during a period of a Nimbus 3 overpass. The CV990 had an 11 μm radiometer, and a microwave radiometer at 19.35 GHz with a 2.8° field of view. Over the sea, assuming constant sea state, the microwave brightness temperature increases about 6.3°K for every cm of precipitable water (vapor) in the atmosphere. For clouds the increase is about 300°K per cm of precipitable water. However, most non-raining clouds contain relatively little precipitable water. The largest increase in temperature comes from clouds with rain. Calculations of the increase in temperature due to rainfall have been made by Paris (1971) for different model atmospheres. His calculations have been applied to determine the increase in brightness temperature as a function of rainfall intensity for a depth of rain of 5 km, which is approximately the height of the 0°C level in the tropics. The result is shown in Figure 1. The increase in brightness temperature for rain intensities of 1, 3 and 5 mm hr^{-1} are 50, 95 and 125°K respectively.

ATLANTIC ITC 11 JULY 1969

Figure 2 shows a rectified Nimbus 3 photograph of the ITC in the region 40-60W on July 11, 1969. The ITC consisted of cloud clusters in a single to double line at 9-10N. Scattered cloudiness occurred to the north and south of the ITC. The aircraft track from Barbados across the ITC is also shown in Figure 2. Surface temperatures calculated from Nimbus 3 IRIS are shown in the circles: 296-298 K north of the ITC and 295-296 K south.

Figure 3 shows a cross section, obtained by the aircraft flying at 11 km, of measurements with the 11 μm radiometer and the 19.35 GHz radiometer. The 11 μm radiometer shows a mean equivalent blackbody temperature (T_{11}) of about 297 K north of the ITC and 295 K to the south. The microwave data shows a brightness temperature about 8°K higher to the south than to the north which in the absence of clouds would indicate the total precipitable water to be 1.2 cm greater to the south than to the north. Figure 4 shows vertical profiles of relative humidity, derived from IRIS measurements, across the ITC. Above the 850 mb level the humidity is considerably lower to the north than to the south. The precipitable water north of the ITC at 13 to 16N ranges between 3.1 and 3.4 cm, while to the south at 2.6 - 7.9N it is 4.1 - 4.5 cm. Thus the IRIS measurements and the microwave data are in good agreement on the relative amounts of humidity north and south of the ITC. The greater humidity to the south of the ITC than to the north also explains the lower values of T_{11} to the south.

The minimum T_{11} in the ITC, as measured by the aircraft radiometer, was 230K which corresponds to a height of about 11 km in a tropical atmosphere. The microwave radiometer showed a maximum increase in brightness temperature of about 80°K in the ITC. According to Figure 1 this corresponds to an average rain intensity of 2.2 mm hr^{-1} over the field of view (500 m from 11 km elevation).

Maps of T_{BB} for 11 July 1969 were prepared from the MRIR data over the tropical regions of the Atlantic. Figure 5 shows a cross section of T_{BB} for the various channels through the ITC at 48W. The minimum T_{11} is 255K. (This is warmer than the minimum T_{11} of 230K measured by the aircraft radiometer because of the 50 km resolution of the satellite radiometer as compared to 500 m for the aircraft microwave radiance.) The minimum $T_{6.7}$ and T_{20} are 229 and 244K respectively and the maximum albedo is 42%.

South of the ITC the water vapor channels show relatively constant values in Figure 5 with $T_{6.7} \cong 240K$ and $T_{22} \cong 260K$ between 0 and 6N. North of the ITC both $T_{6.7}$ and T_{20} increase with latitude and reach maxima of 249 and 273K respectively at 18N. The higher $T_{6.7}$ values also confirm the presence of much drier air to the north of the ITC.

The ITC across the Atlantic on 11 July 1969 was a relatively weak line at about 10N with no very cold temperatures except at about 8N, 20W where an extensive cloud cluster occurred with $T_{11} = 220K$, $T_{6.7} = 215K$ and $T_{20} = 214K$ indicative of a storm with cloud top at about 13.5 km. The dry air was located to the south of this storm with maximum $T_{6.7}$ = 249K and T_{20} = 267K south of 5N as compared to maximum $T_{6.7}$ = 246K and T_{20} = 262K at 17-20N. Over the rest of the Atlantic, however, dry air predominated to the north of the ITC.

PACIFIC ITC, APRIL, 23, 1969

The ITC in the Pacific on 23 April 1969 consisted of a single band of clouds near about 4N from 160E to 140W. The most intense rain cell in the band, as indicated by the lowest T_{BB}, was centered near 4N, 173E. Figure 6 shows a meridional cross section of the MRIR measurements through this intense cell. The lowest equivalent temperatures are at 3.5N with T_{11} = 207K, $T_{6.7}$ = 205K and T_{20} = 200K. The 207K temperature indicates an altitude in a tropical atmosphere of 14.5 km, or about 2 km below the tropical tropopause. The albedo of 77% indicates a complete overcast over the resolution area. Undoubtedly cloud turrets, with dimensions smaller than the radiometer field of view, extended to the tropopause.

The maximum values of $T_{6.7}$ = 243K and T_{20} = 266K at 15 to 18N to the north of the ITC are appreciably higher than values to the south ($T_{6.7}$ = 235K and T_{20} = 257K at 1 to 5S). Thus the middle and upper troposphere is considerably drier to the north of the ITC than to the south. Confirmation of this conclusion is also found in some calculations of humidity from the IRIS data which show precipitable water in clear areas to be 2.7 - 2.9 cm at 13.8 - 14.6N as compared to 3.2 cm at 0.4 to 1.3N; the greatest differences in humidity occurred above the 850 mb level.

The various irregularities to the north of the ITC in Figure 5 are generally all in phase and are probably caused by cirrus cloud streaks which are parallel to the ITC. The streaks affect the albedo by 5 to 10% and T_{11} by 5 to 10°K. Values of the albedo over the clear ocean are as low as 7% at 3 to 5S and 8% near 17N.

An examination of the entire ITC across the Pacific on 23 April 1969 shows that the air was predominantly drier to the north of the ITC, than to the south. In the region between 115W and 100W there were two cloud lines at about 4N and 9N. In this case extremely dry air indicative of subsidence was located between the two lines. At 95W there were two very cold cloud clusters, one centered at 3N and the other at 2S. There was an intrusion of relatively dry air from thw west between the two centers.

CONCLUSION

The use of the water vapor channels of MRIR in Nimbus 3 and THIR in Nimbus 4 and 5 have proved useful in determining areas of relative moist and dry areas in the middle and upper troposphere and inferring fields of vertical motion in the vicinity of jet streams, hurricanes and thunderstorms complexes containing tornados. The cases of 23 April 1969 and 11 July 1969, summarized in this paper, show that the dry air was generally to the north of the ITC over most of the Atlantic and Pacific. However, in the deep eastern Atlantic storm on 11 July the dry air was to the south. In a case of double lines comprising the ITC, very dry air is sometimes found between the two lines.

The predominance of moist air on one side and dry air on the other side of the ITC suggests a feeding of energy into the upward vertical motions associated with the clouds of the ITC from one side while compensating subsidence occurs on the other side. This dynamic process seems to be at odds with the classic concept of the ITC being the result of the convergence of trades from the two hemispheres.

Moisture and cloudiness links to disturbances at higher latitudes are also observed emanating from the ITC. The dry air frequently exists between these links and the ITC suggesting subsidence and a dynamic interaction between the tropics and higher latitudes.

Measurements of a microwave radiometer from aircraft during the Nimbus 3 overpass confirmed the existence of dry and moist regions and showed regions of rainfall in the ITC. The Electrically Scanning Microwave Radiometer (ESMR) on Nimbus 5 has shown that it is possible to map rain areas on a global scale over the oceans and to some extent over land. Further studies using ESMR and THIR (Temperature Humidity Infrared Radiometer) on Nimbus 5 should add considerably to our knowledge of the structure of the ITC.

Acknowledgment

Data from the Atlantic flight through the ITC was first analyzed by Mr. J. Conaway, formerly of GSFC. The flight test had been planned by Dr. William Nordberg partially in connection with BOMEX but also as a preliminary test of ESMR.

References

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Paris, J. F., 1971: Transfer of thermal microwaves in the atmosphere. Dept. of Meteor. Report, Texas A & M Univ. 1971.

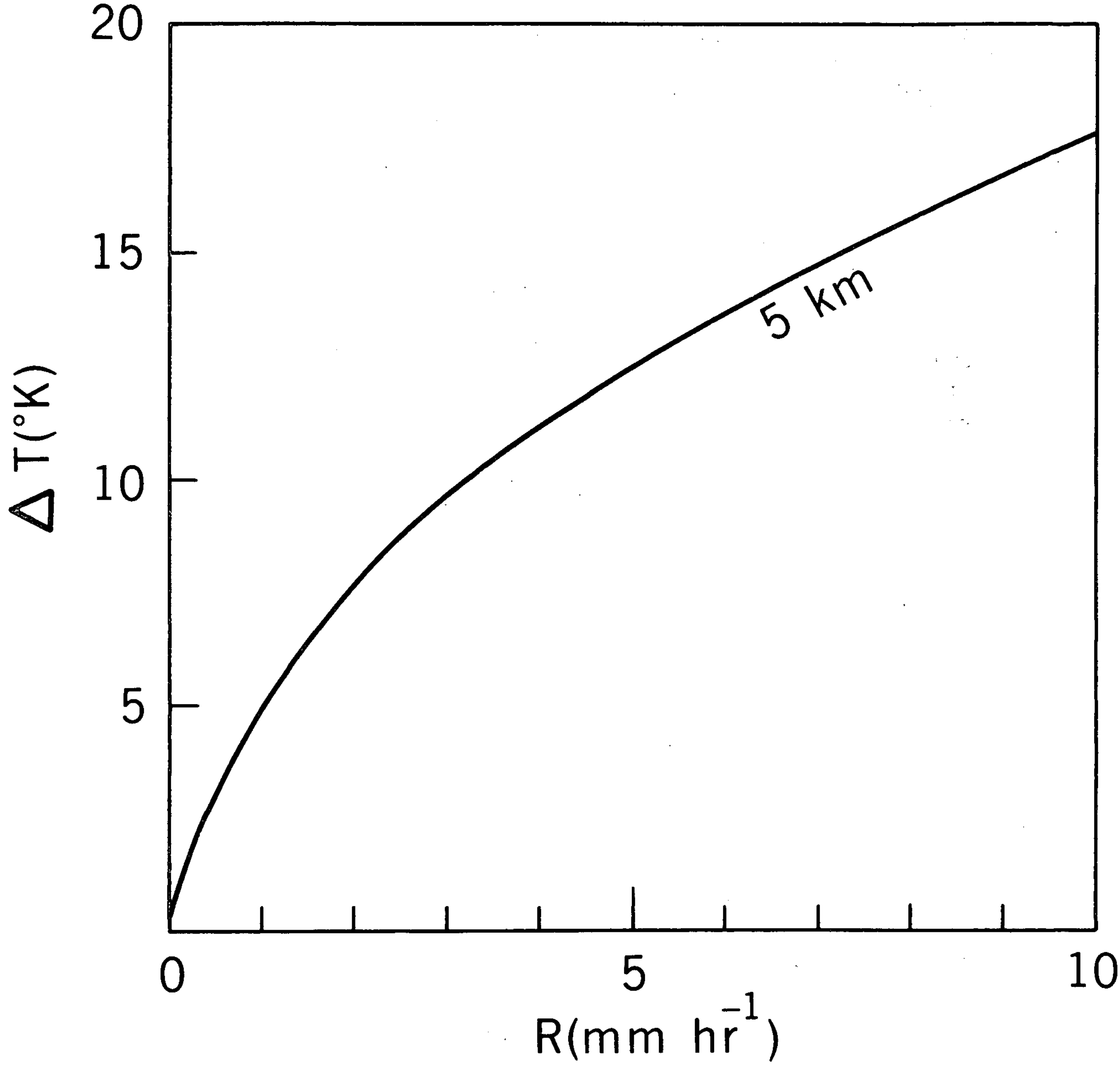

Figure 1. Increase of brightness temperature as a function of rainfall intensity.

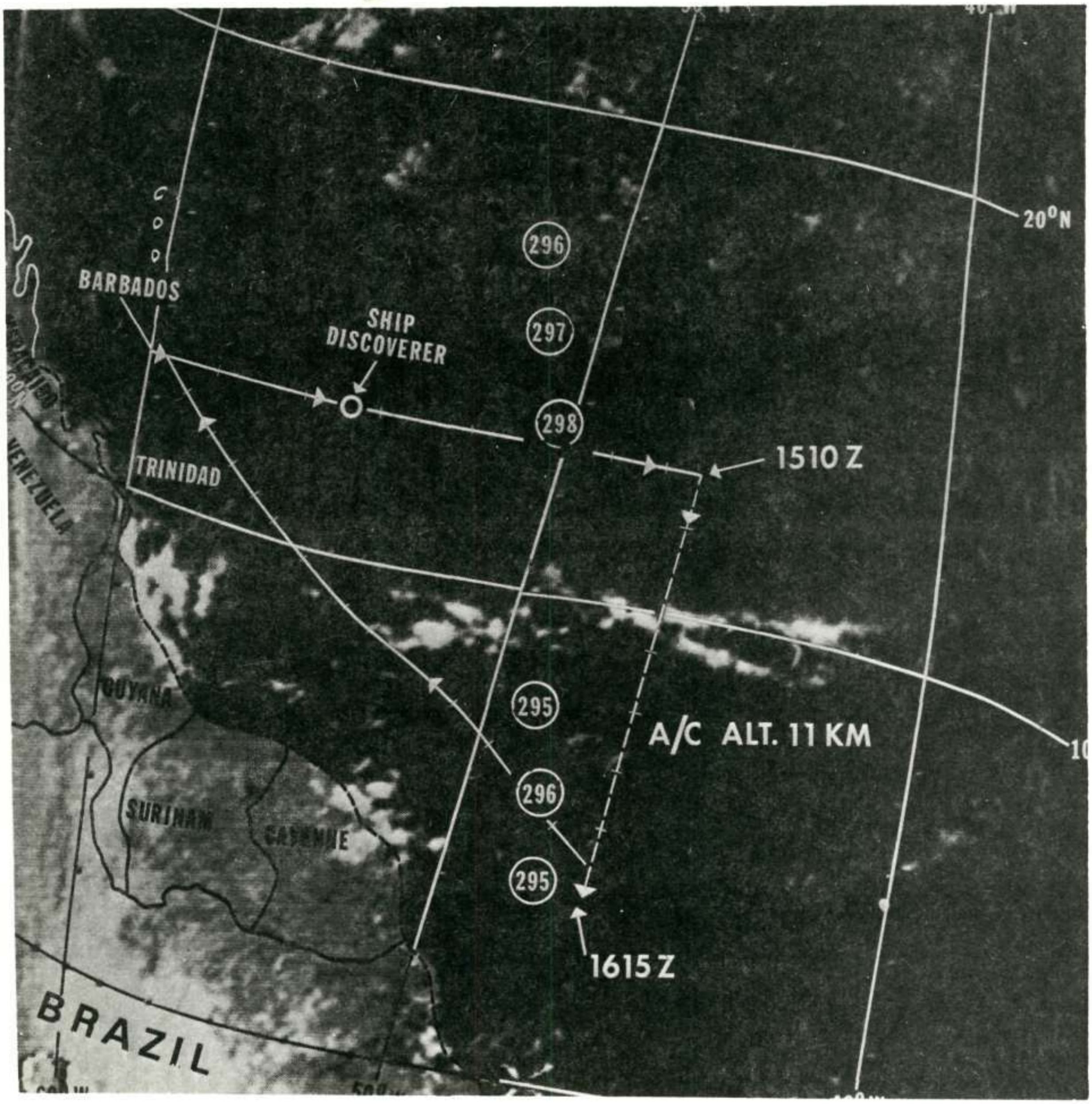

Figure 2. Nimbus 3 photograph of the eastern tropical Atlantic and aircraft track across the ITC, 11 July 1969. Circled numbers represent sea surface temperatures measured by Nimbus 3 IRIS.

B

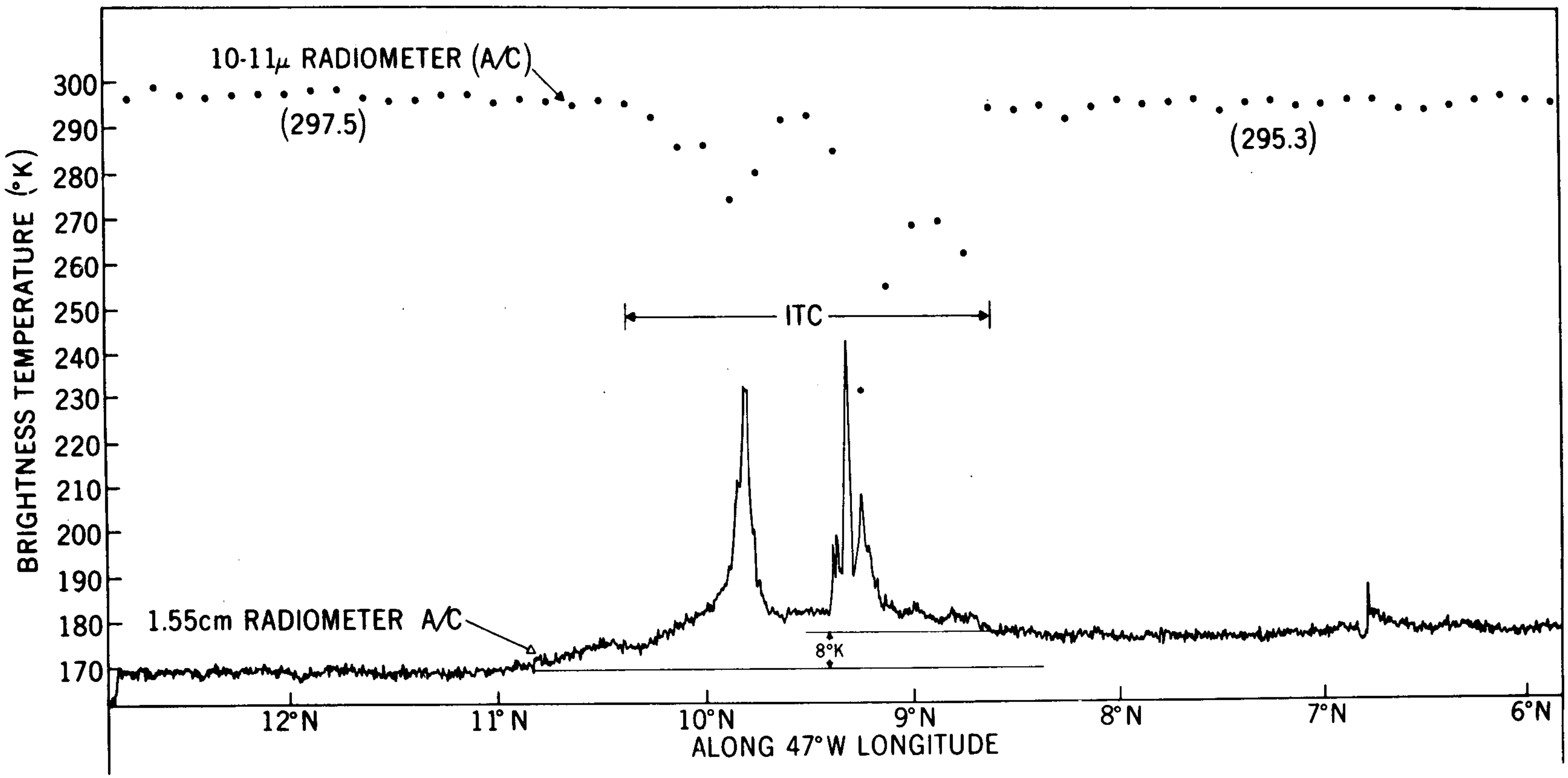

Figure 3. Aircraft cross section of brightness temperatures across the ITC in the Atlantic, 11 July 1969.

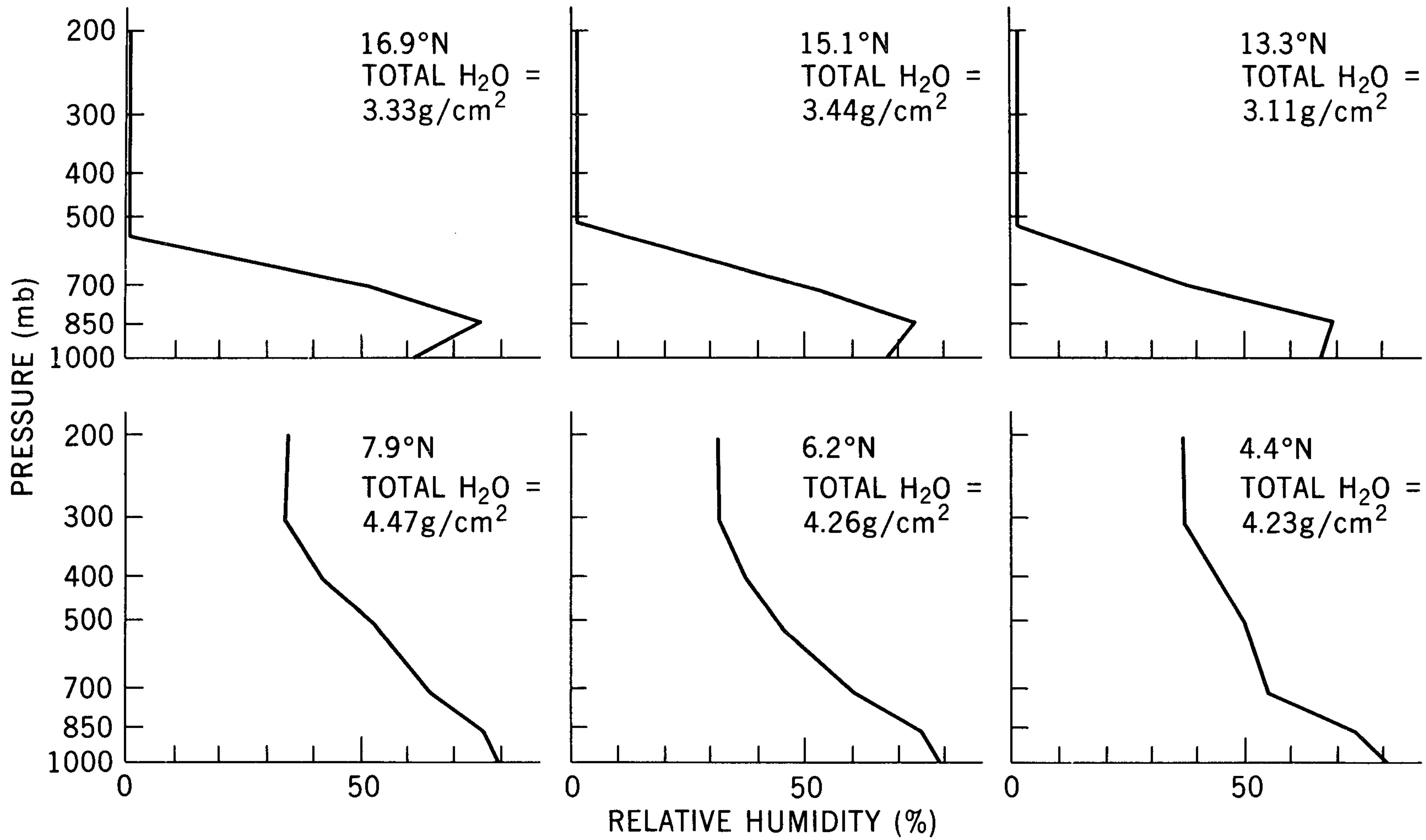

Figure 4. Vertical profiles of relative humidity north and south of the ITC near 48°W, as determined from IRIS, Nimbus 3, 11 July 1969.

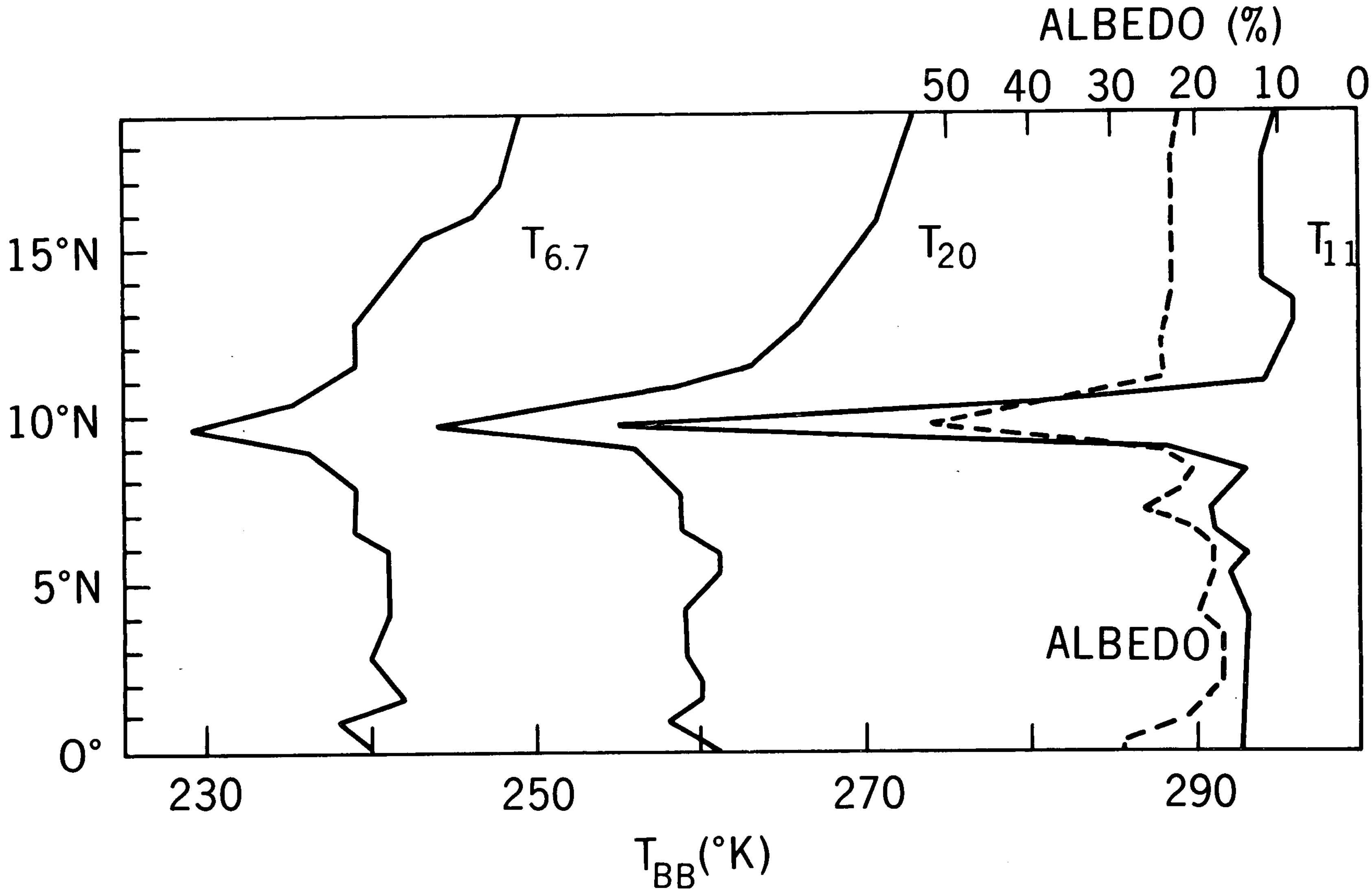

Figure 5. Cross sections of equivalent black body temperatures and albedo through the ITC near the 48°W, orbit 1183, Nimbus 3, 11 July 1969.

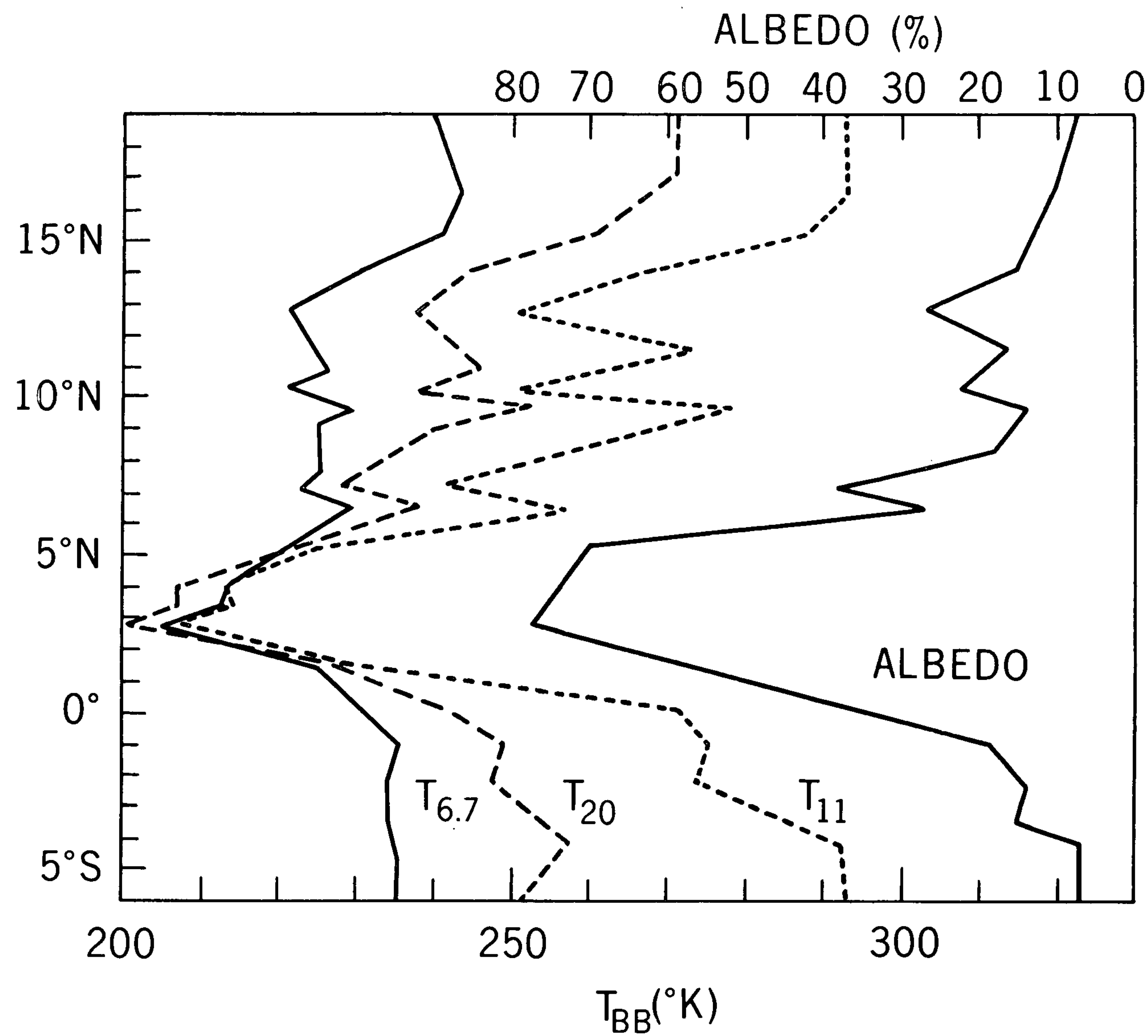

Figure 6. Cross sections of equivalent black body temperatures and albedo through the ITC near 173°E, orbit 130, 23 April 1969.